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1.0 Introduction

This paper presents an investigation into the applicability of fiber optic communication techniques to real time avionic control systems, in particular the TAFCOS System (Total Automatic Flight Control System) used for the VSTOL aircraft.

As presently contemplated, the system is to consist of spatially distributed microprocessors. It is also expected that the overall control function will be partitioned to yield a unidirectional data flow between the processing elements (PE). To enhance system reliability the use of triple redundancy is anticipated.

Some general overall system specifications are listed here to provide the necessary background for the requirements of the communications system. (See Fig.1)

A. Architecture:

1. Estimated total of 11 processors, each with triple redundancy - 3 PEs, for a total of 33 PEs.
2. Processors spatially distributed (in groups of 3 PEs) with a maximum separation of 200 feet.
3. Data flow unidirectional with provisions for local data entry.

Data rates (estimates):

1. Real time sampling rate: 20 samples/sec.
2. Data per sample - 3-3 dimensional vectors.
3. Bits per dimension: 16

   Additional control signals may increase the overall data/control rate.

C. Miscellaneous

1. High reliability, compatible with avionic systems.
2. Error rate comensurate with real time sampling interval and bit rate. A 10^{-6} to 10^{-7} sample failure rate leads to an approximate bit error rate of 10^{-8} to 10^{-9}. (This assumes that a single bit error is tantamount to the failure of a full 3x3 data frame, a very severe assumption.)
3. High system modularity.
4. Maintenance of software simplicity.
5. High degree of system expandibility and flexibility.
6. High maintainability, both software and hardware.
7. High immunity to EMI and RFI.

The number of processing elements involved is a function of the overall control system operational requirements as well as of the functional partitioning. As noted, it is assumed that the interprocess data flow is unidirectional. This assumes the existence of a functional assignment scheme in which PEs are operating in a largely independent pipe-line mode. Each PE operates on data received from only one other PE (and transmits data to other PE), excluding local data inputs. These partitioning requirements may lead to a larger number of PEs than would otherwise be required. The spatial distribution is not related to the functional sequence. As a result, the pipe-lining is logical only and not physical.

The data rate estimates are based on the real time performance of the controlled vehicle. As we see later, these are minimum estimates. The computing system, and of course the communication system, are expected to be able to handle substantially higher data rates, to allow future system expansion and provide for design contingencies.

In specifying a high system reliability, the emphasis is on catastrophic failure. This reliability must be consistent with the overall avionic reliability standards. The avoidance of catastrophic failures requires the incorporation of a multiple of alternative mission success paths (Fig.2). Each of these paths, in itself, must be sufficient to permit full, even if degraded, execution of the mission. The need to provide multiple success paths implies the use of redundancy.

Error rate in real time systems is substantially less severe than that for business applications, for example. The basic system response is in itself a mitigating factor. Variables can not change at rates exceeding the real time capabilities of the system. A single data frame (a sample period) may not be very significant in a well designed real time control system, and hence the loss of even a full frame (9 words) is not likely to severely affect system operation.

This mitigating effect has a strong bearing on synchronization problems. The loss of frame synchronization, as long as it is non cummulative, i.e. worsens with time, is of secondary importance. Full frame synchronization recovery may be provided by software, or hardware, using subsequent real time data. (We refer here to a time shift in the pipe-lined processing system, and not to loss of word or bit synch, as may be encountered in serial data transmission.)

Items C-3 through C-7 in the specifications list are self explanatory.

2.0 The Communications Problem

The large number of processors involved in the system presents a communication problem. In the most general case, we may expect every one of the 33 PEs to communicate with all others. This clearly entails a massive intercommunication network.

The specific system architecture and data flow have a direct bearing on the communication network. In particular, the limited requirements imposed on data flow may permit some simplifications, while the need for multiple success paths (more than the three paths that might be encountered in a triple redundant system) implies more severe performance requirements for the communications network.

First, the communication architecture has to provide unidirectional (or simplex) data transmission only (more on this later). Second, it is essential that the communication structure have distributed control functions. No central communication control is acceptable since a failure in this control unit is "absolutely" catastrophic, and thus, substantially reduces reliability. In a way, this requirement implies that most TDM methods are unacceptable unless timing controls (usually essential in TDM) are distributed, or eliminated. (Such a TDM method requires inclusion of destination address, directly or indirectly, in the transmitted data. We reexamine the alternatives later).

The problems and alternatives, of computer communication architecture have received substantial attention in the literature.[1-9] Although this paper focuses on a specific communication architecture, with some very specific requirements, a brief summary overview of the general computer communication problem is presented first. More precisely, the available alternatives and some of the important features of these alternatives are examined.

3.0 Basic communication architectures (Fig. 3)

Two fundamental communication strategies are distinguished, the direct mode and the indirect, or routed approach. The latter is most suitable for larger networks where alternative communication paths are available and must be considered. This approach is too cumbersome for a local (very local) data communications network in a real time environment. It requires complex data switching and routing algorithms in hardware or software, particularly when a large number of processors are involved.

The direct method can be further classified on the basis of the data transfer paths. A dedicated path provides for direct data transfer between two processors only, unidirectionally or bidirectionally. The communication architecture required to allow direct dedicated data transfer can either be a ring structure, where data is transferred to the immediate neighbor only (Fig. 4); or a "complete" interconnect structure, where every process is connected to every other process (Fig. 5). In the ring architecture, the path to non-neighbors passes through the immediate neighbors.

The general description of this type of communication network, which includes both ring and complete interconnect structures is the K-connected network (Fig. 6). Here K denotes the number of other nodes each node is connected to. Thus, for a N-node network, if K=N-1, we have a "complete" interconnected network, while for K=1, we have, effectively, a ring structure.

Contrasting the dedicated strategy is the shared data link, where data is communicated via a shared resource. A central memory, communicating with all processors, or a common data bus are typical examples of the shared approach (Fig. 7).

The classifications made in the foregoing discussion should not be taken as absolute. The design of the communication system may very well contain features that cross the boundaries of these classifications. Various multiplexing methods may imply hardware resource sharing while maintaining the characteristics of a fully dedicated data network.

It is useful, at this point, to examine the various communication system designs against the background of the requirements of the proposed flight control system. In the shared interconnect system, there are by definition, one or more resources common to all (or some) of the processors. The use of this shared resource, network or memory, requires conflict adjudication and access control. In other words, in addition to sharing the communication network, the system must have a resource allocation control unit. This may result in substantial degradation of reliability. It substantially reduces the gains in reliability expected from the introduction of triple redundancy.

In general, the control of the common communication resource may be either centralized, or distributed (Fig. 8). In the centralized mode, the functions of communication resource allocation, and conflict resolution are assigned to a central control unit. Typically, when a central memory is used as the communication media, the access to the memory is carefully monitored and controlled by a memory access and allocation unit. In the distributed mode, each processing element contains a communication control unit (in software or hardware). The first communication strategy, the centrally controlled system, may cause substantial deterioration in reliability due to the centralized nature of the control function. It introduces a weak, potentially catastrophic link into the system.

The distributed control approach may present some synchronization problems, precisely because of the distributed nature of the operation. It does, however, preserve the reliability advantages derived from the triple redundancy. (The synchronization difficulties are minor in light of the real time nature of the system.)

From the discussion so far, the most suitable communication architecture design is the dedicated data links or the shared network with distributed control. It should be noted, again, that the actual communication network design may indeed be a cross between these two, with some additional features resulting from the specific hardware used.

Mention must be made here of the choices of "protocol" available. The term "protocol" refers to the conventions used in establishing the communications between processing elements. At its lowest level, we are concerned with the control signals used in this process. Without going into great detail, this control signal flow can be classified as synchronous or asynchronous[31]. The essential difference between these is the need for a central and common timing signal (system clock) to provide overall timing in the synchronous approach. Again, the use of a single central element common to all PEs introduces a critical path, thereby degrading reliability.

The asynchronous mode may operate with various degrees of control signal interchange. Typically, we have the one way command where the sender (or receiver) commands reception (or transmission). This assumes that the receiver (or sender) is always ready to take the appropriate action.

A two way control link includes a request-acknowledge interchange. The sender (or receiver) requests the action and the receiver (or sender) acknowledges its readiness to take the requested action.

The one way command has the advantage of simplicity and the disadvantages of possible serious conflicts. It is usually appropriate in very special applications where conflicts are inherently impossible by virtue of the characteristics of the overall system. The one way method also allows a greater degree of independence between the communicating PEs. This leads to a higher degree of modularity, both hardware and software, which is a major system advantage.

The two way data flow control is more complex. It may lead to increased data/control rates; and it ties the communicating PEs together. It should be noted that error detection and retransmit are possible only in the two way control. (It then becomes a much more complex interchange.) This latter advantage is of minor importance in real time systems, since as noted previously, an error in a single sample is usually insignificant in a real time environment. Moreover, on-line error detection strategy can easily eliminate if not correct, the erroneous data, thereby avoiding real time error-induced transients.

Most communication systems provide a higher level protocol; that is, a protocol which is not concerned with the hardware oriented control function, but rather with the higher language data flow control.[3,8] Here, the user is unaware of the lower levels of the communication system. He is presented with a virtual communication path directly to the receiving processor (or process).

The triple level of communication protocol shown in Fig. 9 represents a typical interprocessor communication link. Additional intermediate levels may be included to enhance the overall operation. For example, a temporary storage may be inserted between the OS and the communication device (Fig. 10). This addition provides increased isolation between the processors resulting in greater independence of both software and hardware in the distributed system. Each PE can now be independently programmed with no (or very minimal) time dependence on other PEs, (essentially asynchronous execution of assigned function). Needless to say, this independence is likely to result in marked improvement in system modularity.

4.0 Hardware-considerations-Fiber optics

The design of a communication structure for the TAFCOS system, (which provides great measures of modularity, flexibility, expandibility, independence, both software and hardware, reliability, redundancy, and simplicity) is difficult at best. One is tempte to propose a completely connected,dedicated network with triple redundancy (Fig. 5). Implementing such a system with conventional hardware, wired links, is nearly impossible, and certainly too cumbersome. It's reliability is questionable as there are too many contact points and its weight is unacceptable. The lack of RFI-EMI protection is intolerable in an airborne system.

The use of coax, or wave-guide <u>bussing</u> (as opposed to fully dedicated wired data links) has a number of drawbacks: first, insufficient EMI-RFI protection; second, a triple redundant coax system is no improvement in terms of weight. In addition, methods must be developed to provide the needed module independence. (The module may consist of a single PE or a triple PE unit.) Consideration must also be given to the bandwidth involved in transmitting the data of <u>all</u> PEs through a single cable.

The use of optical fibers as the communication medium presents a near perfect solution, at least theoretically. The fiber is highly protected against RFI-EMI, it is extremely lightweight, and has a bandwidth capability a few orders of magnitude greater than that of a coax cable. However, a number of practical problems, involving optical power coupling, optical power sources and detectors as well as methods of modulation and demodulation, must be solved before a practical optical fiber data link can be applied to the distributed processor system. (It should be noted that the nature of these problems is substantially different from those encountered in fiber optics telephone communications which has received most of the attention in recent years.)

Before investigating some of the fiber optics difficulties, and as a preliminary to the development of an overall fiber optics approach, it is useful to review some of the characteristics of fiber optics as related to data transmission. The basic principles underlying the transmission of optical power through an optical cable are similar to those involved in the confinement of electromagnetic waves in a wave-guide (or coax cable). The confinement of the optical power is accomplished by varying the refractive index, n, from the inside of the optical cable towards the outside (Fig. 11) where $n_2 < n_1$.

Two basic types of fibers are presently in use: the step index where n_1 and n_2 are distinct values (usually around 1.4 to 1.5 with $\Delta n \approx 1-2\%$, and the graded index, where the index is continuously varied from the center outward (usually a parabolic index distribution). The characteristics of these two types differ substantially. In particular the dispersion is substantially lower in the graded index, hence the bandwidth is substantially higher. These differences are, however, of secondary importance in applications with relatively short transmission paths (For the airborne system, it is estimated that the maximum path length will be 100', or 200' if a ring approach is taken.) This is somewhat of an oversimplification. Poor dispersion characteristics lead to higher power requirements at the receiving end for a particular data rate and a given error rate. This subject will receive some further attention in the discussion of general system design.

The typical commercially available fibers have a wide range of performance characteristics. They are available with attenuation as low as 4 db/Km (cables with less than 1 db/Km have been constructed on an experimental basis), dispersion of about 1.5 ns/Km (about 300 M bits/sec) and length (without splices) of about 3 Km (Table 1)

Table 1 Typical Premium F.O. Cable

Loss	5db/Km	@ .8 um wavelength	
	.65db/Km	@ 1.27 um wavelength	
Bandwidth (3db)	400 MHz-Km	@ .8 um	($\approx$ 300 Mbits/s)
	3 GHz-Km	@ 1.27 um	($\approx$ 2 Gbits/sec)

Misc.

Core	50 um	($n_1 \approx 1.4$)
Cladding	125 um	
Δn	$\approx$ 2%	
Price	$1/m	(of single fiber)
Length	3 Km	

Note: The radical improvement in attenuation and BW for the 1.27 um wavelength is typical for fiber optic cables. The .8 um wavelength is, at least presently, predominantly used, due to the availability of sources and detectors in this region. Present research is heavily directed at the development of sources and detectors at the 1.27 um wavelength in order to take advantage of the almost ideal characteristics of the cables at this range.

It should be noted that a 200' length of a cable with a bit rate of, say 400 Mbits/sec for 1 Km length (the BW decreases with increased legnth since the dispersion, or pulse broadening, are given per Km length) yields a usable bit rate of about 400 x 3300'/200'= 7.0 Gbits/sec which is well beyond the rate expected to be used in the proposed system. Similarly, an attenuation of 4db/Km results in a total cable attenuation (for the 200' length) of about .25 db. The conclusion is clearly that attenuation and BW characteristics of available cables are far better than required for the avionic system.

The advantages of the fiber optic cable, as compared with wired busses, coax or waveguides are:

1. Wide band transmission which helps improve
   a. Flexibility. The system can be reconfigured with no wiring changes.
   b. Expandibility.
   c. Modularity. The high available BW permits the use of the equivalent of a fully dedicated interconnect system resulting in improved functional isolation between the PEs and hence a highly modular sytem, both from software and hardware points of view.
2. High RFI-EMI and lighting immunity, leading to improved reliability under adverse conditions.
3. Electrical isolation
   a. Minimize ground loop effects.
   b. Permit fully self contained (hardware isolated) PEs.
4. Substantial size and weight reduction (better than 20:1 improvement in weight has been demonstrated)[10]
5. Simple installation.
6. Highly cost effective (in particular where high data rates are required).

5.0 Fiber Optics Communication Architecture.

To make use of the large BW of the fiber optic approach, it is necessary to use a single fiber (with appropriate redundancy) for the transmission of data to-from a number of PEs. It is anticipated that all 11 processors will utilize a single fiber. The composite data carried by the fiber may take one of three basic forms.

a. Time division multiplex (TDM) method.

b. Frequency division multiplex (FDM) method.

c. Wavelength division multiplexing (WDM).

All three techniques may be used, at least theoretically, to provide the interconnect network. Note that the hardware involved is a single optical cable (redundancy will be considered later), implying a shared, not dedicated, approach. Whether the communications network is to be characterized as "shared" or "dedicated", functionally, if not in terms of the hardware, depends largely upon the method of communications used, TDM, FDM, or WDM.

Even though the main thrust of this paper is the FDM (and to some extent the WDM approach), a brief description of all three is presented. In order to tie technology more firmly to the actual system, we assume a PE architecture which is intended to provide great independence between PEs. Figure 12 shows the basic PE structure.

As far as the user (programmer) is concerned, the only significant level of communication is that which provides the path between the PEs (dashed line). From the system designer's viewpoint, the lower levels, and particularly the local buffer, are essential if asynchronous operation is to be considered.

The complete data path can be described in general terms as follows:

1. Data is transmitted, including frame synchronization and receiver address.
2. Interface identifies destination and decodes data.
3. With proper protocol, to avoid simultaneous read-write in local buffer, data is stored in local memory.
4. PE accesses data (with proper protocol).

The details of this sequence depend strongly upon the communication method used: TDM, FDM, or WDM.

TDM [11] When using TDM, the data arriving from the different sources are assigned specific time slots, dynamically or statically. For simplicity, a static time slot assignment, that is, not under program control ("fixed for all time") is assumed. Typically the data will take the form as shown in Fig. 13.

This time slot assignment assumes a master timer, or frame synchronizer, which controls the time allocation to the various PEs. It is evident that this type of operation can be classified as a centrally controlled system, with all its inherent disadvantages: strong PE interdependence, degraded reliability due to the existence of a central control whose failure is catastrophic.

One can envision a distributed control approach. This would involve the preassignment of the sequence of transmission, e.g. PE #1 followed by #3 etc. Each PE will use the cable after its predecessor, as predefined, has completed transmission. Note that, while the decision to transmit is relegated to each processor, the failure of one transmission (e.g., the absence of the bit that identifies completion of transmission, or an error in the sender's address) may completely disrupt communications, and special provisions for failure recovery must be made. These may be complex, and may involve a master executive of sorts, which brings us back to central control. (See Asynchronous TDM, ATDM [12,13])

Many TDM systems have been constructe . A good portion of these systems are used in telephone communications, CATV [14,15] or other noncritical applications [10,11,16,17,18,19]. All have some central control strategy with either selfclocking signals or the use of a F.O. cable dedicated to distribution of clock signals.

From a technical point of view, the TDM approach is easiest to implement. It relies on direct intensity modulation (IM) of the optical source. Most present TDM systems utilize pulse amplitude modulation (PAM) of the intensity of the source (PAM-IM). This approach minimizes effects of nonlinearities in the light source and results in extremely simple transmit and receive circuitry. Other techniques, such as pulse frequency modulation (PFM) (essentially frequency-shift-keying-FSK) combined with IM have so far had very little use. While it is not the purpose of this paper to promote the use of PFM, it must be seriously considered in the design of the communication system. Its inherently better immunity to noise (and hence, usefulness at lower power levels, about a 20db improvement over PAM) may be a well worth compensation for the usually increased bandwidth requirements associated with PFM (more on this subject in our discussion on FDM).

FDM [16,20,21]

In the TDM approach, addresses are synonymous with time slots. Addressing is done in the time domain. The FDM techniques relies on frequency domain addressing. Each source (or destination) is assigned a subcarrier frequency. Address decoding is accomplished by detecting the subcarrier frequency via resonant circuits, or phase-lock loops (PLL). The receiving station responds only to its preassigned subcarrier frequency.

In a multiple channel station-to-station (trunk line) transmission, each data channel (logical channel, not a physical connection) modulates a distinct subcarrier. The composite signal, which contains all modulated subcarriers, intensity modulates the light source. In this method the "mixing" of the data channels is done at the subcarrier level (Fig. 14).

Another approach to FDM, which is more suitable for the distributed system under investigation, is often referred to as the broadcast technique. It relies on mixing of the modulated subcarriers at the optical power level (Fig. 15). Each data source modulates its own subcarrier, which then intensity modulates its own light source. The optical power from all channels is transmitted to the respective destinations via the fiber optic cable.

The use of FDM Broadcast methods, as contrasted to TDM, leads to a communication system with very loose (or no) central control. The receiving station listens continuously and takes action only when its preassigned subcarrier frequency is detected. The transmission of multiple channels may take place simultaneously.

Since the Broadcast technique involves multiple light sources and multiple photodetectors, it is essential that all sources and photodetectors be compatible. In other words, the wavelength of all light sources must be approximately the same and compatible with the photodetectors' optical response.

WDM [22,23,24]

Wavelength division multiplexing may be compared with standard radio broadcasting. Each data channel is assigned a wavelength, say of .8 um, .85 um etc., similar to the carrier frequency assignments in radio broadcasting. This clearly indicates that each channel is associated with a specific light source (or appropriate optical filter) operating at the preassigned wavelength. The optical power from all sources is 'mixed' in the optical fiber which serves as the transmission medium (Fig. 16). On the receiving end, an optical filter directs the different incoming wavelengths to different photodetectors.

Many optical filters rely on the dependence of refraction index on wavelength (the prism effect) or on grating effects.

Dichroic beam splitters have been investigated for use in WDM [25]. All these methods require extreme mechanical tolerances and hence are very sensitive to temperature variations. As a result, the experiments with these techniques have been confined to large fiber bundles (500 um diameter). The large size of the fiber cable, somewhat alleviates the problem of mechanical tolerance.

Other methods, such as limited bandwidth photodetectors and light sources, are presently being investigated.

An interesting, and marginally relevant, wavelength filtering method has been developed by Sperry Research Center[31]. The basic principle used is the dimensional changes, hence changes in optical characteristics of a crystal when varying voltages are applied to the proper axis. This method has permitted, at least experimentally, switching optical power from one detector to another. In all cases, the diffraction angle depends on wavelength and on the voltage applied to the crystal. The result is a voltage variable optical filter (wavelength filter).

6.0 FDM Bussing.

The following section discusses in some detail, a specific approach to the communication system using FDM techniques. Initially, we consider an FDM communications bus as applied to a single, non-redundant, processing system. A basic bus architecture is proposed and some detailed design problems investigated.

One of the major advantages of the FDM approach is that it accomodates a full duplex data transfer, that is, data may be received and transmitted simultaneously by every node. In this way, each processor in the distributed system operates independently of all others, with no need for synchronization, or <u>central</u> data flow control. Each PE performs its preassigned function on the received data and then transmits the partially processed data down the pipeline. (It may be necessary to provide some internal timing so that sample timing is maintained). Read-write (receive and transmit) of each PE are executed under local software, with <u>no</u> central executives. This approach closely simulates the dedicated complete interconnect network. The word "dedicated" here refers to a dedicated subcarrier rather than to a dedicated physical bus. The basic architecture is similar to the broadcast FDM discussed in the section on FDM. This approach results in a minimum of bus protocol, no access conflict and hence a very simple network. (The structure of the individual processing nodes is, fundamentally, that shown in Fig. 12). Figure 17 shows a typical segment of the complete distributed system indicating subcarrier assignments (SEi SEj) and the direction of data flow. As we noted, data flow is unidirectional in the bus., consequently we use a "U" type architecture [26,27], providing communication between all P E s. If we assume, for the sake of an example, that PE_i (the ith PE) receives data from PE_k and say PE_k received from PE_j then the subcarrier assignment is as shown in Fig. 17.

All data is "received" from the "return leg" of the F.O. cable. This portion of the bus contains data from all PEs. Hence, every PE may receive data from any other PE (Bidrectional data flow structures have been investigated [27]. It is however the feeling of the author, that the unidirectional approach is much simpler and less problematic). By selecting an appropriate "front end" subcarrier filter and demodulator, we have the freedom of affecting changes in the communication process with great ease and without the "awareness" of the PEs themselves, that is the PE software is fully independent of the data source. This approach enhances modularity, since both PE software and hardware are associated with fully independent entities. Note that each PE has a light receiver and demodulator and a modulator and light transmitter. The mixing of the multiple channels is done in the fiber cable itself at the optical power level.

Bandwidth.

Based on the overall system data rates (see Introduction) and assuming that transmission time may not exceed 5% of total sample period (2.5 ms), we get a data rate of about 60 kbits/sec per PE. With data from 11 P E s using the bus, the bus data rate becomes about 660 kbits/sec. Allowing for increases in this rate due to the addition of frame synchronization bits and a variety of control signals, a good estimate for bus data rate is 1.0 Mbits/sec. Using TDM, the buss bandwidth can be estimated at about 1.5 MHz. Since we propose the use of FDM with frequency modulation, PFM, (as opposed to amplitude modulation, PAM) we can estimate bus bandwidth as about 6.0 MHz. This is based on: a. MOD Index=1, that is $F_d=F_m$(F_m=modulation frequency, F_d=Freq. Dev.) b. B.W.=$2F_d+2F_m$. This bandwidth can very easily be accomodated by the fiber cable [18]. Even if a substantial increase in this bandwidth is required to provide for a greater flow of control signals and possibly wider guard band separating the subcarriers (reducing intermodulation, and "spillover") the fiber cable bandwidth will still be grossly underutilized. Fiber cable bandwidths in excess of 300 MHz have been demonstrated for longer cables (1 Km or more) [10,15]. It is expected that for the short cable contemplated (200') there will be no bandwidth limitation for all practical purposes.

The use of PFM is proposed, since its noise characteristics are about 20db better than those for PAM (hence a lower bit error rate) and since its attendant increased bandwidth is of no consequence.

Note that the extremely large available BW permits large increases in computation power (addition of PE s) without any major system modifications (the simple incorporation of additional subcarriers.)

<u>Power, data rate and BER.</u>

Receiver signal power, the data rate in the cable (utilized BW), and the BER (Bit Error Rate) are strongly interrelated. The BER is essentially a function of the signal to noise ratio, S/N, at the receiver [10,26,27,28,29]. The signal to noise ratio is clearly dependent on the equivalent noise power of the receiver, from all sources, and the signal power. (The effective BER is also, somewhat dependent on the type of code used and the detection threshhold. In this general presentation, we will not be concerned with these details). The total equivalent noise power is related to the B W (or data rate). With a constant signal power it is expected that the wide BW system will yield a worse BER. Stated differently, if we attempt to maintain the BER, say at 10^{-9}, we then have to increase signal power as bit rate is increased. The specific values, that is what signal power is required for what BER at what BW are a complex function of the specific circuits and techniques used. A typical plot of received signal power vs. bit rate for a 10^{-9} BER is given in Fig. 18. [31]

There are various ways of improving S/N. A simple approach would be to increase signal power at the transmitter, use of lasers as opposed to LEDs, and use more sensitive photodetectors, APD as opposed to PIN. This cannot always be done. In particular, the use of lasers in analogue modulation (note that the FDM approach requires sinusoidal modulation of the laser at the subcarrier frequency) may present some problems due to the nonlinear behavior of the laser. (Even more serious are the typical "kinks" in the light vs. drive current characteristics of the laser). It is then essential that all signal power losses along the transmission path be carefully considered, in an effort to minimize these losses.

One of the major noise sources in the system is the receiver itself, the photo diode circuit, the amplifier etc. It is not our intention here, however to proceed with the analysis of the receiver.

Noise sources, such as subcarrier interference, or subcarrier intermodulation can be reduced by providing "heavy" subcarrier filtering which may substantially increse the total BW , however, it decreases the actually utilized BW. (wider frequency separations between the subcarriers). Intermodulation may be kept at a minimum by a judicious selection of subcarrier frequencies and by use of linear light sources (LEDS) to reduce harmonic generation.

The Power Budget.

We now proceed to investigate the power loss through the F.O. cable. For the sake of simplicity we do not consider power loss involved in the optical signal launching into the cable at a transmission node, or with the specific coupling losses at the photodetectors. This is not to imply that these factors are negligible. It is our desire to concentrate on the transmission medium itself with its many power "taps". The purpose of this analysis is to provide guidelines for the establishment of optical power requirements. In addition, the analysis will point to problem areas that need further detailed study.

The bus shown in Fig. 17 serves as the system model (It is partially redrawn in Fig. 19).

The F.O. Bus contains a total of n nodes (n subcarriers) each node including a receive and transmit tap. A maximum cable length (roundtrip) of l feet, with a loss of kdb/ft. (usually cable loss is given in db/km. It is convenient here to deal with db/ft).

L_t - Loss at a transmission tap (coupling loss)

L_r - Loss at a receiving tap (coupling loss)

L_d - Loss due to power division

$k \times l$- Transmission loss in given cable length l. L_t is largely due to "unpredictable" cupling effects. Power is added to the cable at the transmit tap, nevertheless, since an interruption in the cable may be necessary to allow for the transmit tap, some coupling loss is expected. L_t can be kept to a minimum by avoiding connectors, that is, making the tap permanent. A connector which is necessary in order to permit removal of the PE may be provided on a pigtail permanently coupled to the bus. (See Fig. 19)

L_r is similar in nature to L_t.

L_d represents the power removed from the bus and coupled to the receiver. For example, a 5%-95% power division means that 5% of the power in the cable is diverted to the receiver while 95% is fed through. Note that only a small portion of the 5%, 1/n, is power within the desired subcarrier band. (Unfortunately there is no way we can selectively divert from the cable optical power of single subcarriers). L_d in this example is taken as .95 feedthrough loss (.2 db). The power eventually coupled to the receiver is $(1-L_d)$ times the power in the cable at the coupling point. This, for our example is equivalent to a loss of 13 db (5%).

The worst case transmission loss occurs for data from PE_2 transmitted to PE_1 (on the return leg). Involved are n-2 transmission taps and n-1 receiving taps. (The path PE_1 to PE_2 may appear to be another worst case transmission loss. It involves n-1 transmission taps and n-2 receiving taps. However, since receiving taps introduce larger losses, L_d+L_r, this path is not a worst case path.)

The total transmission loss in db is given by $L=1xk+(n-2)L_t+(n-1)(L_r+L_d)+\bar{L}_d+2Lc$ (where $\bar{L}_d=10\log(1-L_d)$, L_d expressed as a fraction. The term $\bar{L}_d$ represents the portion of the power in the cable that is coupled to the receiver of PE_1. To account for the two connectors that are involved, transmit connector of PE_2, and receive connector of PE_1, we add $2L_c$, L_c representing connector loss.

In order to gain some perspective, let's evaluate L for a typical system. Admittedly, it is difficult to assess what is "typical." The figures used are typical to the extent that they are taken from experimental, or commercially available data.[31,33]

For a 5 db/Km cable, k=.0015 db/ft. For a 200' cable of this type $k*l=.3$ db. L_t and L_r are usually very small, about .1-.2 db. (For a fused T tap structure). L_c is in the range of .5 to 1 db depending on the particular type of cable and largely a function of connector alignment. We may now give L approximately as

$$L=.3+(n-2)\times.2+(n-1)\times.2+2\times1+(n-1)L_d+\bar{L}_d$$

$$L=2.3+(n-1)\times0.4+(n-1)L_d+\bar{L}_d \text{ where } (n-1)\approx(n-2)$$

Table 1 tabulates the total loss L, the power division loss $(n-1)L_d+\bar{L}_d$ as a function of L_d and n.

Table 1 Bus Losses in db vs. L_d and n

L_d	n=10 L	n=10 $(n-1)L_d+\bar{L}_d$	n=15 L	n=15 $(2-1)L_d+\bar{L}_d$	n=20 L	n=20 $(n-1)L_d+\bar{L}_d$
.97	22.3	16.4	24.95	17.05	27.6	17.7
.95	20.9	15	24	16.1	27.08	17.18
.9	20	14.1	24.34	16.4	28.64	18.74
.85	20.45	14.55	26.04	18.14	31.59	21.69
.8	21.6	15.73	28.48	20.58	35.33	25.43

Fig. 20 shows a plot of L vs. L_d for three values of n. While the analysis is only approximate, it nevertheless clearly points to the power division terms, $(n-1)L_d+\bar{L}_d$ as the major contributor to total transmission loss. Improvement in L_c, L_r and L_t are of secondary importance. Improvement in the power division loss however, requires a modification of the approach rather than a simple component improvement. An approach, which practically eliminates power division loss is the conversion of every receiving tap into a repeater. Further study is required in order to ascertain the feasibility of this approach.

Alternately, a single repeater may be introduced, about half way through the system loss. It may also be possible to utilize a mix of T and star couplers. The latter has a much improved power division loss.

A brute force solution to the problem of system loss is simply to increase the power launched into the cable by the light source. E.G. use of laser yields a 10 db power increase compared to LED. Here again, further study is necessary, in particular as related to the effect of laser nonlinearities. In addition, connector and tap feedthrough losses may be reduced by the use of "fat" fibers, fibers with a large core diameter, exceeding 200 um. This reduces coupling losses, but somewhat increases cable loss per Km.

It should be noted that a 25 to 30db loss can still provide a 10^{-9} BER (at a reasonable BW), with a LED and APD system.

In our power budget analysis we must also take into account such things as increase of losses with aging, temperature variations, etc.

Redundancy.

The discussion, so far, considers only a single transmission loop. As we noted earlier, the distributed system is to have triple redundancy, consequently, the bus system must provide a similar triple redundancy. A simple approach is shown in Fig. 21. All three cables operate with the identical subcarriers, so that the connections are interchangeable.

The use of WDM to provide soft redundancy may be considered only if hardware reliability is orders of magnitude better than the reliability of transmission (noise immunity, etc.). WDM, however, may be useful in providing a full bidirectional fiber optic system.

It should be noted, however, that there are many difficult problems that have to be solved before WDM can become practical.

Data Structure.

The exact data and word synch format will not be considered here. It can be similar in form to the 1553B std. (to the extent that it can be applied to FDM). Self clocking code, such as the manchester code may be used. Additional diagnostic data may be included in the word format,or else transmitted on a separate diagnostic subcarrier, common to all processors.

The PFM, (or FSK) may consist of essentially two frequencies, around the subcarrier frequency f_{sc}, representing logic '1' and logic zero.

$f_{sc} + \Delta f \rightarrow$ '1'

$f_{sc} - \Delta f \rightarrow$ '0'

It may be useful to have a "neutral state", i.e. transmission of f_{sc}.

$f_{sc} + \Delta f \rightarrow$ '1'

$f_{sc} \rightarrow$ no data

$f_{sc} - \Delta f \rightarrow$ '0'

This will facilitate on line monitoring of the transmission even with the absence of data.

Summary Review

The proposed fiber optic bus system consists of:

1. A unidirectional loop (triple redundant).
2. Power division taps for receive and suitable taps for transmit (fused taps).
3. FDM with wide guard-bands to provide fully asynchronous communication between all processors.
4. Data format using PFM to improve noise characteristics (at a cost of loss of available BW).
5. PFM itself essentially a three-frequency FSK system.
6. As a first step, LED sources and PIN detectors.
7. Connectors to facilitate installation.
8. The necessary electronics for transmission and detection, with provision for repeaters if required.

The above system will provide:

1. A bandwidth substantially above the 6.0 MHz estimated as the system requirement.
2. An autonomous operation of the processors in the system.
3. BER better than 10^{-9} (for a 10 node bus).
4. All the advantages associated with a fiber optic cable, e.g. lightweight, RFI-EMF immunity, etc.
5. Simple expandability (As contrasted with substantial difficulties involved when expanding a TDM system).
6. Simplicity, software and hardware.
7. Ease of installation.
8. Cost effectiveness.

Conclusion

It is felt that the proposed system is technically feasible with today's components, and certainly with 1981-82 technology. The main problems are typically not those encountered in telephone trunk systems. Cable attenuation is unimportant. There are no field requirements, e.g. splicing, cable installation problems, etc. Bandwidth available is substantially more than that required by the system.

The major problem entails the development of improved optical power distribution, taps, connectors, etc. The use of high power light sources with efficient coupling to the cable requires further investigation.

Development effort must go into design of circuitry suitable for use in PFM-FDM applications. These circuits must have the necessary dynamic range to cover the optical signal range (OSR). In other words, the receiver must be capable of handling the signal level variations involved in the system. The OSR can be estimated to be somewhat less than the worst case signal loss (See Table 2).

It is felt that a demonstration system with somewhat relaxed goals can be developed with existing components and technology. (It would be sufficient to demonstrate 6.0 MHz BW, with a simulated maximum cable loss and a single subcarrier transmit receive system with other subcarriers artificially injected).

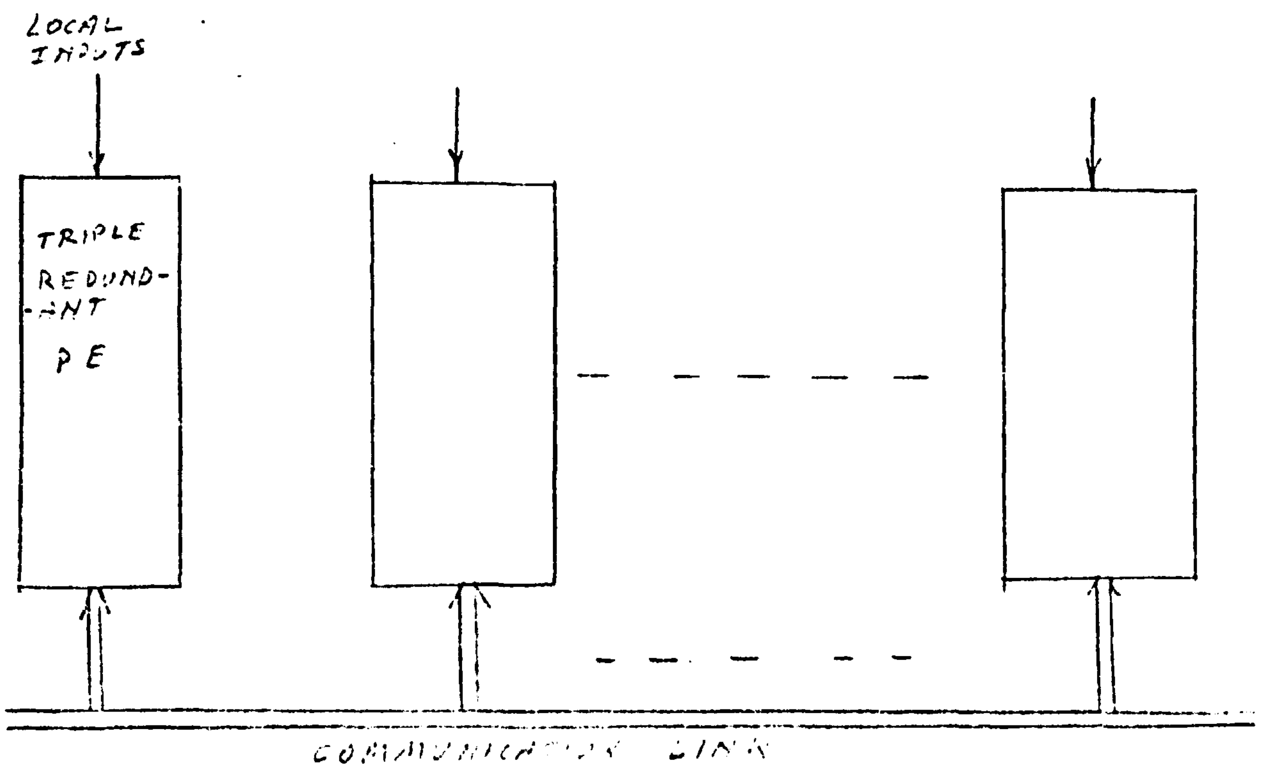
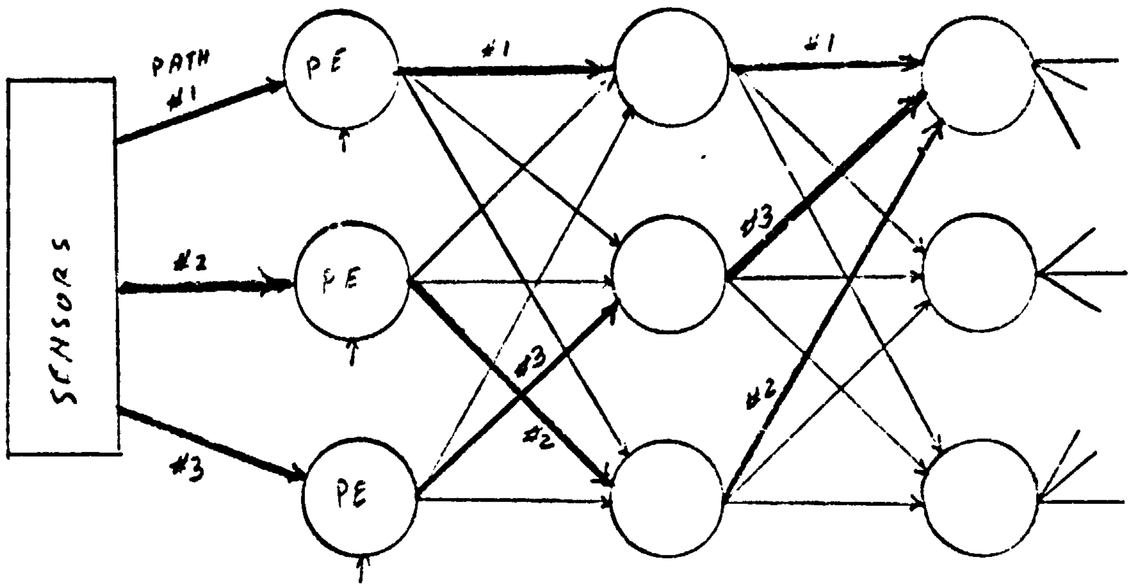
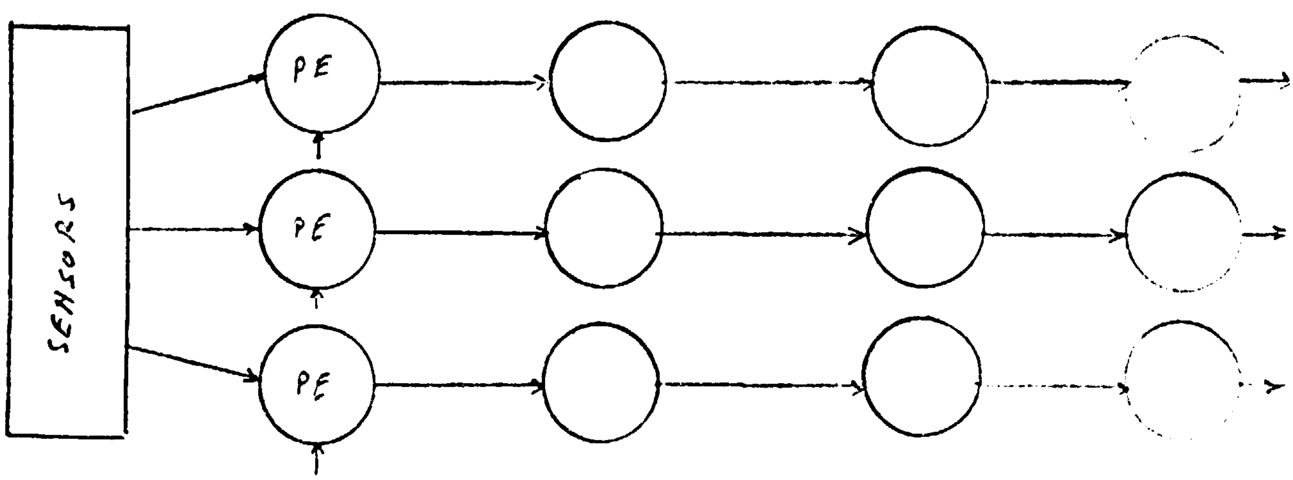


FIG. 1 TYPICAL SYSTEM ARCHITECTURE



b. MULTIPLE SUCCESS PATHS (THREE TYPICAL PATHS SHOWN IN HEAVY LINES)



a. TRIPLE SUCCESS PATH

FIG. 2. MULTI-PATH REDUNDANCY

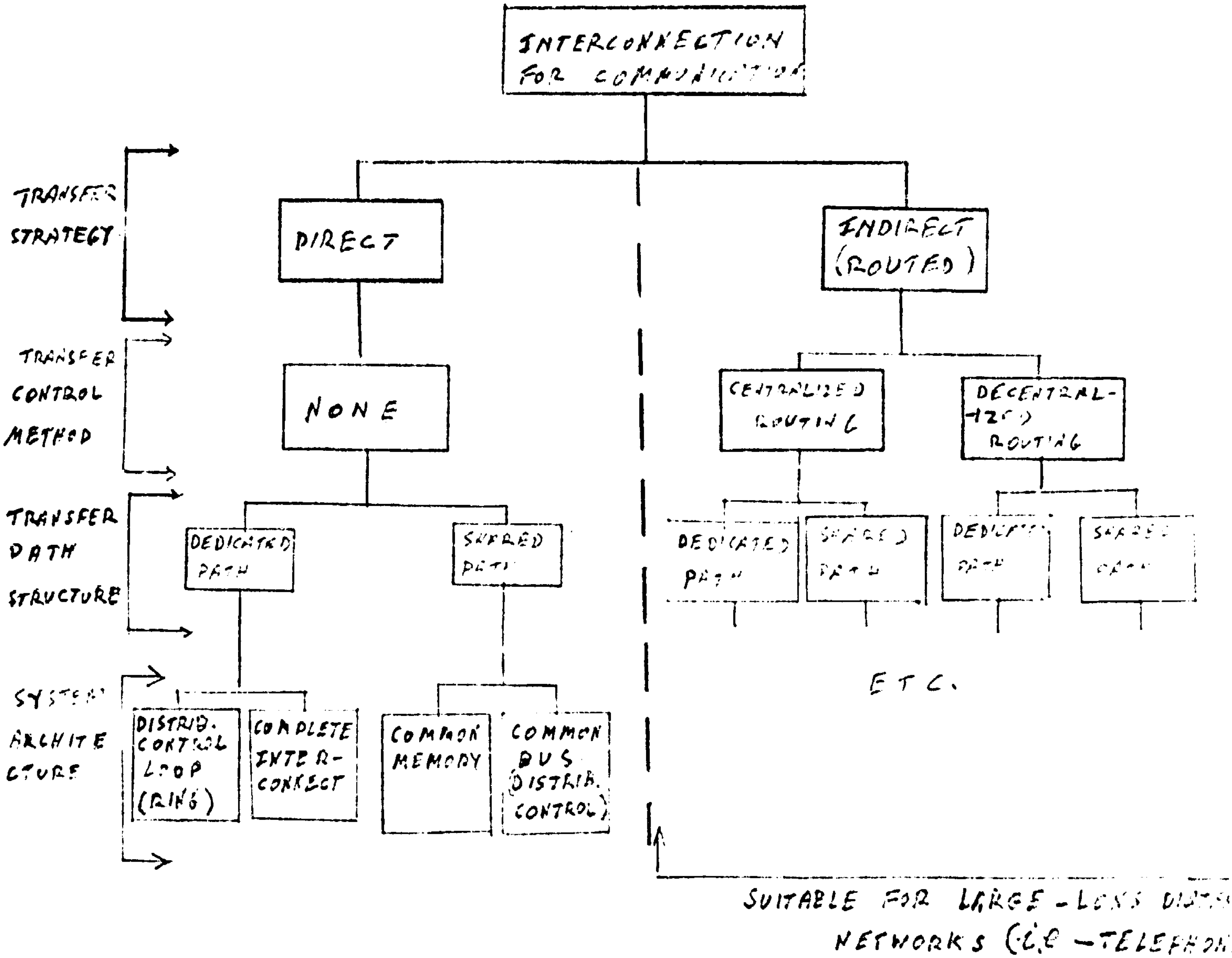


FIG. 3. COMMUNICATION TOPOLOGIES (ANDERSON/JENSEN

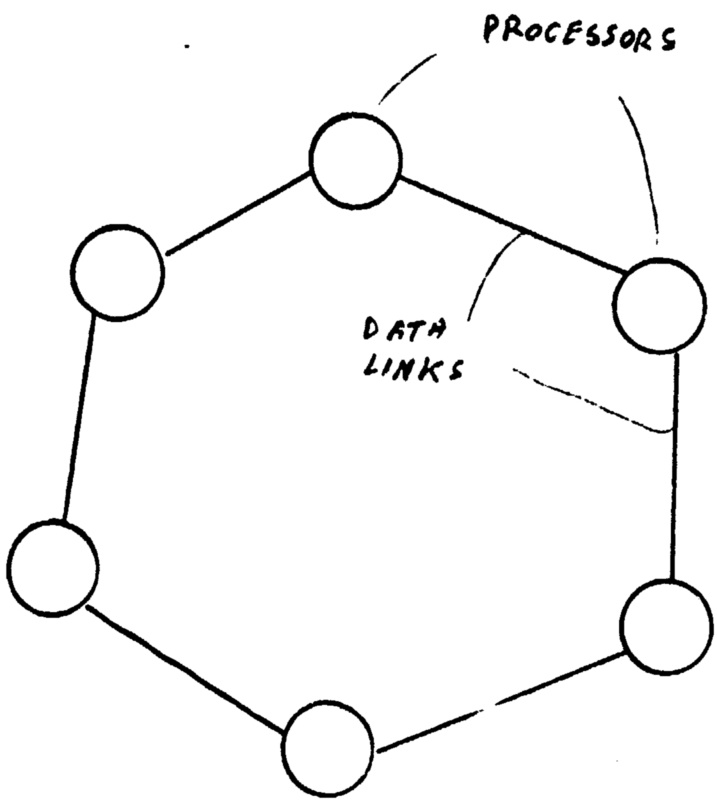


FIG. 4. RING STRUCTURE

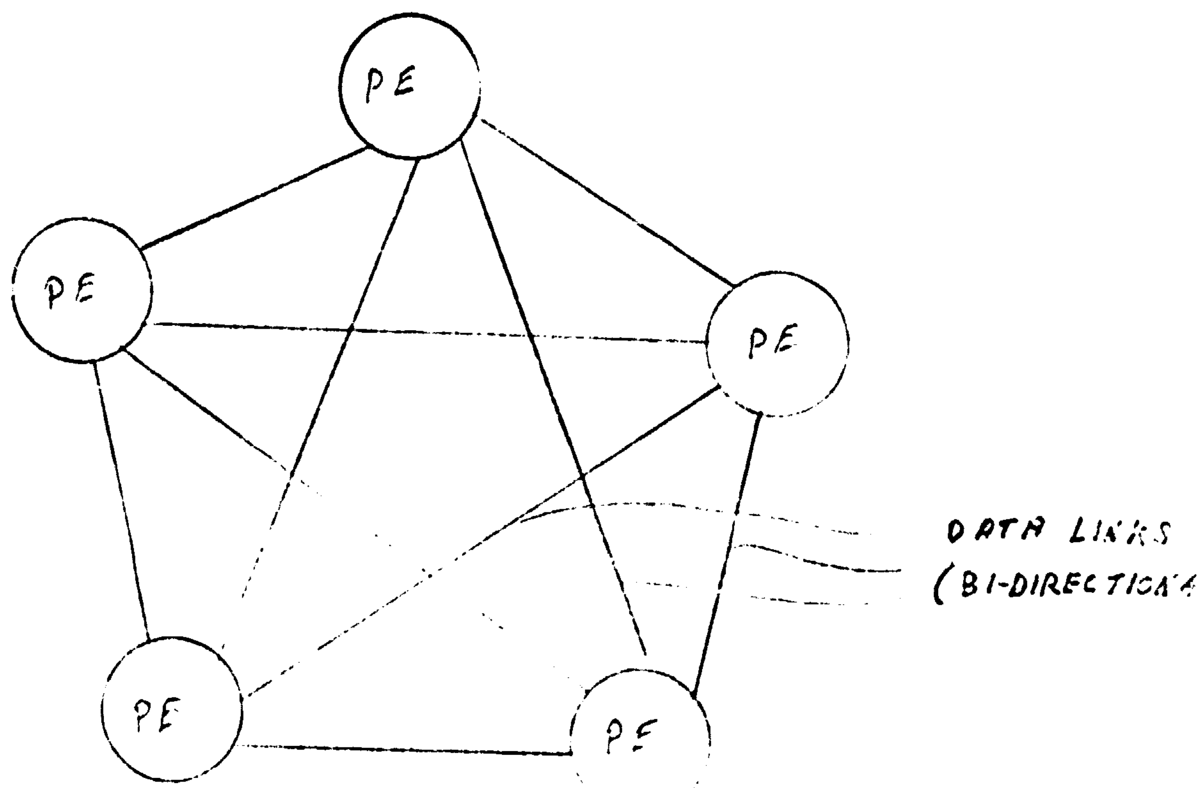


FIG. 5 COMPLETE INTERCONNECT

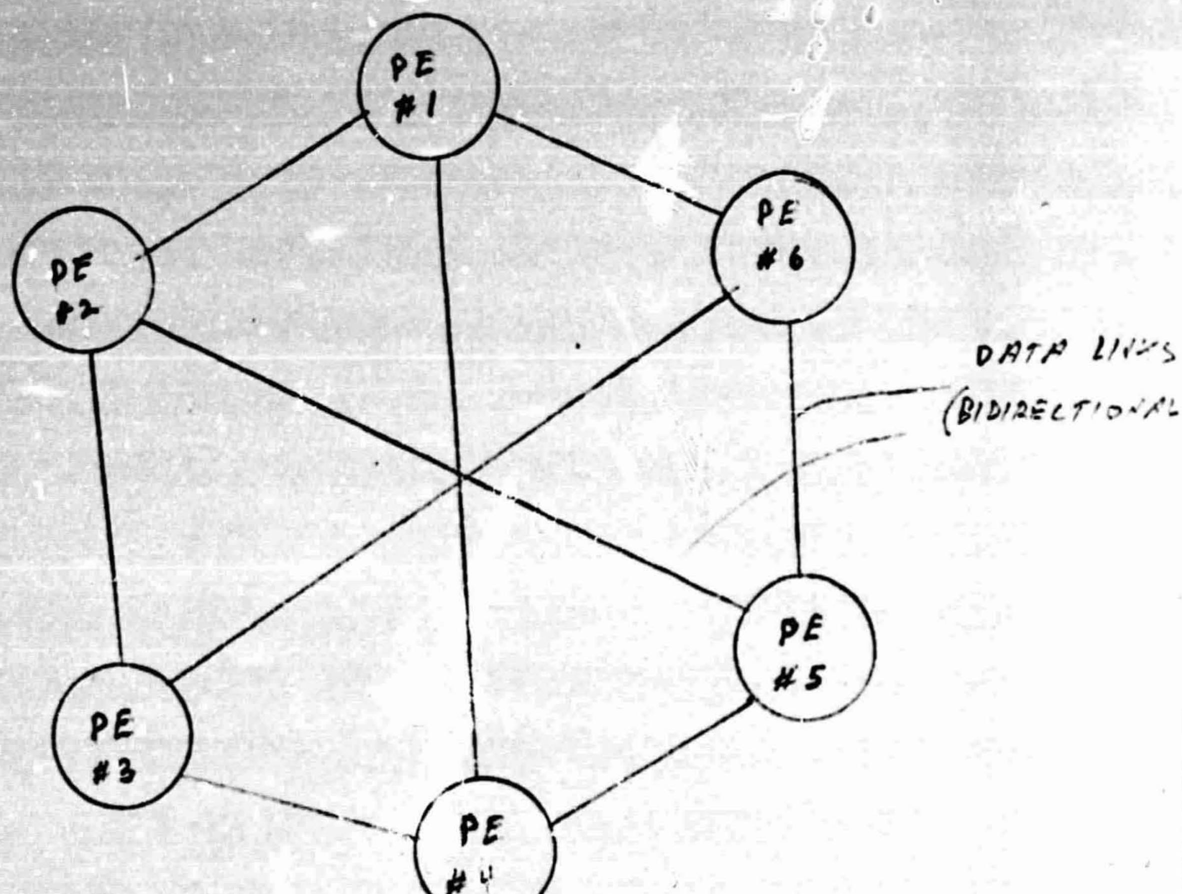
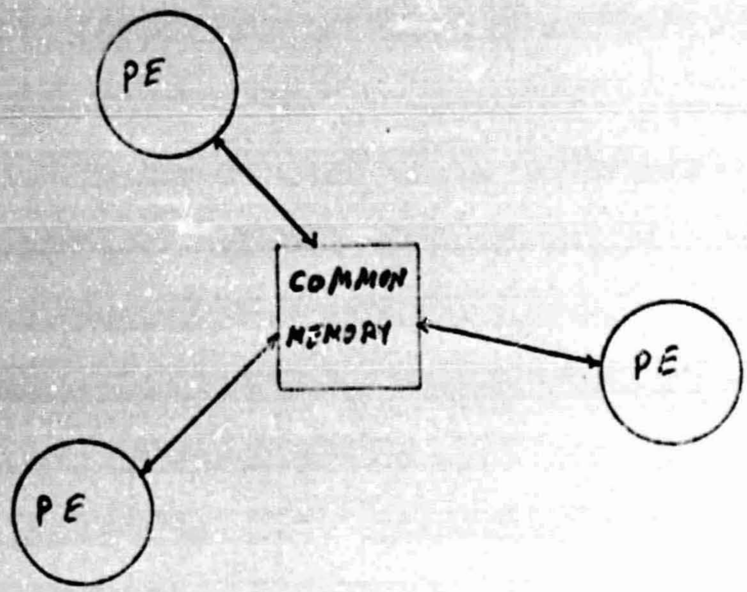
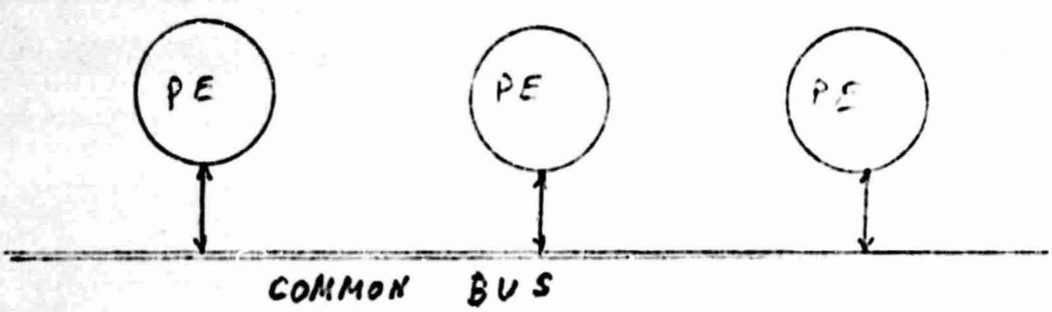


FIG. 6 K CONNECTED NETWORK
N=6. K=3 E.G.. PATH FROM
#1 TO #2 - DIRECT. #1 TO #3 - INDIRECT

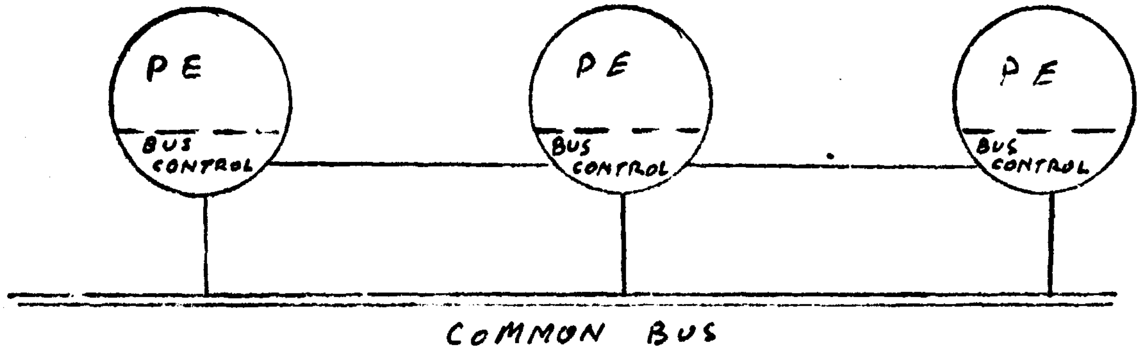


b. SHARED MEMORY

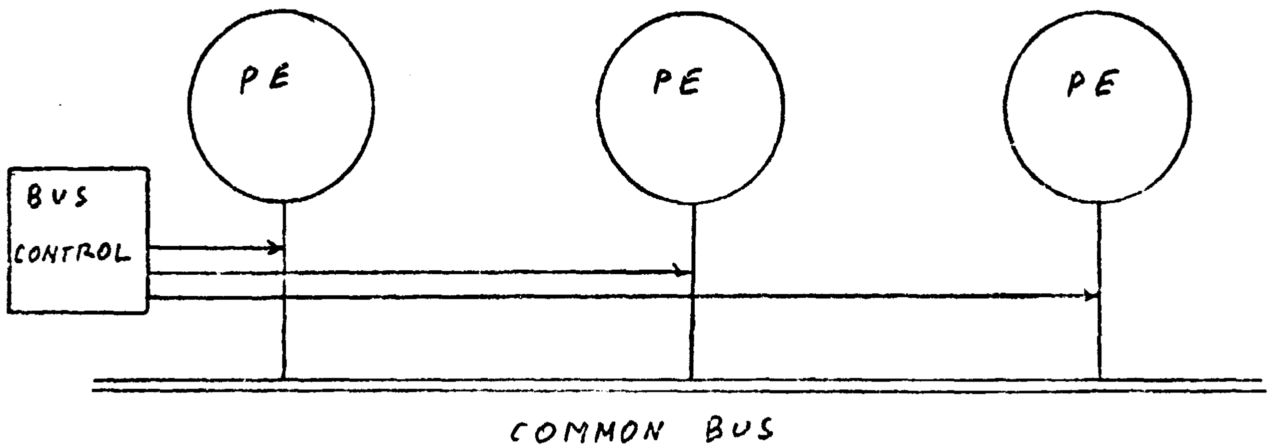


a. SHARED BUS

FIG. 7 SHARED PATHS.



b. DISTRIBUTED CONTROL (E.G. DAISY CHAIN)



a. CENTRALIZED CONTROL

FIG. 8 BUS CONTROLS

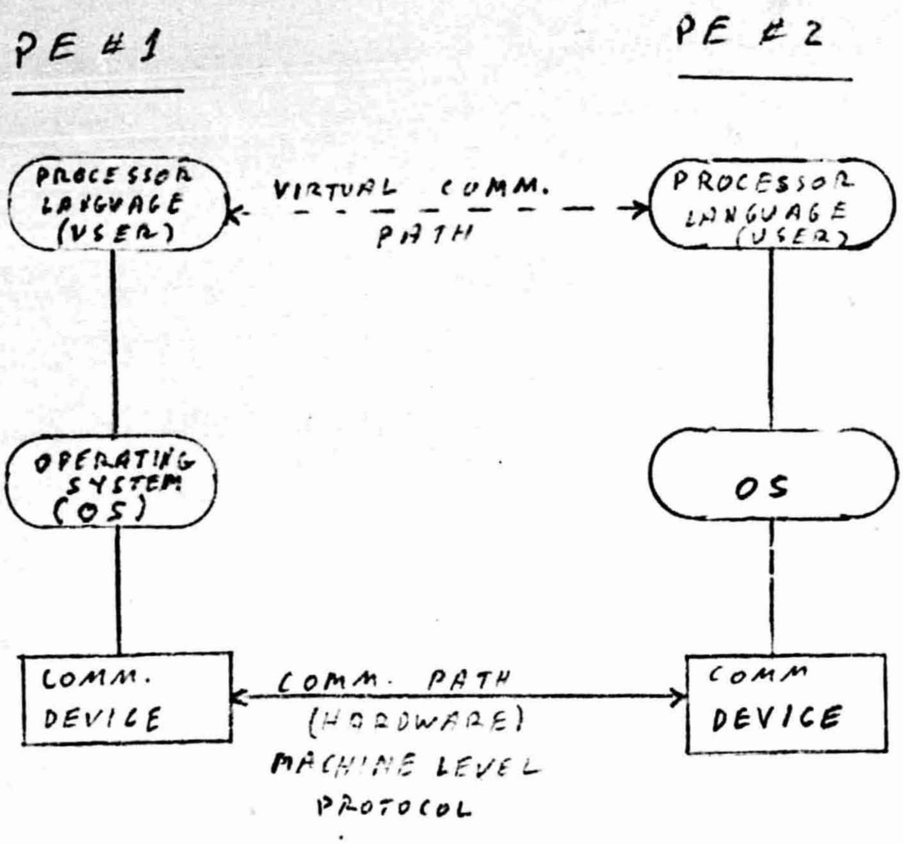


FIG. 9 COMMUNICATION LEVELS

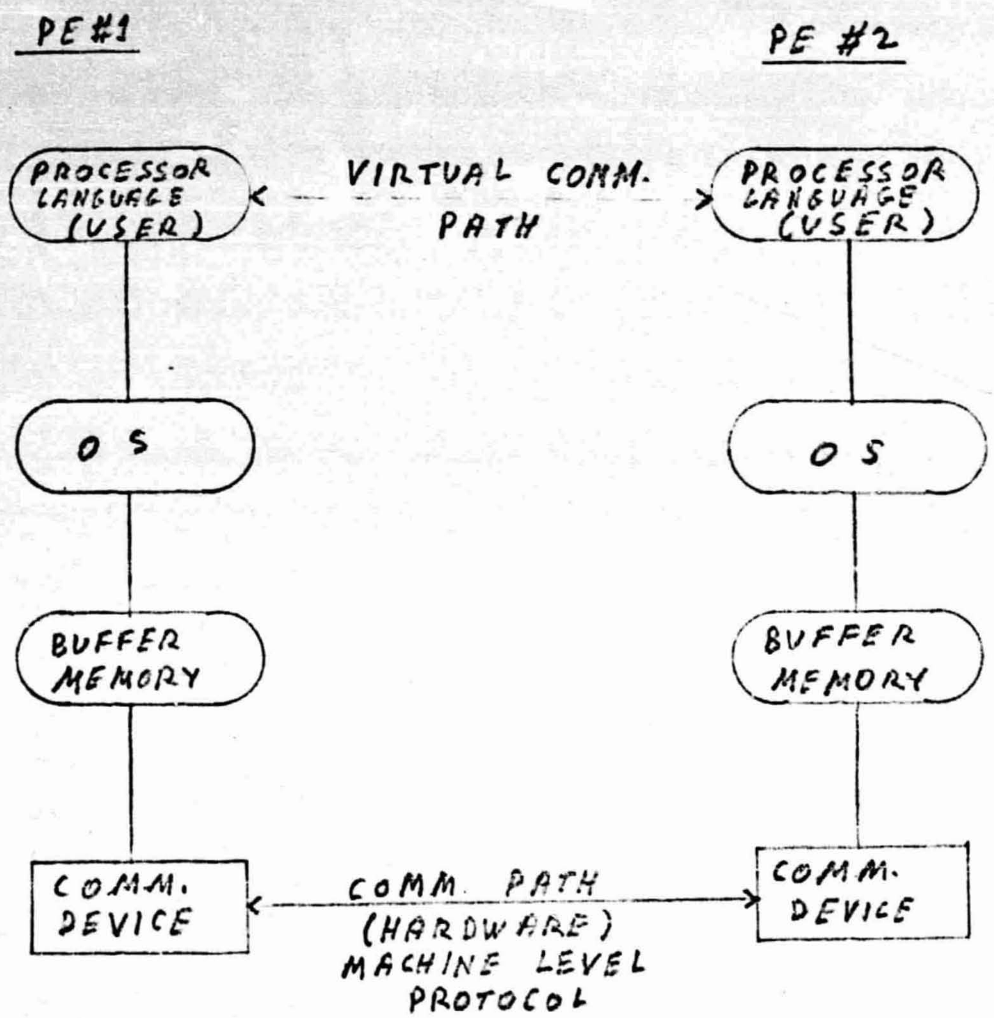


FIG. 10 COMMUNICATION WITH BUFFER MEMORY

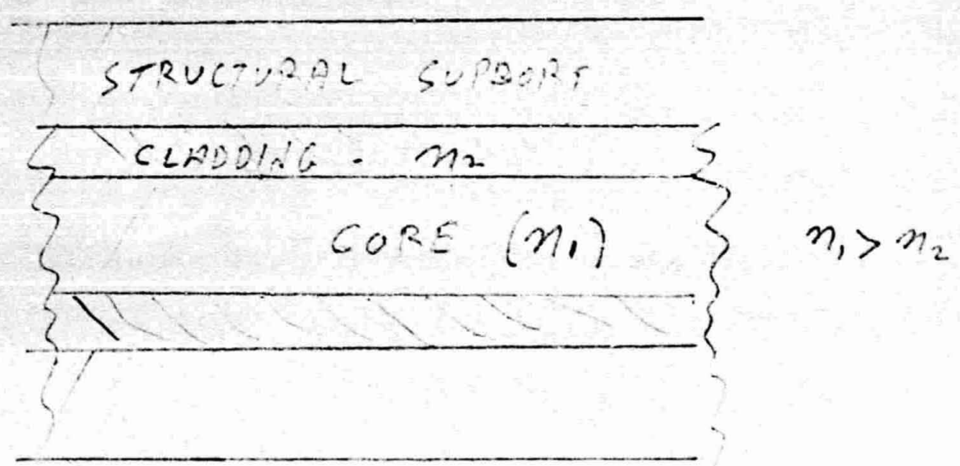


FIG. 11 FIBER OPTIC CABLE. STEP INDEX (SCHEMATIC).

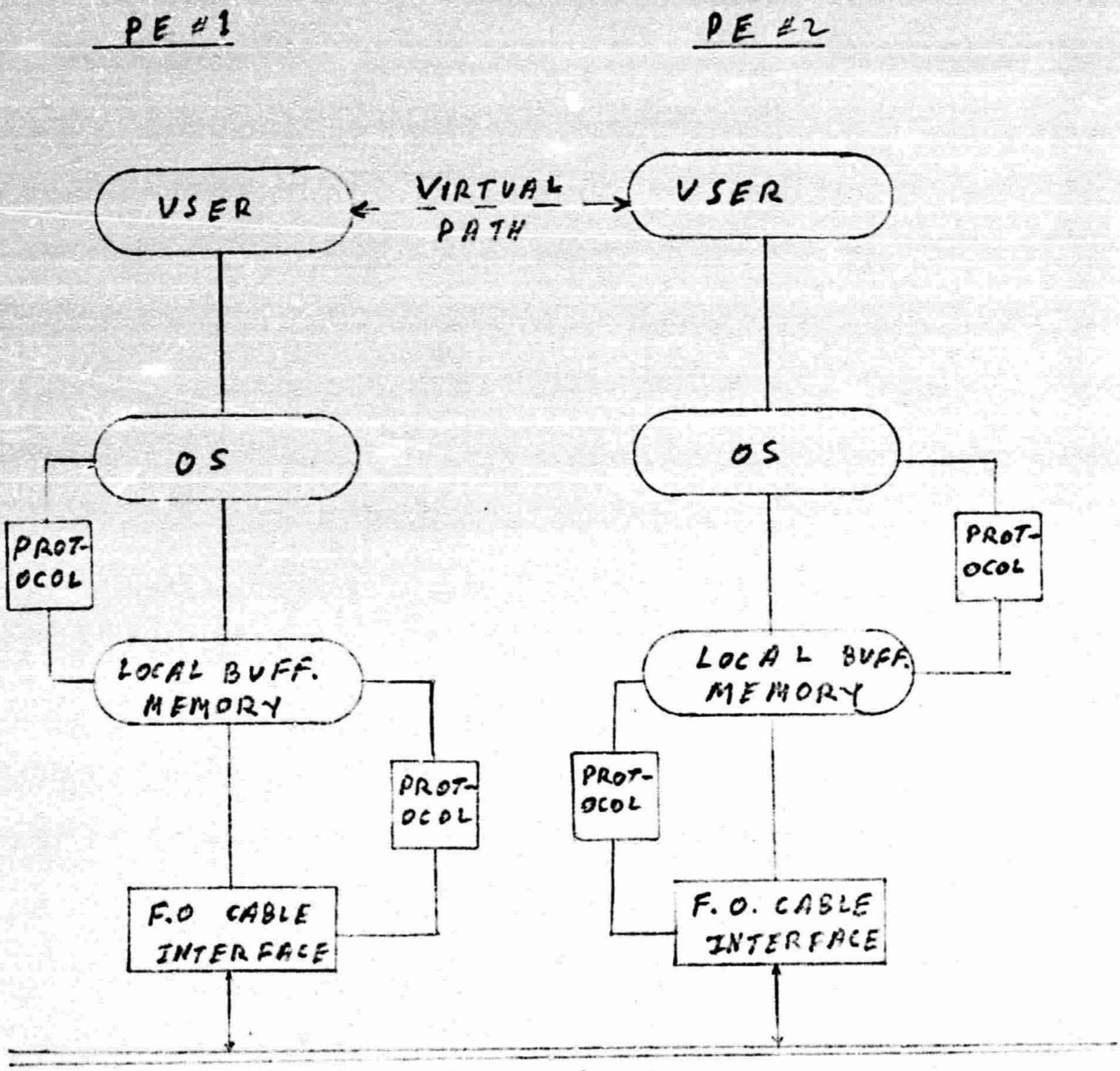


FIG. 12. BASIC COMM. ARCHITECTURE

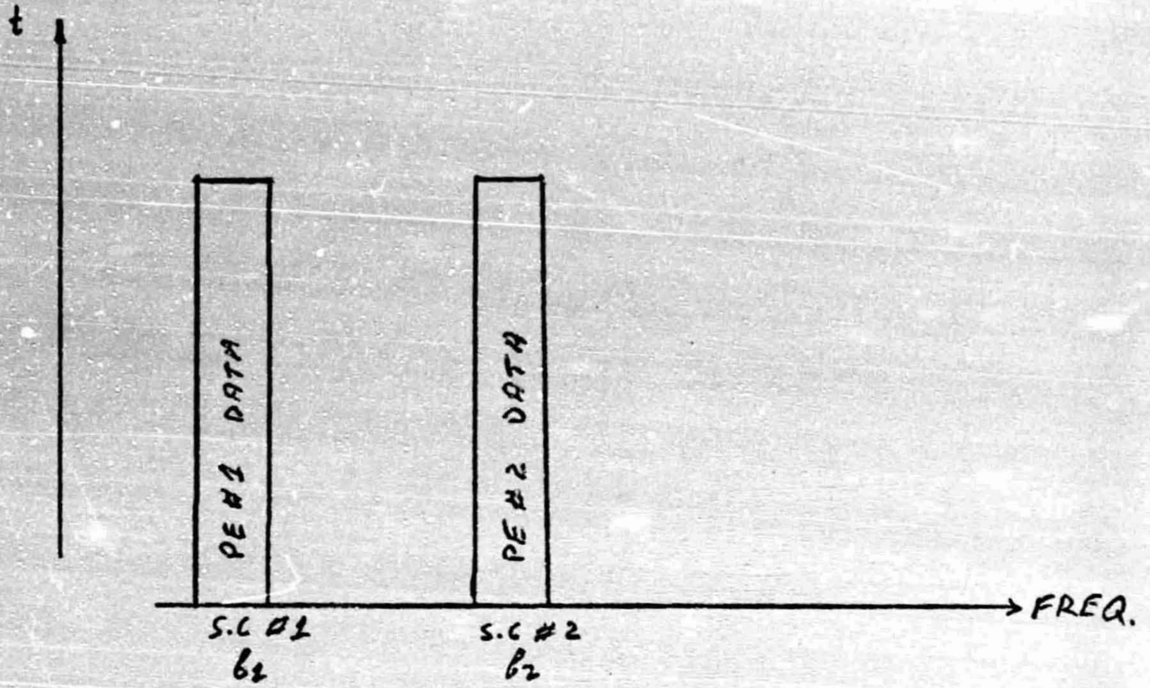


FIG. 13b. FDM FREQUENCY SLOTS

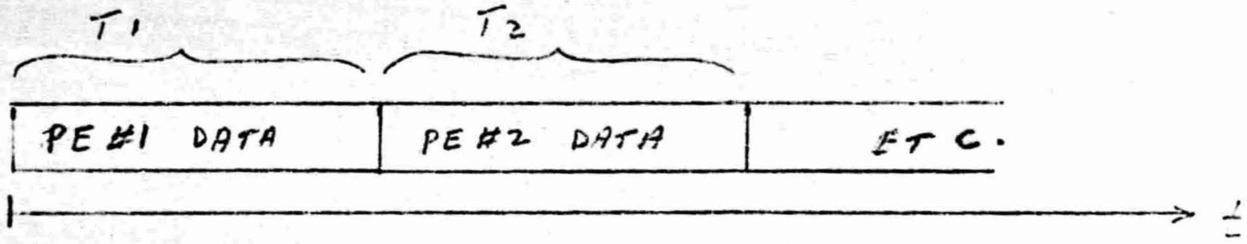


FIG. 13a TDM TIME SLOTS

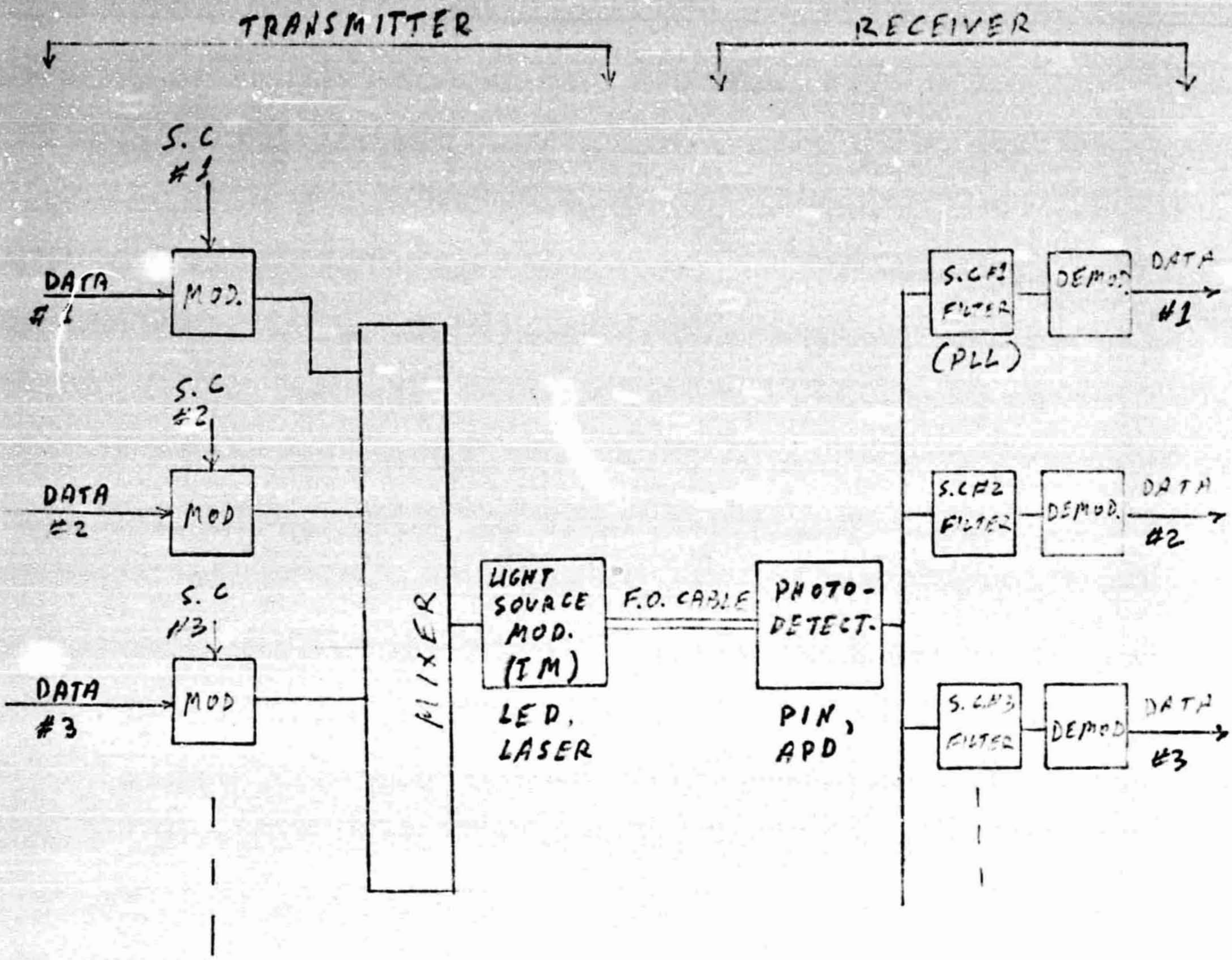


FIG. 14 FDM SYSTEM BLOCK DIAGRAM.
MIXING AT SUB-CARRIER LEVEL

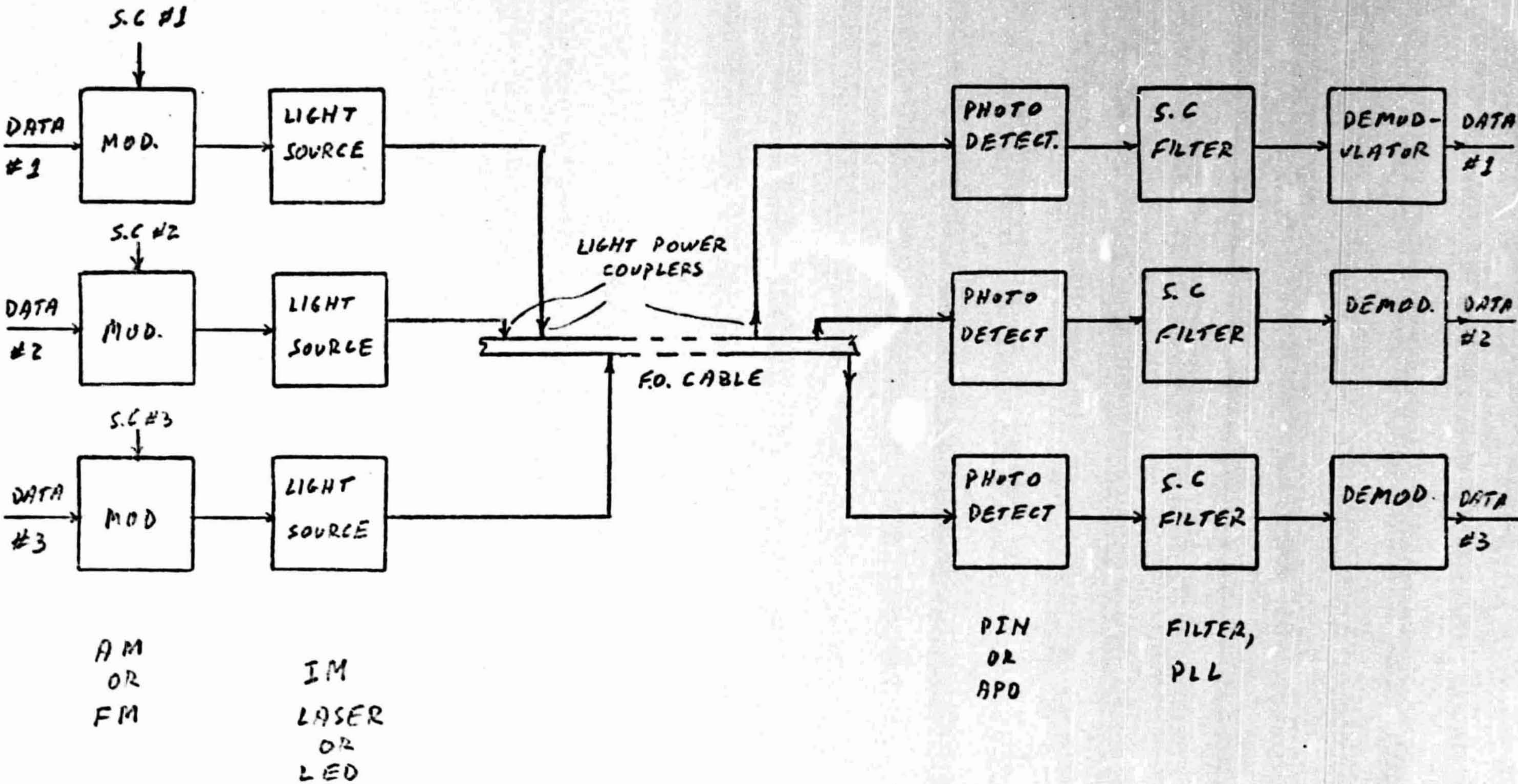
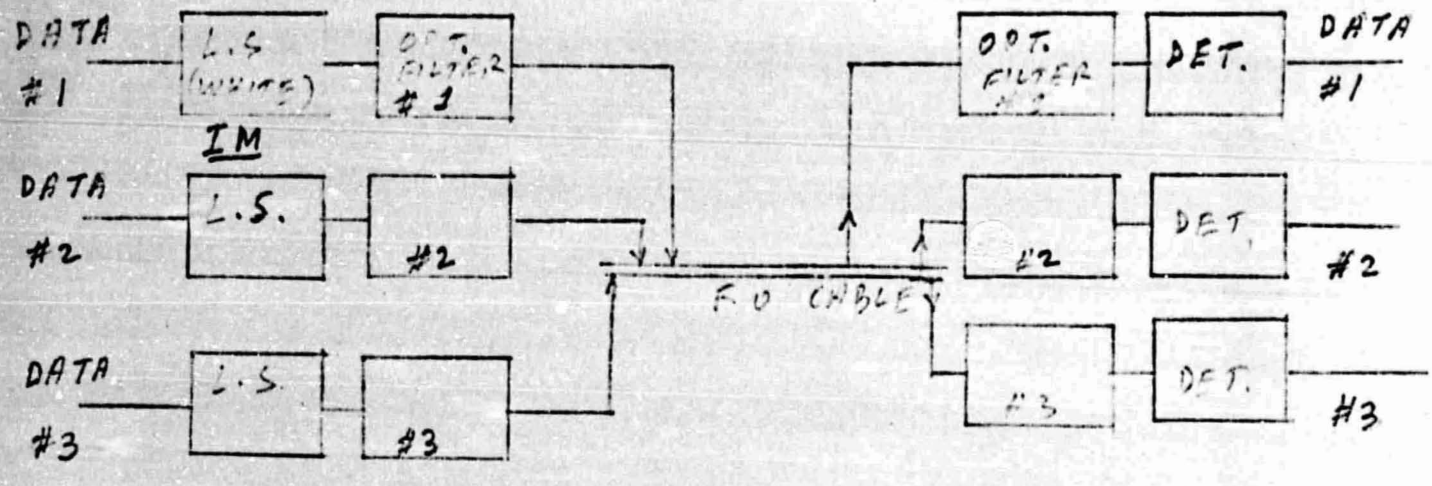
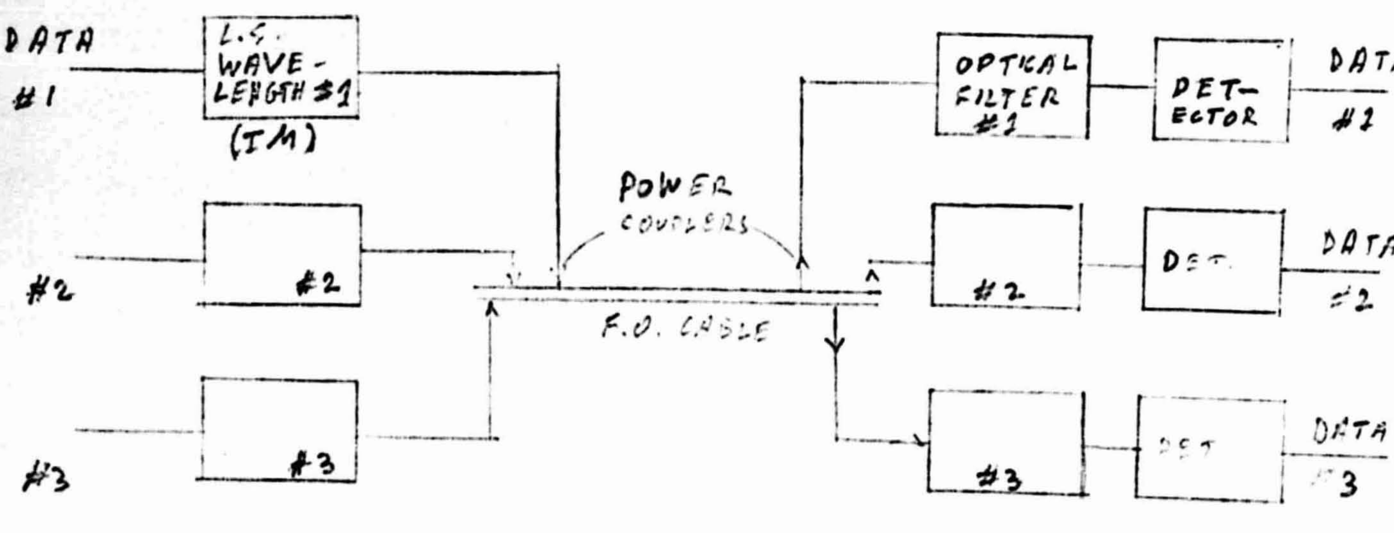


FIG. 15. FDM SYSTEM BLOCK DIAGRAM MIXING AT LIGHT POWER LEVEL.



b. USING OPTICAL FILTERS WITH "WHITE" LIGHT SOURCE



a. USING NARROW LINEWIDTH LIGHT SOURCES

FIG. 16 WDM BLOCK DIAGRAM

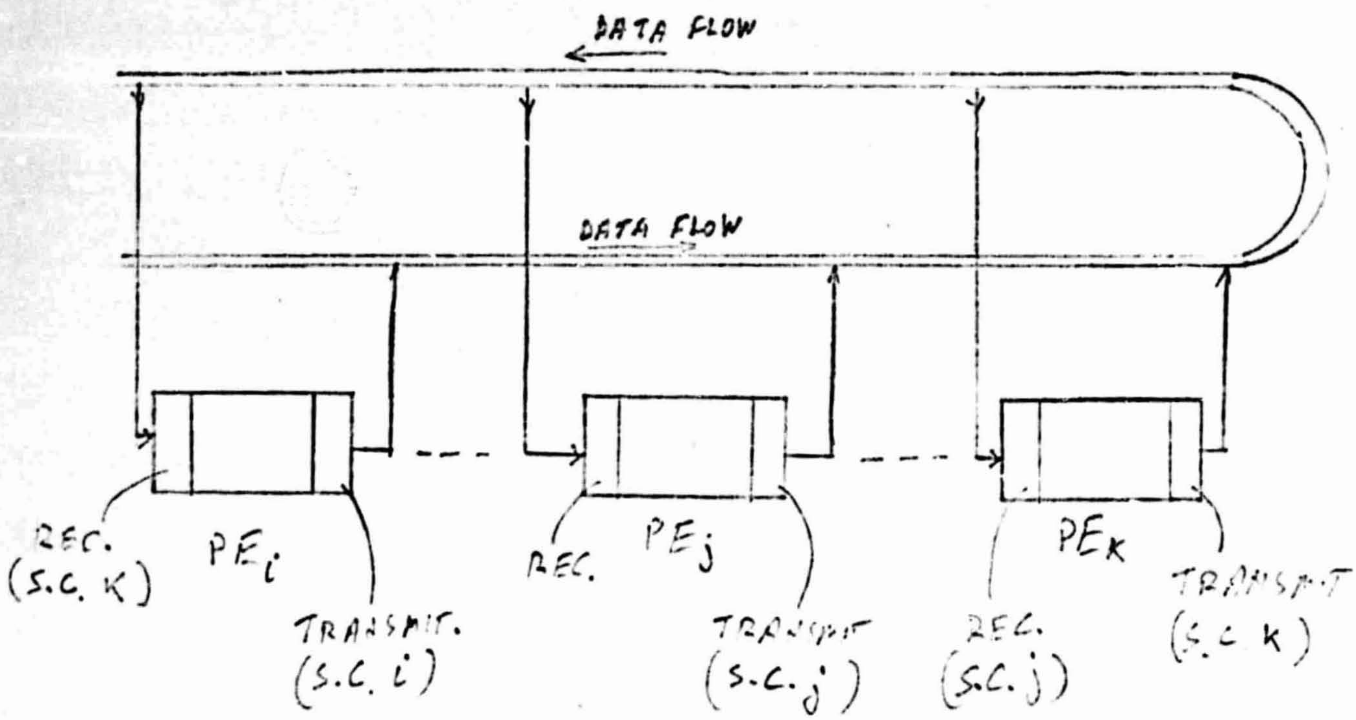


FIG. 17 F.O. FDM BUS

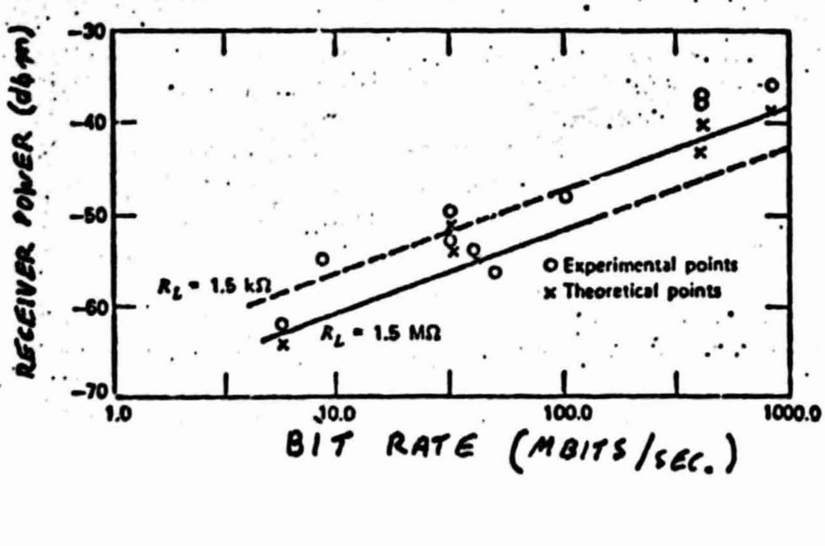


FIG. 18 TYPICAL PLOT OF RECEIVER POWER VS. BIT RATE FOR RECEIVER OPERATING AT 10^{-9} BER.(32)

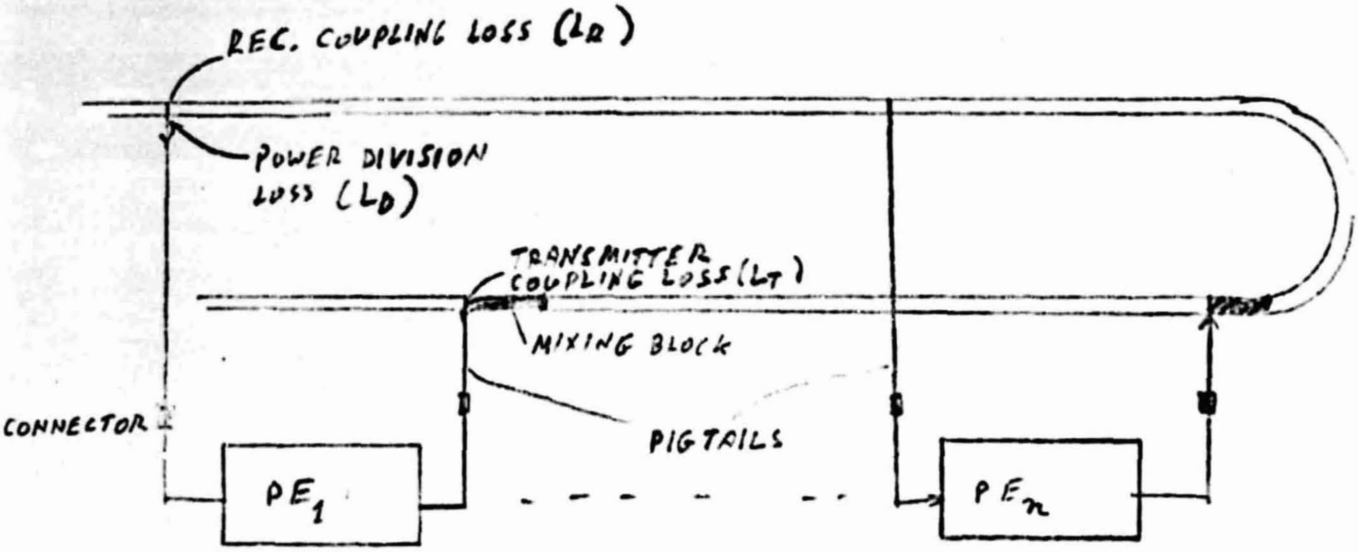


FIG. 19 BUS ARCHITECTURE SHOWING TYPICAL POWER LOSS SOURCES.

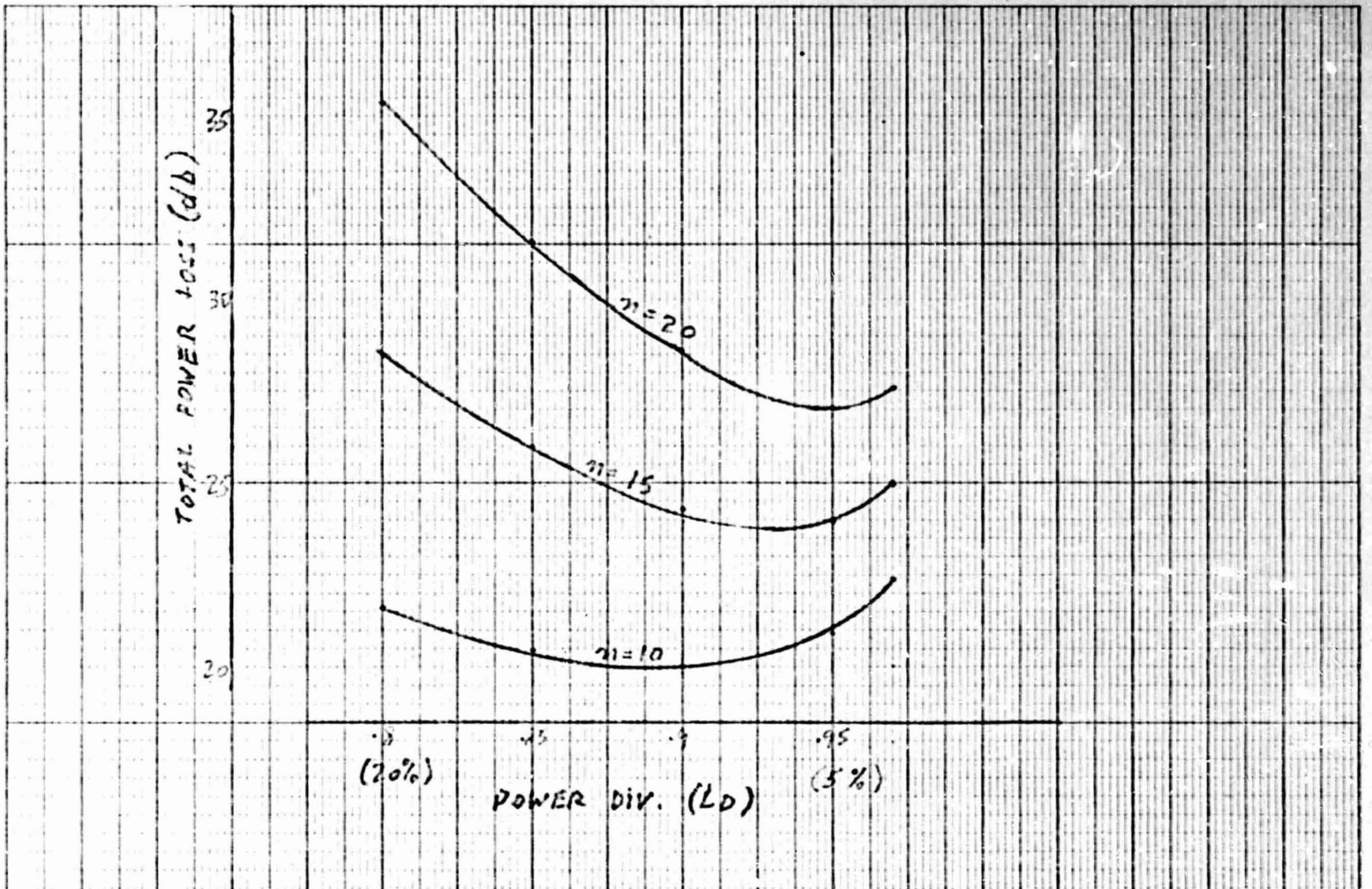


FIG. 20 MAX. POWER LOSS VS. POWER DIV. RATIO

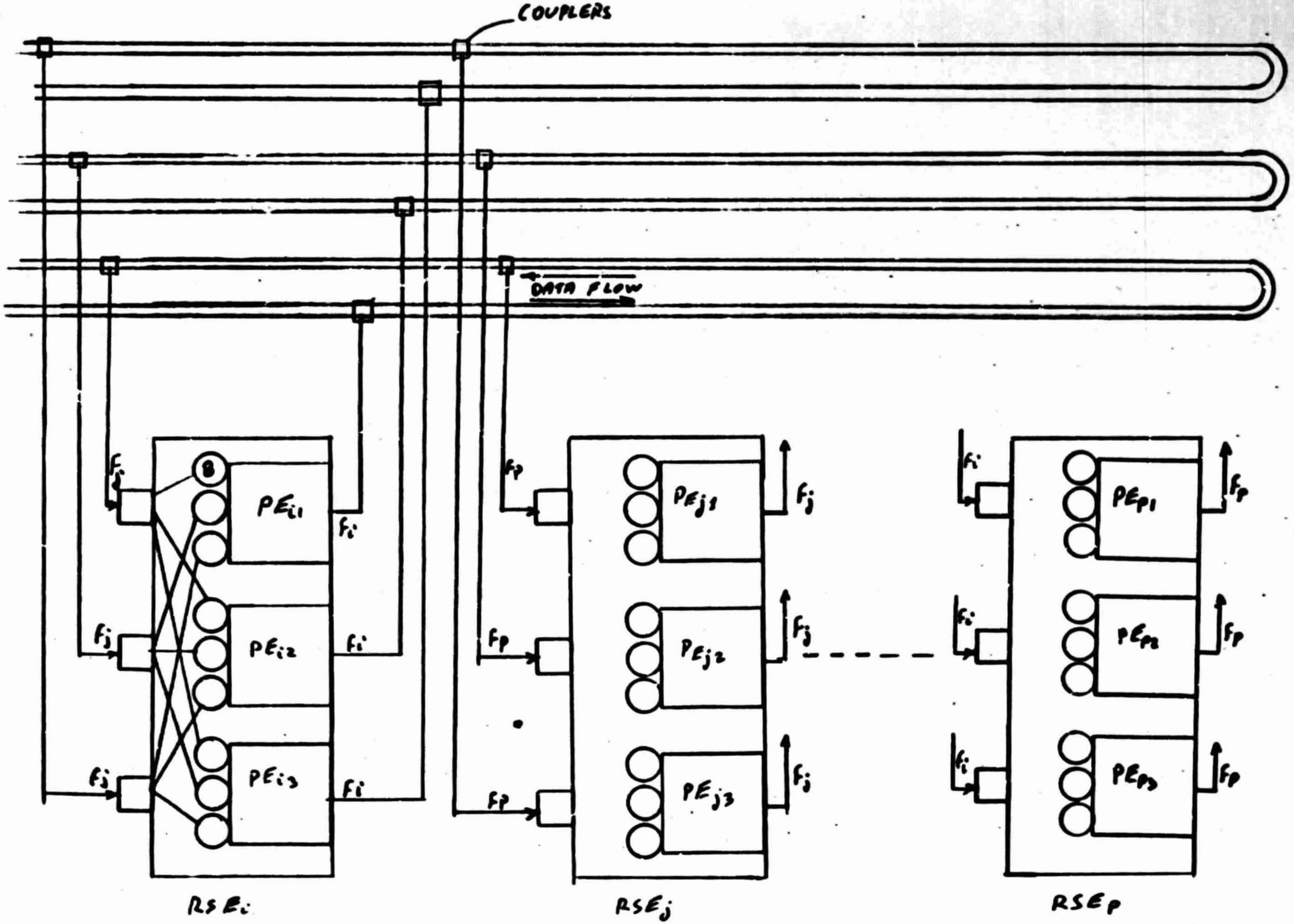


FIG. 21 TRIPLE REDUNDANT SYSTEM
RSE - REDUNDANT SYSTEM ELEMENT. PE - PROCESSING ELEMENT B - LOCAL BUFFER AREA
F - SUBCARRIER FREQ. AS SHOWN DATA FLOW IS $RSE_j \rightarrow RSE_i$, $RSE_i \rightarrow RSE_p$, $RSE_p \rightarrow RSE_j$

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