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DEFINITION, ANALYSIS AND DEVELOPMENT OF AN OPTICAL DATA DISTRIBUTION NETWORK FOR INTEGRATED AVIONICS AND CONTROL SYSTEMS

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16. Abstract

A study was conducted to assess the potential and functional requirements of fiber optic bus designs for next generation aircrafts. State-of-the-art component evaluations andprojections were used in the system study. Complex networks were decomposed into dedicated structures, star buses, and serial buses for detailed analysis. Comparisons of dedicated links, star buses, and serial buses with and without full duplex operation and with considerations for terminal to terminal communication requirements were obtained. This baseline was then used to consider potential extensions of busing methods to include wavelength multiplexing and optical switches. Example buses were illustrated for various areas of the aircraft as potential starting point for more detail analysis as the platform becomes definitized.

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CONTENTS

I INTRODUCTION

I.1 BACKGROUND

NASA is conducting several programs investigating fault-tolerant signal (and power) transmission for future-generation commercial aircraft. In connection with this technology research, Hughes is investigating the feasibility of wavelength-multiplexed fiber optic signal bussing by developing a multimode wavelength demultiplexer. The concept and demultiplexer are demonstrated in a four-terminal, four-color fiber optic bus. This study is part of this development effort.

Fiber optic systems developments have been rapidly progressing over the last several years, especially in the area of single-strand fiber technology. The advantages of fiber optics, summarized in Figure I-1, are well known.[1] Point-to-point fiber optic telecommunications is becoming well established for commercial use. The application of fiber optics to bus system applications is of great importance in order to take full advantage of the potential that this technology offers.

If fiber optics is to show its full potential, the system must be optimized for light communications, not only in terms of bus topology, but also modulation techniques and communications protocols. Fiber optics also allows multiplexing in the optical frequency region (color or wavelength multiplexing) as well as standard frequency or time division multiplexing. Other emerging components, such as optical switches,[2] may influence the overall system design philosophy. The number of terminals allowed on a passive bus is limited by the efficiency of the optical access coupler, connectors, and splices as well as the power budget offered by state-of-the-art sources and receivers. The power budget limitations imply that active bus designs may be required for a system with a large number of terminals. An insight into the advantages and limitations of fiber optic buses will allow optimization of a system architecture as design progresses from concept to implementation.

FIBER OPTICS - PRO's & CON's

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Figure I-1

ADVANTAGES

- LARGE BANDWIDTH
- SMALL SIZE/LIGHT WEIGHT
- NO COMMON MODE PROBLEMS
- HIGH TENSILE STRENGTH
- EMI, RFI, CROSSTALK IMMUNITY
- NO SIGNAL LEAKAGE (TEMPEST)
- POTENTIAL NUCLEAR RADIATION HARDENING
- HIGH VOLTAGE ISOLATION
- OPERATION IN EXPLOSIVE OR CHEMICALLY ACTIVE ENVIRONMENT

DISADVANTAGES (IMPROVING THROUGH DEVELOPMENT)

- COST
- CONNECTORS/SPLICES FIELD REPAIR

Significant changes are anticipated by NASA for commercial aircraft avionic system architectures and designs. After the turn of the millenium, totally integrated systems with fault tolerant computers are envisioned which could present significant busing challenges for communications among the various subsystems and computers comprising the total avionic system.

Although these system concepts are only now emerging and evolving and are not yet well defined, it is an appropriate time to generally assess the applications of fiber optics to such systems and to begin to project the future state of the art of fiber optics at the time of deployment.

I.2 SCOPE AND CONTEXT

This study addresses the use of optical data distribution in civil aircraft applicatons. This broad scope of study was focused on objectives that could be accomplished within the resources (half-man-year level-of-effort) available for this task.

The ideal way to proceed in such a study would be to define a platform and its functional requirements including traffic flow, message timing, etc. This platform could then be used to define and analyze a variety of optical data distribution systems. The baseline system would be used in comparing the advantages and disadvantages of each configured optical system. Each system definition would include the transmitters, receivers, switches, couplers, number of wavelengths, modulation schemes, connectors, multiplexers, demultiplexers and component placement aboard the aircraft. Once the system definitions are complete, tradeoff analysis on each defined system could be performed in terms of parameters such as reliability, cost, performance capability, maintainability, lighting/EMI immunity, etc.

Since the definition of the platform representing year 2000 civil aircraft and its requirements is only in the concept formative stage, this study has been conducted in the context of generalized requirements and architectures. A baseline MIL-STD-1553B architecture is defined to scope a set of generalized functional requirements. Architectural concepts presented in the Charles Stark Draper Laboratory, "Interim Report on Fault-Tolerant Aircraft Signal and Power Transmission Structures" (R-1298) are employed to illustrate and trade off among various fiber optic bus alternatives using state-of-the-art and projected component parameters. This broad-brush analysis provides a set of baseline concepts, illustrations, examples and results that may assist a system designer in formulating an integrated system design utilizing optical signal communications.

I.3 OBJECTIVE

Thus, within the scope and context as outlined above, the objective of this study is one of providing a basic compendium of fiber optic multiplex bus technology to serve as a primer for system designers and as a baseline for tradeoffs in greater depth as the detailed design of the future civil aircraft platform emerges. Specifically:

- Define and evaluate possible data bus system architecture using fiber optic technologies.
- Investigate and summarize state-of-the-art fiber optic technology and its projection.

The objectives are realized through presentation of a number of topics. In Section II, a general discussion of data distribution system concepts serves as an introduction to busing topologies, protocols, and special requirements. This is followed in Section III by a description of a multiple level architecture using MIL-STD-1553 data buses. This baseline system serves the purpose of illustrating a possible "next-generation" system implementation and at the same time identifying a number of functional requirements likely for both present and future civil avionic systems. Next, Section IV concentrates on a general description of fiber optic buses including component description and properties, analysis of performance achieved by various structures, multiple wavelength and switched buses and a discussion of reliability issues. Specific examples of fiber optic buses are presented in Section V. Conclusions and recommendations, Section VI, complete the report.

II GENERAL DATA DISTRIBUTION SYSTEM CONCEPTS

In order to configure, design, analyze and trade off among potential data distribution systems, a number of considerations must be taken into account. The major ones applicable to this study are listed in Figure II-1 and discussed below. The following discussion is not intended to be complete or exhaustive, but rather to provide a foundation for a common vocabulary as well as to generally and broadly raise some of the issues of importance to the specific analyses that follow.

II.1 ARCHITECTURE

The word "architecture" when applied to a system connotes many things to different people. In the context of this study, we use this term to encompass methods employed to interconnect among electronic systems and sensors and the method used to communicate data. The former we shall refer to as the topology, while the latter we call the protocol.

II.1.1. Topology

Within the general area of topology we consider, as indicated in Figure II-2, the network path, whether the path is serial or parallel, the transmission technique employed and the redundancy.

NETWORK PATH. System design includes partioning the requirements into a set of functions. These are then allocated to a physically positioned subsystem, generally according to a list of operational requirements. This leads to configuration comprised of subsystems that must communicate with one another to fulfill the system mission. We call the interconnect of the subsystems the network path. The network path can usually assume many structures that will provide the required communications. Therefore, one must trade off among these structures in order to select the optimum network path for the particular system. The parameters used for the trade-off would include those important to the subject system, such as cost, size, weight, reliability, maintainability, etc.

DATA BUS SYSTEM DESIGN CONSIDERATIONS

Figure II-1

- ARCHITECTURE
  - Topology
  - Protocol
- TRANSMISSION MEDIUM
- RELIABILITY
- MAINTAINABILITY
- POWER DISTRIBUTION
- COST
- OTHERS SPECIFIC TO THE APPLICATION

Figure II-2

- NETWORK PATH
- SERIAL/PARALLEL
- TRANSMISSION TECHNIQUES
    - Simplex
    - Half-duplex
    - Full-duplex
    - Wavelength Multiplexed
- REDUNDANCY

Some of the network path structure that will be considered for fiber optic implementation are shown in Figure II-3. These are point-to-point links, serial buses and star buses.

The point-to-point link provides a direct path between two points. There is no branching or tapping of the optical signal power to provide data to other points. This is the simplest structure which is sometimes referred to as a dedicated structure; that is, the communication line is not shared.

The point-to-point link structure can be used as a building block to provide complex bus structures such as those shown in Figure II-4. Here Figure II-4A shows a dedicated point-to-point link for each interconnect. For purposes of discussion, we will refer to the generalized function represented by the boxes as a "terminal." In this network there are n(n-1)/2 paths or links required. Obviously as n becomes large the system implementation becomes unwieldy and costly. If a terminal can receive a message, note it is for another terminal, and route it forward (i.e., serve as a switching mode) then some of the dedicated paths can be eliminated and the number of links reduced. The extreme case of this is evidenced in the loop or ring structure illustrated in Figure II-4B where each terminal passes the message on. (The system protocol must break the retransmission at the originating [or final] terminal to avoid endless looping.) The case of a single node or central terminal is usually referred to as "star" topology as shown in Figure II-4C, while Figure II-4D illustrates a hierarchical topology constructed from point-to-point link.

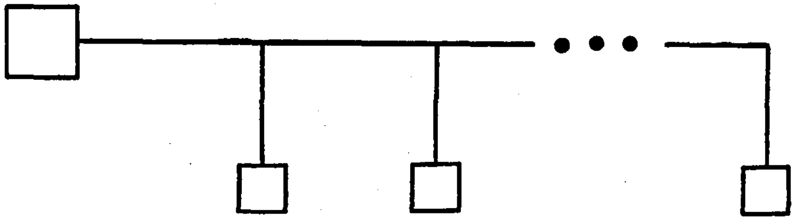
Use of signal power splitters or taps allow multiterminal passive bus structures to be configured. The serial and star buses shown in Figure II-3 are examples. The serial or linear bus is made up of a number of taps along the communication line while the star bus has a single signal power combining and redistribution point. Here, this element is passive, while the bus of Figure II-4C utilized an active terminal to produce the same type of star network topology.

NETWORK PATH STRUCTURES

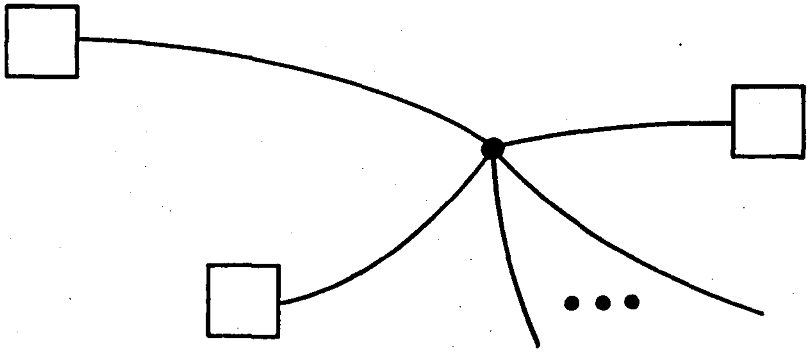
Figure II-3

- Point-to-point link

- Serial bus

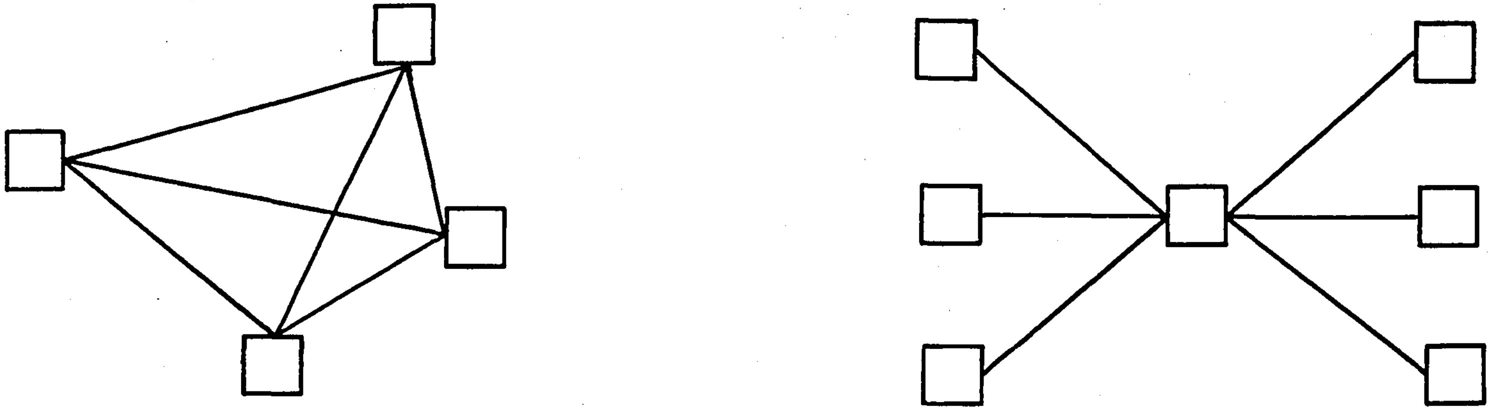


- Star bus



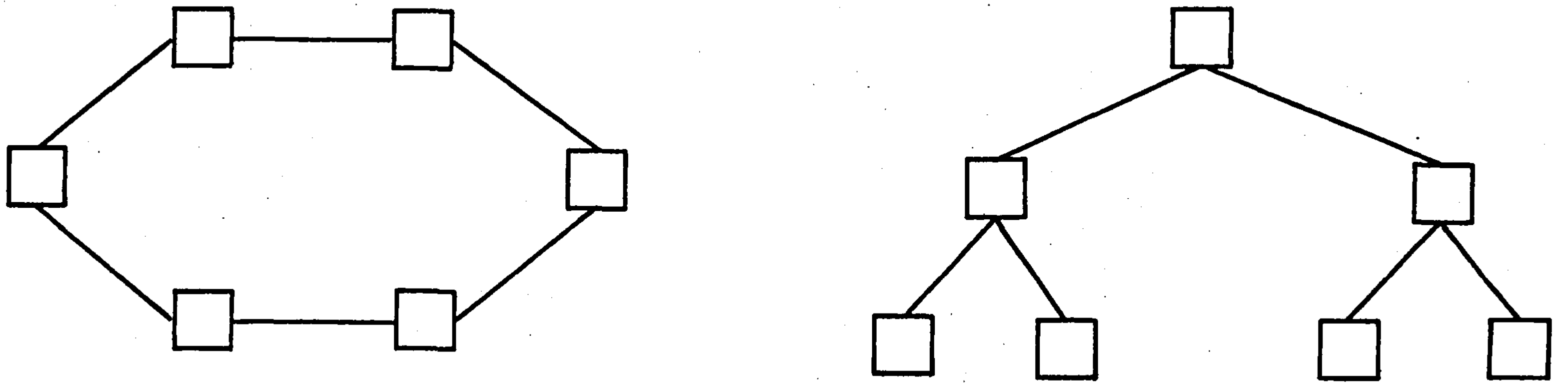
POINT-TO-POINT LINK BUS STRUCTURES

Figure II-4



A) Dedicated

C) Star



B) Loop/ring

D) Hierarchical

As in the case of the point-to-point links, these bus elements can be used to construct more complex networks. For example, three examples of complex architectures based on serial buses are shown in Figure II-5. The so-called major-minor topology, Figure II-5A, consists of the "major" serial bus (shown to left vertically) with a "minor" serial bus emanating from each of the terminals of the major bus. Note the major bus terminals could be eliminated so that the minor serial buses are tapped directly from the main bus. The natural extension of this is the matrix topology shown in Figure II-5B. The tree-branch topology consists of appropriate serial buses supported by terminals or passive taps as required to complete the network. An example of the infinite number of combinations is shown in Figure II-5C.

Interconnection of stars can also form more complex networks. For example, Figure II-6 shows a star-star interconnect. Similarly, combinations of star buses, serial buses and point-to-point links, such as the examples in Figure II-7, provide hybrid bus structures. Likewise, major-minor, matrix and other complex structures can be constructed from star-star or star-serial interconnections.

The major point that emerges from this discussion of network paths is that complex networks can be decomposed into point-to-point links, serial buses and star buses. Therefore, there is immediate need for analysis and trade-off among these structures and this can proceed without a detailed knowledge of the ultimate network to be employed for future civil aircraft platforms.

SERIAL-PARALLEL. In the above examples, the network paths have been indicated by a single line. This line joining two terminals may represent a more complex structure; for example, several parallel paths of data flow. If there are several channels of data, there is a trade off between electronically multiplexing the channels to form a single new data channel or transmitting the channels in parallel. The electronic multiplexing can be either time division multiplexing (TDM) or frequency

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COMPLEX NETWORKS
UTILIZING SERIAL
BUSES

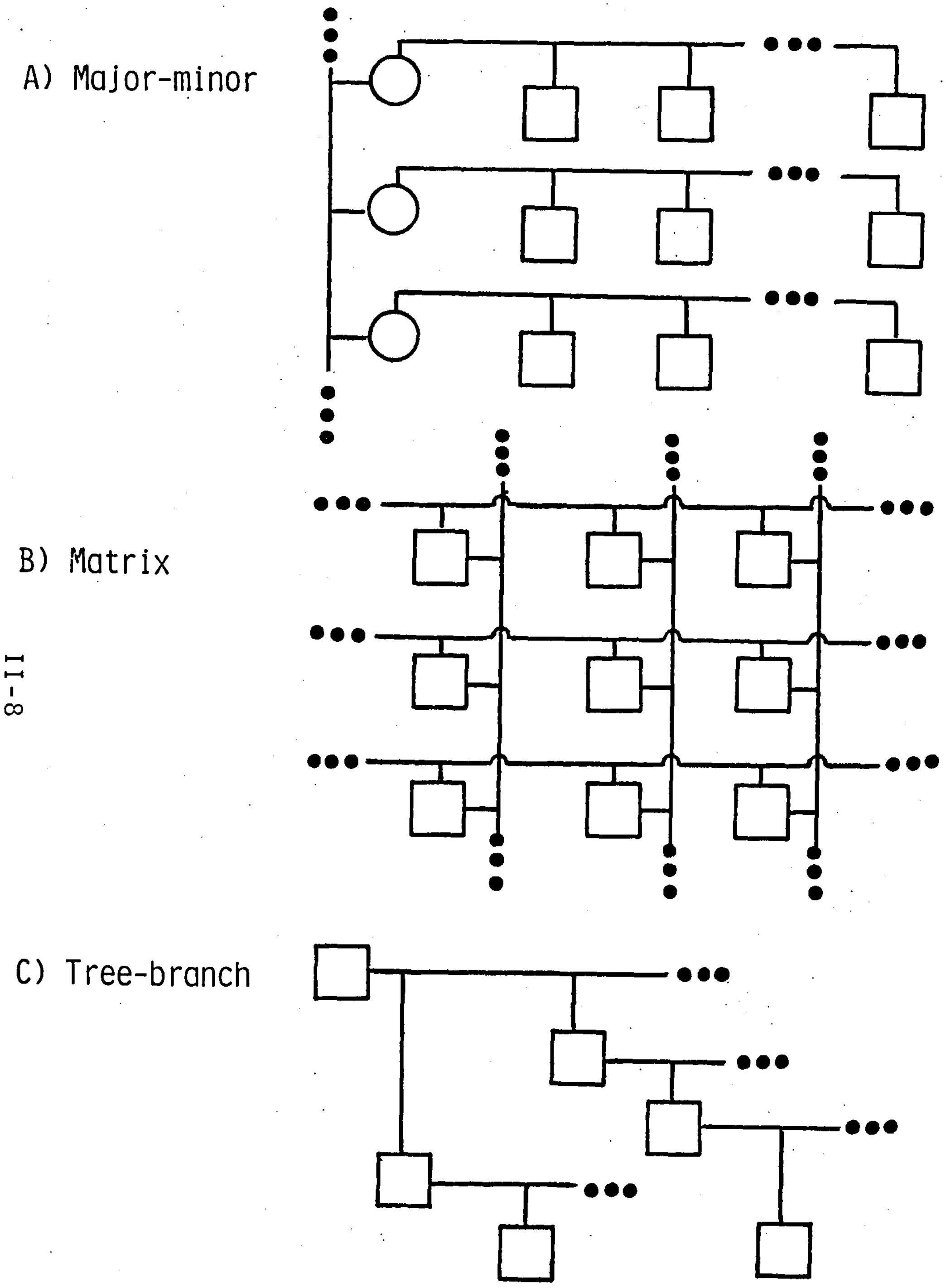
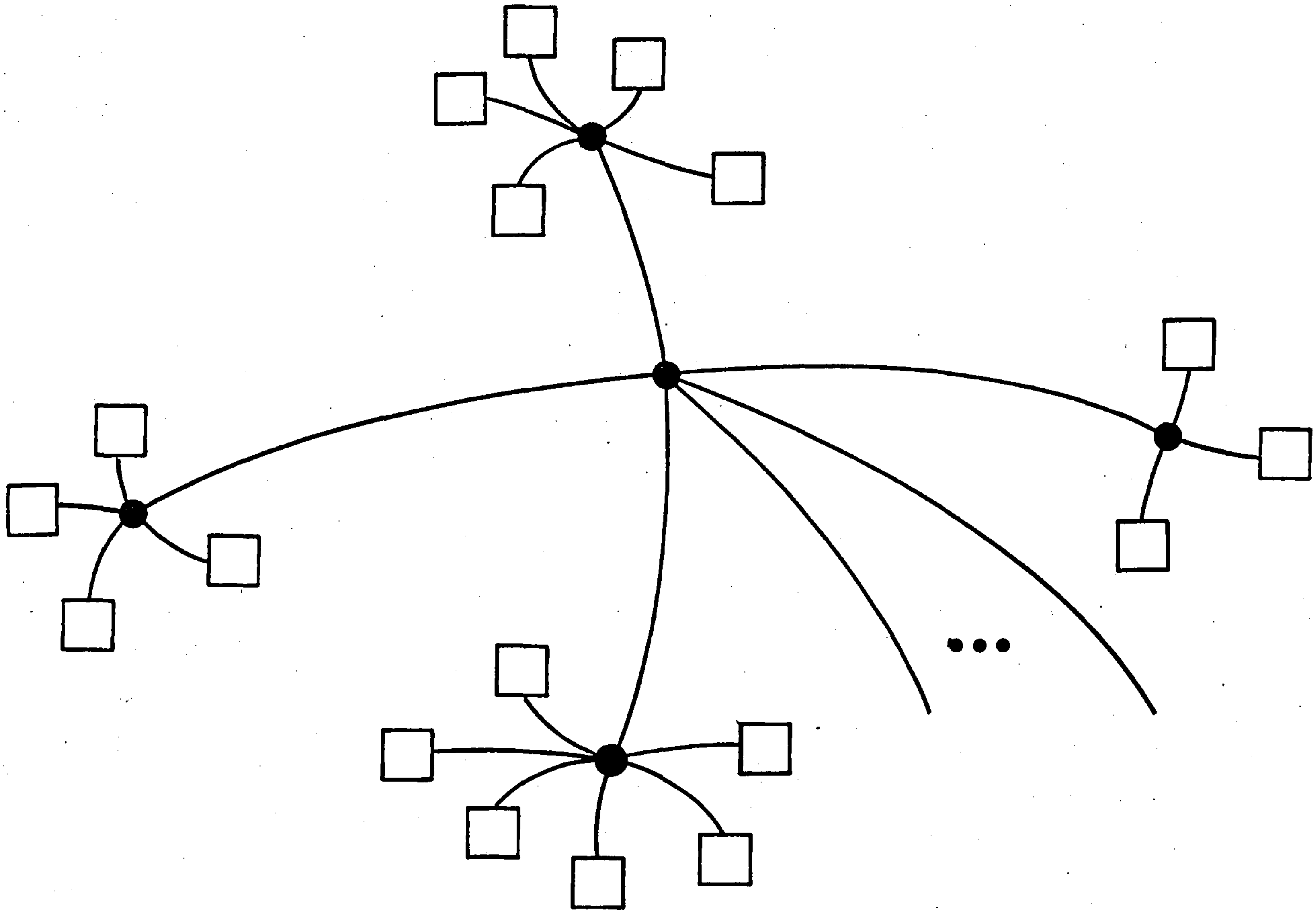


Figure II-5

STAR-STAR INTERCONNECT

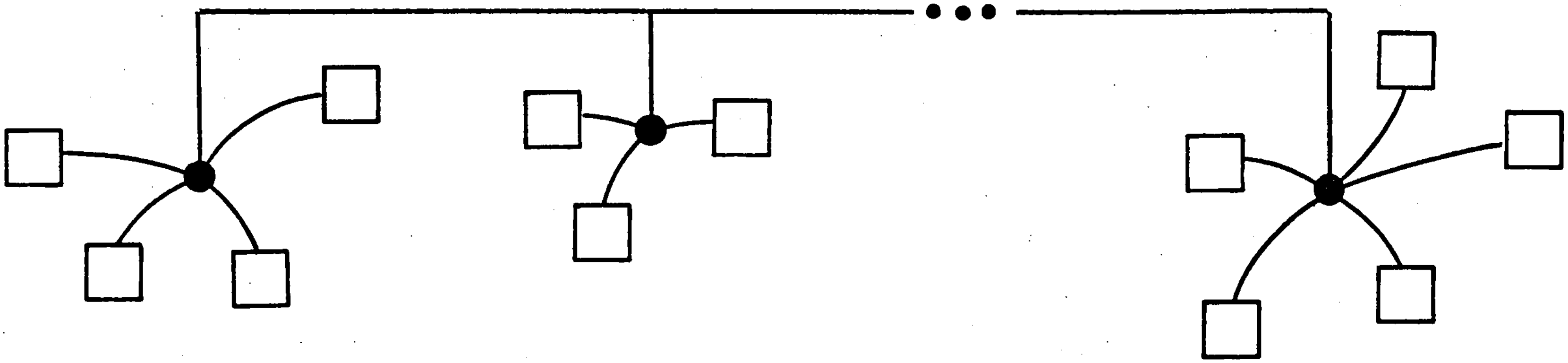
Figure II-6



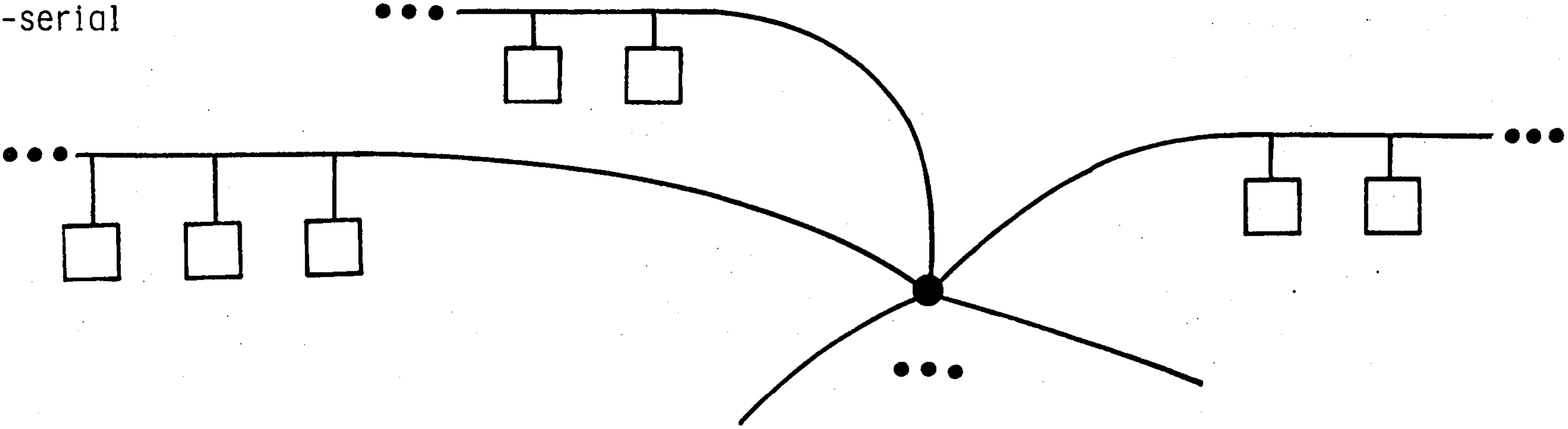
HYBRID BUS STRUCTURE

Figure II-7

A) Serial-star



B) Star-serial



device multiplexing (FDM) (and combinations). The bandwidth of the transmission medium employed may limit these options.

TRANSMISSION TECHNIQUES. Also encompassed in the simplified network diagram is the potential requirement for two-way communications between the terminals. In Figure II-2, four transmission techniques were listed: simplex, half-duplex, full-duplex and wavelength multiplexed. The first three of these are schematically illustrated in Figure II-8. Simplex refers to a single one-way channel, while half-duplex uses two simplex links to provide two-way communications. Full-duplex employs a single link for two-way communications. The communications may either occur simultaneously or the link is shared depending on the implementation.

REDUNDANCY. When a high system availability is required, protection against single-point failures must be designed into the system. A common method is to employ redundancy. For example, the critical flight control function may have triple redundancy with voting. Thus, the single lines shown in the network may also include multiple physical channels (carrying the same data), possibly over different routes in order to provide the degree of redundancy necessary. In the analysis to follow we generally will not show explicitly the redundancy except in cases where the network path is affected.

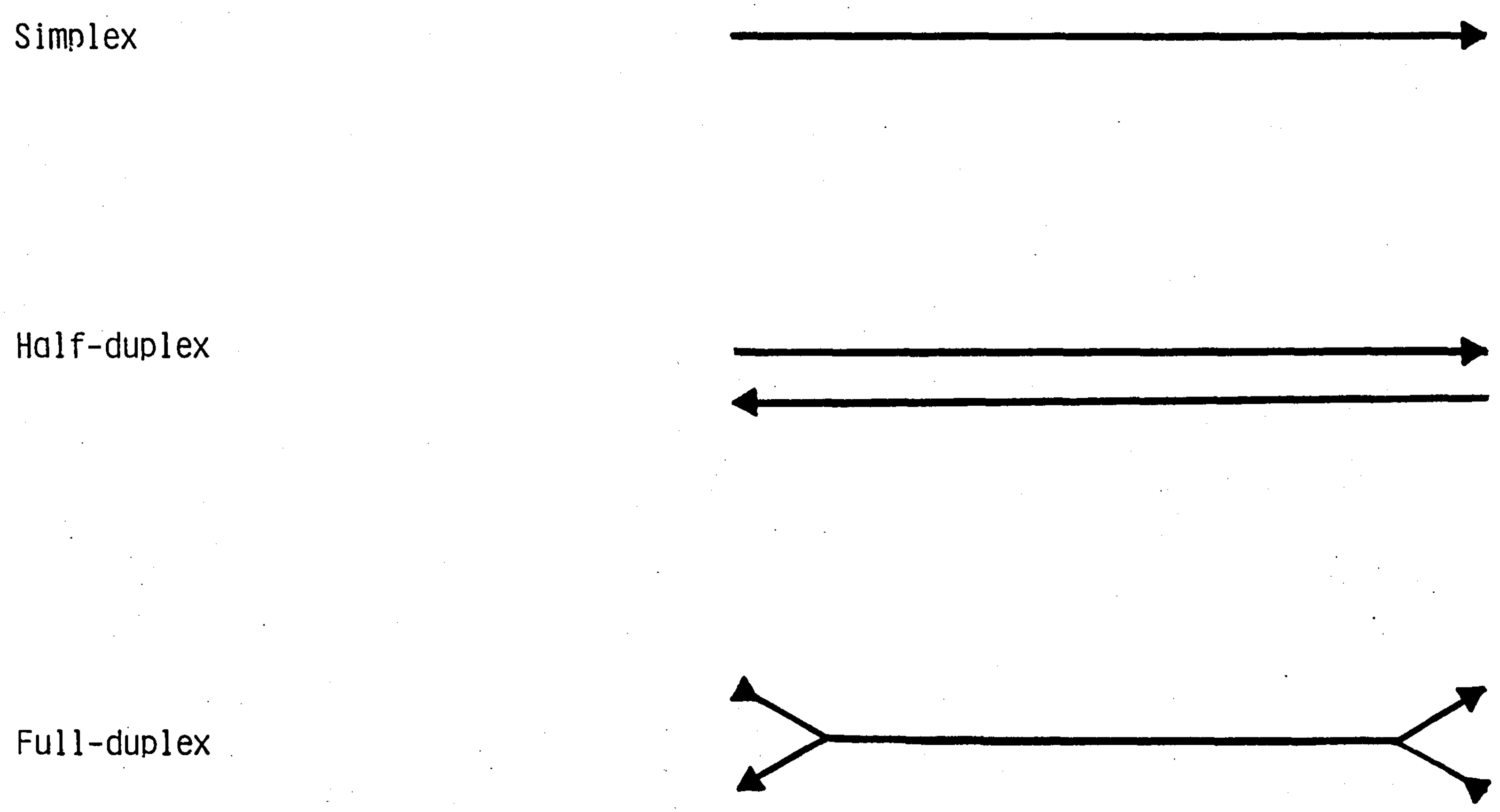
II.1.2. Protocol

Protocol, in the context of this study, refers to the method used to control the data communications. It is beyond the scope of this study to delve very deeply into the details of protocols, however certain path networks may support a given protocol better than other network paths; therefore some mention is necessary.

For our purposes, we divide the protocols into high level and low level protocols. The high level protocols are system related and may affect the topology, while the low level protocol tends to details of line communication. This simple division is shown in Figure II-9. The latter is

TRANSMISSION TECHNIQUES

Figure II-8



Simplex

Half-duplex

Full-duplex

ARCHITECTURAL CONCEPTS - PROTOCOL

Figure II-9

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- SYSTEM PROTOCOL
  - Polling
  - Command-response
  - Contention

- LINE PROTOCOL
  - Data rate/format
  - Modulation technique
    - baseband vs carrier
    - digital vs analog

generally transparent to the user and should not affect the system architecture; however in cases it may. For example, a link implementation that requires a header for "line conditioning" may require a higher data rate or degrade bus efficiency which could require an architectural modification to assure priority message handling. Also, within this level, modulation techniques such as baseband versus using carriers and digital versus analog data transmissions must be considered to achieve an optimum system design.

The system protocols may be broadly divided into three types: polling, command-response and contention. In a polled system, a master terminal has control of the bus and "quizzes" in some preset order (fixed timing) the other terminals to provide control or data to them and obtain status or data from them. This, the simplest protocol, has evolved into a similar but more sophisticated protocol: the command-response protocol. Here a central or master controls the actions of the other terminals asychronously. That is, a command is sent; after it is received by the appropriate terminal, that terminal responds as defined by the command. After its action is completed, the central terminal regains control of the bus and continues the process.

The control function need not be maintained in the same terminal at all times. The protocol can include commands that pass the master terminal status among several or all terminals in order to allow distributed processing of the data and other functions. However, a characteristic of the command-response and polled system is that positive control of the bus is maintained at all times. That is, the controlling terminal is the bus master and all other terminals are slaves to it.

The third protocol type, contention, is one that is democratic in the sense that all terminals have equal opportunity to access the bus at any given time. If two or more terminals access the bus simultaneously, the system design must be such that this condition is detected and the data retransmitted. This type of protocol is useful for a system where a large number of terminals have low message rates. In this case either a polled or command-response protocol may have low efficiency due to the large amount of overhead in comparison to actual data flow. Contention protocols obviously do not have the positive bus control required for managing critical functions.

Figure II-10 summarizes these three protocol types and shows a potential application area for each. Here the assignment of a protocol to the functions should not be taken too literally, but interpreted as a statement that a single "global integrated" bus for a complex system may not be desirable since different protocols may better serve different functions in optimizing the system.

II.2 RELIABILITY

For applications such as commercial aircraft, reliability is the most important factor. One speaks in terms of 10^{-9} system failures per hour. The allocation of reliability requirements can only be made after the platform is specified and details of the system design are known. It is, however, certain that the busing subsystem must be such as to contribute only a (small) fraction of total 10^{-9}/hour failure rate.

Presently, fiber optics is an emerging technology; knowledge of its reliability is sketchy at best. Therefore, we will summarize only the present state of the art and indicate areas where performance improvements or tests must be made to assure meeting reliability requirements.

II.3 MAINTAINABILITY

We mention maintainability for completeness in summarizing major system design considerations. In our view, there are two areas of importance at this stage of the system design. The first, system maintainability, is related to fault isolation and repair. This is one of the major reasons

PROTOCOLS

Figure II-10

PROTOCOL	POTENTIAL APPLICATION
POLLING	COMPUTER INTERCONNECT
COMMAND-RESPONSE	FLIGHT CONTROL/EMUX
CONTENTION	AVIONICS

that most airframers speak in terms of separate systems for separate functions (especially for the flight control system) rather than in terms of integrated systems. Here we will not enter into this controversy; we will consider buses in a general enough sense that the results can be universally applied.

The second maintainability issue we would refer to as physical maintainability. That is, the actual repair of the hardware once installed. This raises a number of questions for a fiber optic system. The viability of fiber optics may rest very heavily on this parameter alone. At this point it suffices to say that this is an area of concern in terms of fiber field termination, equipment reconfiguration, etc. Once the advantages of fiber optics to avionic system designs are established, detailed investigation into this maintainability issue will be appropriate.

II.4 POWER DISTRIBUTION REQUIREMENTS

In the case of fiber optic data distribution system, no metalic conductor is required to bus the data. However, the terminals still require power to generate and receive the optical signals. Thus, power may still have to be distributed along paths roughly parallel to the data signals. This does not negate advantages of fiber optics, but in some cases the advantage may be lost. In systems requiring high data rates or EMI immunity, a fiber optic implementation enjoys large advantages over wire links. Also when a bus is to be employed to an area for local distribution to a number of different terminals, the data and power paths may be quite independent.

Again we emphasize that without a detailed platform definition, the impact of a requirement such as a power distribution cannot be fully evaluated. The problem is clearly more acute in a longhaul system where repeaters must be employed than in a localized platform where many power forms are available. Thus for this study we do not address this topic further.

II.5 COST

In a trade-off analysis among system options, a number of (weighted) parameters are evaluated to establish a measure of effectiveness (MOE). This is usually done without including cost in dollars in order to determine the best systems technically. In the course of such as trade-off analysis some options are rejected due to failure of one or more required critical categories (e.g., reliability) or a low MOE.

If several alternatives remain, the MOE is combined (in some weighted manner) with cost estimates to determine the figure of merit (FOM) of the system. The winner of this trade off is then the lowest cost, technically acceptable system. Usually, for a large system, the cost considered is not only the initial cost, but the total life cycle cost (LCC), which includes maintenance, spares, logistic support, etc., over the total system life. Here we will not be able to accomplish determination of a FOM in detail but will restrict cost analysis to indicate trends in the initial procurement cycle only and mainly in relative terms since establishing the technical approach and merit is really the first order of business.

II.6 OTHER

There are a number of other areas that may be of importance specific to a particular design and must be considered. Examples are size, weight, human factors, ease of system reconfigurability, etc.

II.7 SUMMARY

Within the scope of this study as defined in Section I, we will be able to accomplish the first step in establishing a system measure of effectiveness: a technical analysis of fiber optic buses. Further it has been established that complex bus structures, such as will probably be employed for future civil aircraft, can be decomposed into simple structures (point-to-point, serial, and star) that are amenable to analysis without knowledge of the details of complex structure.

While detailed trade-off cannot be accomplished at this stage of the system design, broad brush comparisons among alternatives are made in the subsequent sections in terms of selected parameters.

III A 1553 BASELINE DESCRIPTION

In this section, we demonstrate a baseline set of bus subsystems based on a 1553-type implementation in order to show a potential configuration for next generation aircraft as well as to summarize an estimate of the function requirements for the avionics systems in that time frame. The system philosophy approach here reflects inputs from aircraft manufacturers as well as our own current thinking. The buses to be presented are 1553-type in the sense that rough order of magnitude estimates of data rates and number of terminals are compatible with MIL-STD-1553B; however, the networks to be shown do not preclude other potential bus standards from providing the same function with essentially the same topology.

An apparent underlying theme in the thinking of those considering this approach is the need for independent buses for independent functions. This stems largely from reliability and maintainability (RAM) issues. We will discuss other approaches in Section V. Special concern lies with the flight control bus with its high reliability requirements. This has resulted in a configuration with a triply redundant flight control bus that is simultaneously independent from any of the other buses. The bases of the independent bus approach for next generation implementation are summarized in Figure III-1.

Figure III-2 shows a potential configuration for a flight and propulsion control bus that is triply redundant. The A, B and C buses are each connected to a separate processor. The three processors jointly represent part of a fault-tolerant computer system wherein the command-response operation is subject to a data integrity check by means of a voting performed within the Higher Order Transfer System (HOX) shown in Figure III-3.

Note the flight control buses of Figure III-2 each support 11 terminals. Certain of the terminals shown may in reality be implemented as several

1553 BASELINE

Figure III-1

- NEXT GENERATION
- HELP TO IDENTIFY AND SCALE FUNCTIONAL REQUIREMENTS
- REPRESENTS AIRFRAMERS "PRESENT THINKING"
- RAM FUNCTIONS REQUIREMENTS ARE INDEPENDENT

  EXAMPLE: TRIPLE REDUNDANT FLIGHT CONTROLS
  EACH SYSTEM IS STAND-ALONE
- CHANGE IN "COMPUTING PHILOSOPHY" ALLOWS EVOLUTION TO MORE INTEGRATED SYSTEM IN NATURAL WAY

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FLIGHT & PROPULSION CONTROL

TRIPLEX BUSES & TERMINALS
COMMAND/RESPONSE PROTOCOL

- P - PITCH
- R - ROLL
- Y - YAW
- RT - REMOTE TERMINAL

INPUTS

REDUNDANT INPUTS (DIGITAL ANALOG) FOR CONTROL OF THE FLT CONT/PROP/PROPULSION/LND GR SYSTEMS

OUTPUTS

OUTPUTS TO DEDICATED AND MULTIPURPOSE DISPLAYS FOR CONTROL OF FLT CONT/PROP/LND GR SYSTEMS

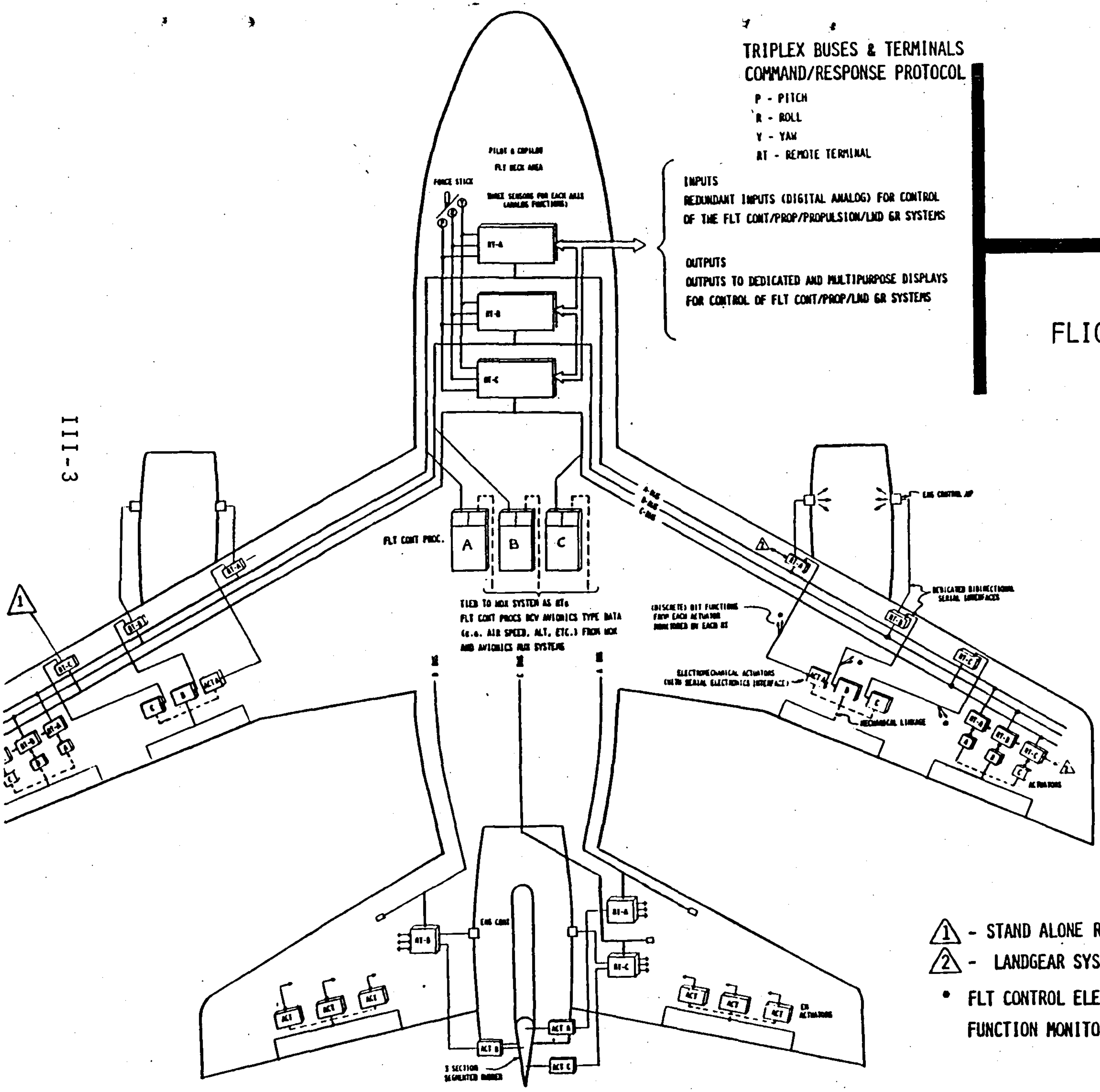

Figure III-2

1 - STAND ALONE RT WITH CONSIDERABLE SIGNAL CONDITIONING

2 - LANDGEAR SYSTEM FUNCTIONS

- FLT CONTROL ELECTROMECHANICAL ACTUATORS HAVE BUILT IN TEST FUNCTION MONITORED BY EACH RT

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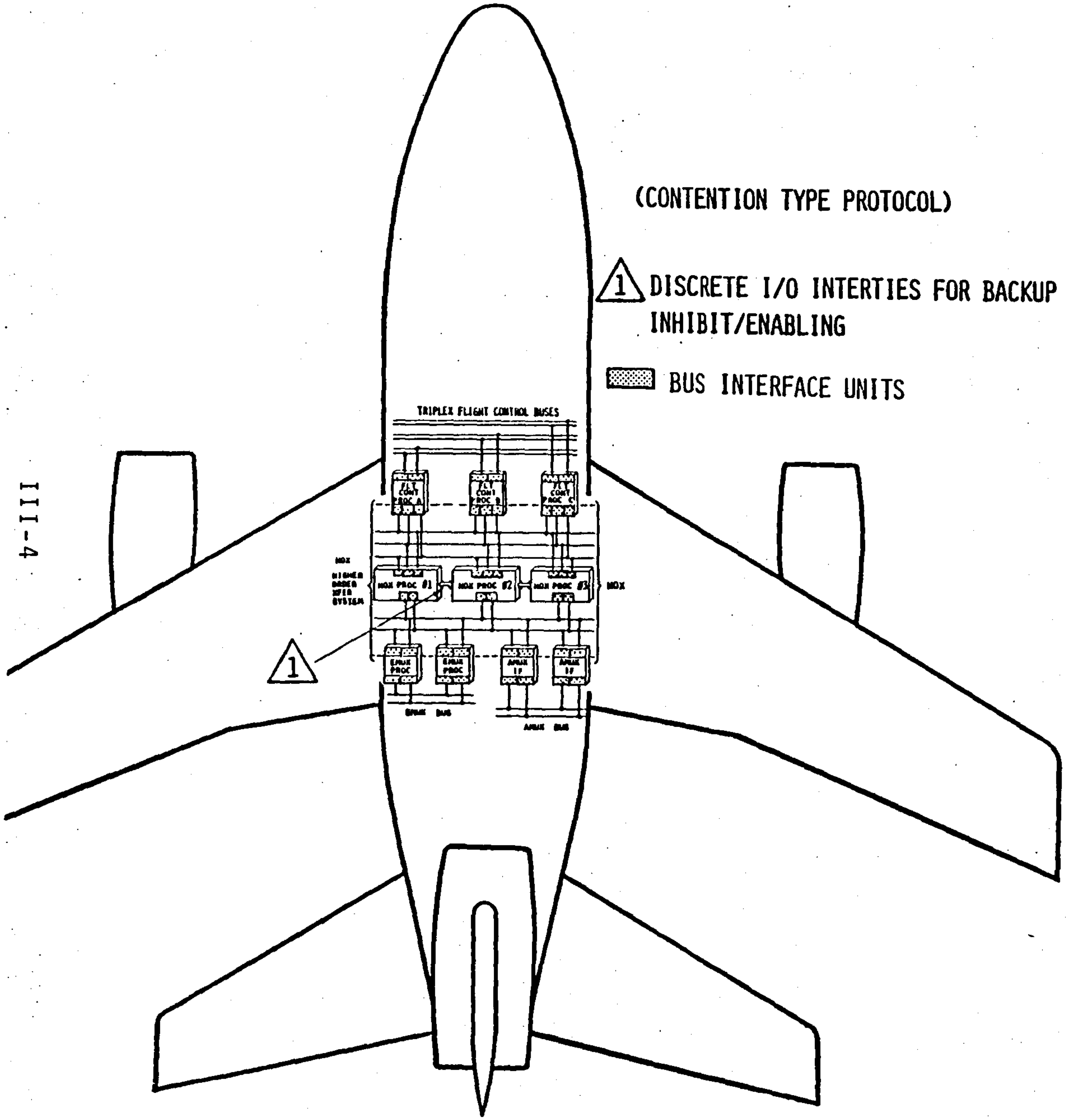

(CONTENTION TYPE PROTOCOL)

△1 DISCRETE I/O INTERTIES FOR BACKUP INHIBIT/ENABLING

▨ BUS INTERFACE UNITS

HIGHER ORDER TRANSFER SYSTEM (HOX)

Figure III-3

terminals (e.g., propulsion) each located more closely (integrated with) the control or monitor function that it serves. Even with this bus expansion, implementation would doubtless still be less than the 32-terminal maximum of 1553.

Figure III-4 shows a doubly redundant avionics bus with distributed computers on the bus serving various dedicated functions. This bus also connects to the HOX. Here the bus protocol can be either MIL-STD-1553 or one of contention protocols due to relatively unimportant timing and estimated low message traffic. Similarly, Figures III-5 and III-6 depict control display subsystem and EMUX system buses respectively. These are also doubly redundant and would probably utilize a command-response protocol. Note there are dedicated high-speed links between the video sensors and their respective processors. It is the processors that are on the 1553-type bus.

In general, the implementation of these buses is conceptually straightforward: 1553 plus several high-speed, dedicated coaxial links. It is also conceivable that there can be one-to-one implementation in fiber optics. More importantly, with this set of functional requirements summarized in Figure III-7 and approximate physical locations, we have a baseline to begin considering fiber optic implementations in different system partitioning.

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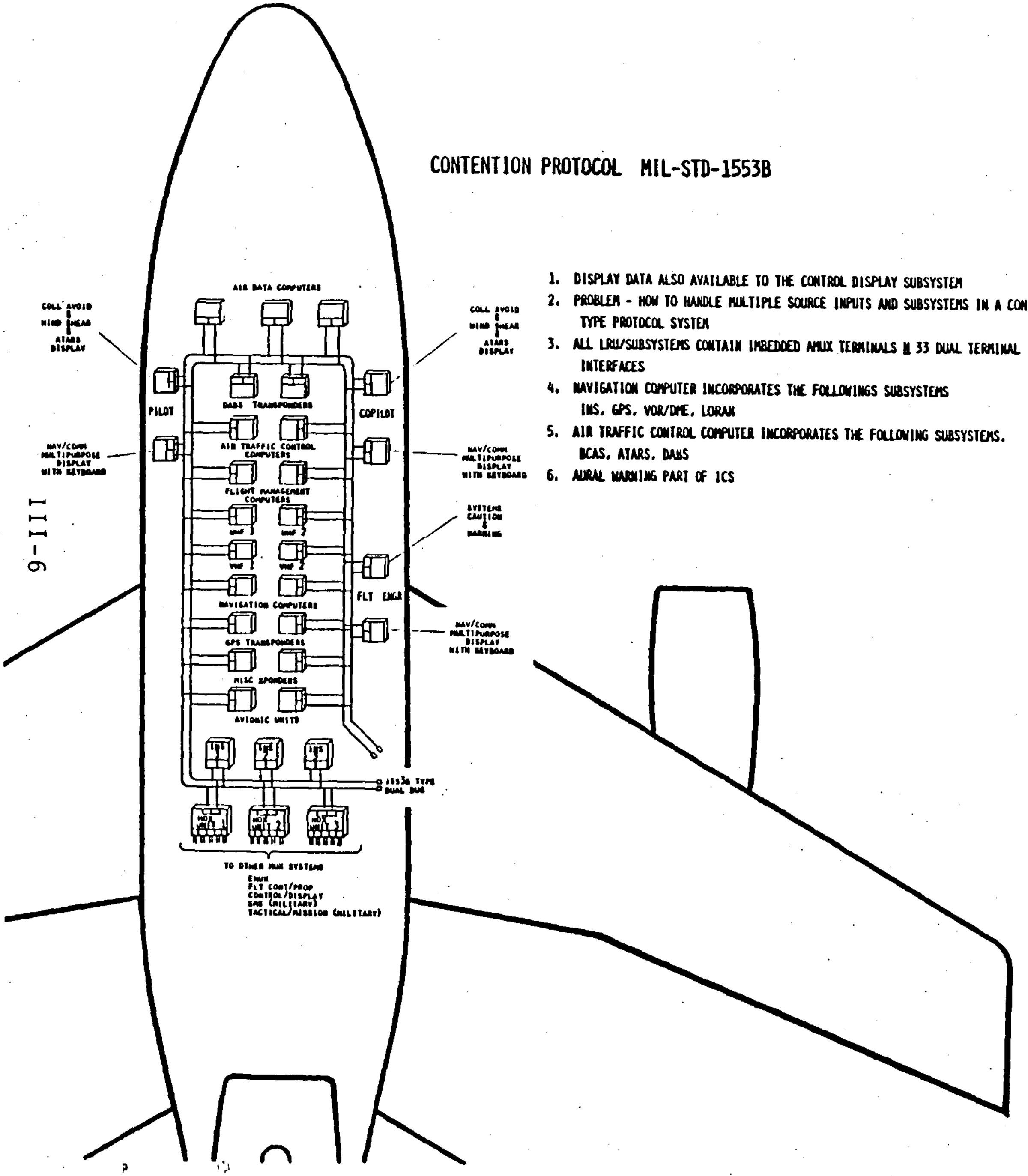
CONTENTION PROTOCOL MIL-STD-1553B



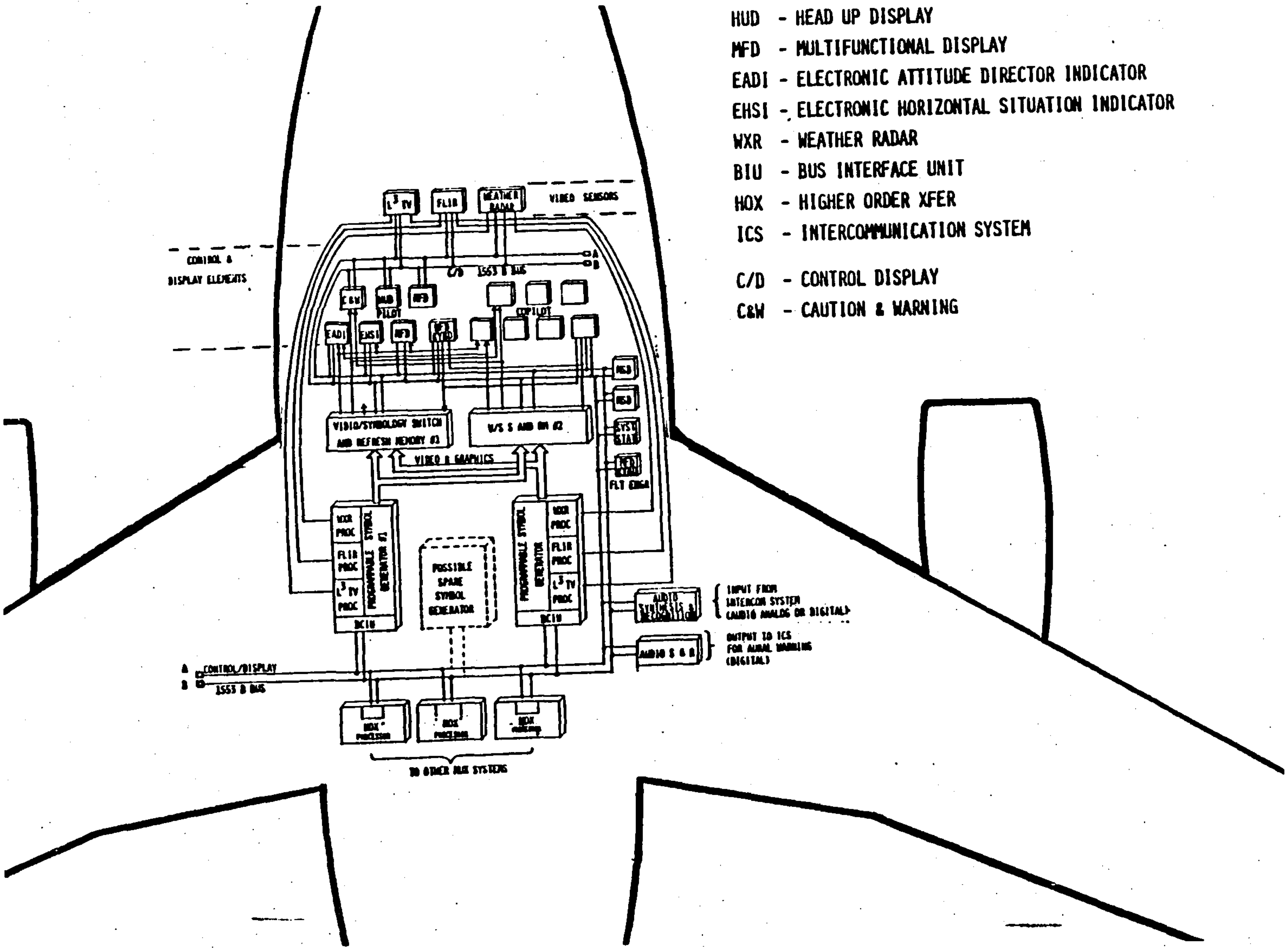
1. DISPLAY DATA ALSO AVAILABLE TO THE CONTROL DISPLAY SUBSYSTEM
2. PROBLEM - HOW TO HANDLE MULTIPLE SOURCE INPUTS AND SUBSYSTEMS IN A CONTENTION TYPE PROTOCOL SYSTEM
3. ALL LRU/SUBSYSTEMS CONTAIN IMBEDDED AMUX TERMINALS M 33 DUAL TERMINAL INTERFACES
4. NAVIGATION COMPUTER INCORPORATES THE FOLLOWINGS SUBSYSTEMS INS, GPS, VOR/DME, LORAN
5. AIR TRAFFIC CONTROL COMPUTER INCORPORATES THE FOLLOWING SUBSYSTEMS. BCAS, ATARS, DABS
6. AURAL WARNING PART OF ICS

AVIONICS SUBSYSTEM

Figure III-4

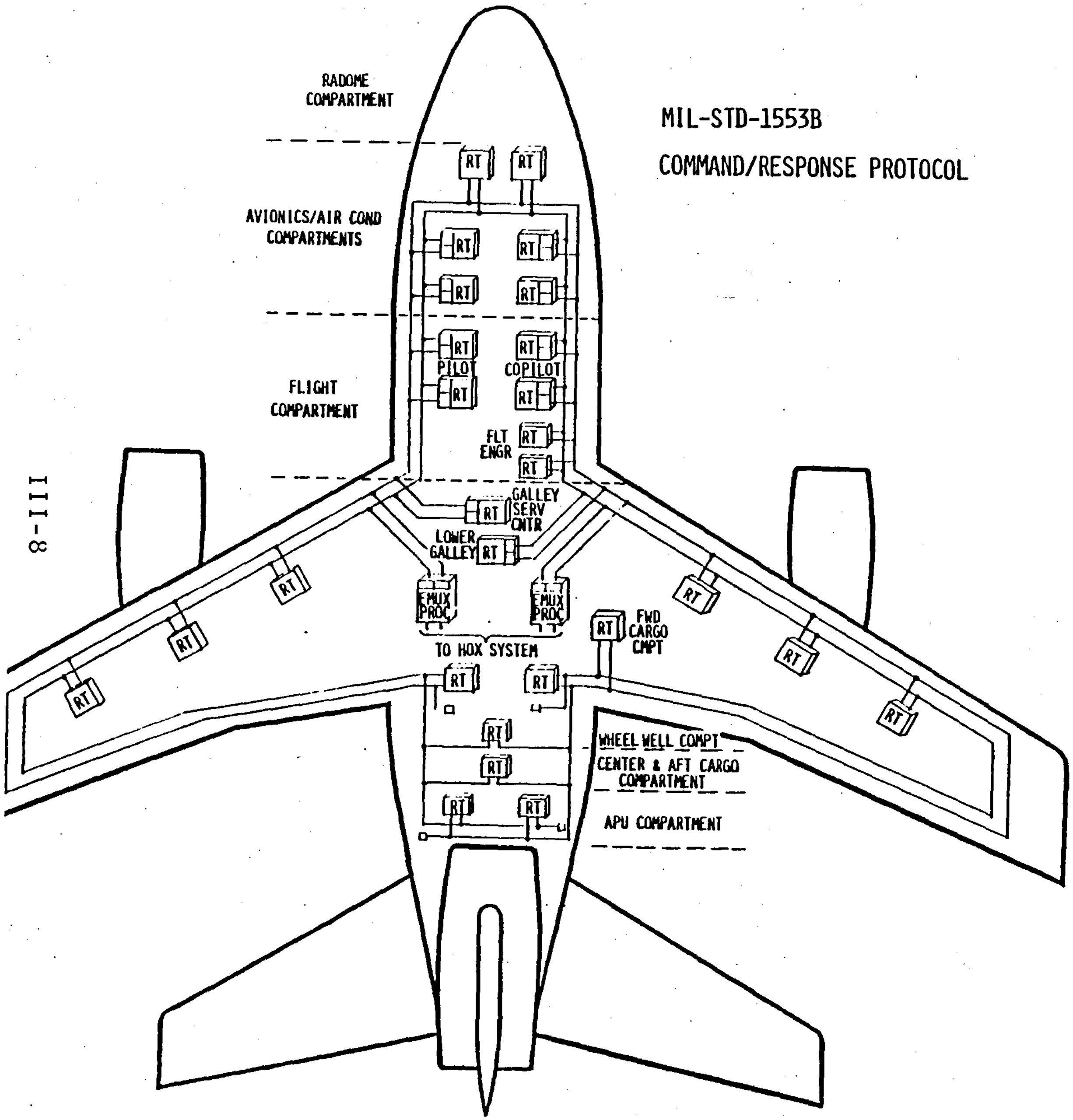
CONTROL DISPLAY SUBSYSTEM

Figure III-5



HUD - HEAD UP DISPLAY
MFD - MULTIFUNCTIONAL DISPLAY
EADI - ELECTRONIC ATTITUDE DIRECTOR INDICATOR
EHSI - ELECTRONIC HORIZONTAL SITUATION INDICATOR
WXR - WEATHER RADAR
BIU - BUS INTERFACE UNIT
HOX - HIGHER ORDER XFER
ICS - INTERCOMMUNICATION SYSTEM

C/D - CONTROL DISPLAY
C&W - CAUTION & WARNING



HUGHES

COMMERCIAL AIRCRAFT

EMUX SYSTEM

Figure III-6

BASIC FUNCTIONAL REQUIREMENTS

Figure III-7

AVIONICS

- NAVIGATION
- COMMUNICATIONS
- DATA INSERTION (FLT CREW)
- INTEGRATED RADIO CONTROL

EMUX

- POWER CONTROL
- AIR CONDITIONING
- LIGHTING
- PNEUMATICS

FLIGHT/PROPULSION/LANDING GEAR

- FLIGHT CONTROL/DISPLAYS
- FUEL/ENGINE/DISPLAYS

PASSENGER SERVICE/ENTERTAINMENT

VIDEO/ALPHANUMERIC DISPLAY

- MLS
- LLLTV
- FLIR
- ACARS
- MAPPING
- WEATHER RADAR
- VSI/EADI
- HSI/EHSI
- COLLISION AVOIDANCE
- CENTRAL WARNING
- GPS
- TRAFFIC INFORMATION
- SYSTEM STATUS/WARNING
- EADI/HUD
- CHECK LIST

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IV A GENERAL DESCRIPTION OF FIBER OPTIC BUSES

IV.1 INTRODUCTION

In this Section, a general description of fiber optic buses is presented. The fiber optic bus system requirements are presented to identify the components required for implementation. The components are described and their properties discussed in order to establish the present state of the art performance level of transmitters, receivers and distribution media (i.e., fiber, optical access couplers, wavelength multiplexers/demultiplexers, and optical switches).

This is followed by an analysis of topologies including dedicated structures and both serial and star bus structures. A comparison among these structures is made before discussing multiple wavelength buses and switches buses. With this background in hand, examples of how the network and protocol can interact are given.

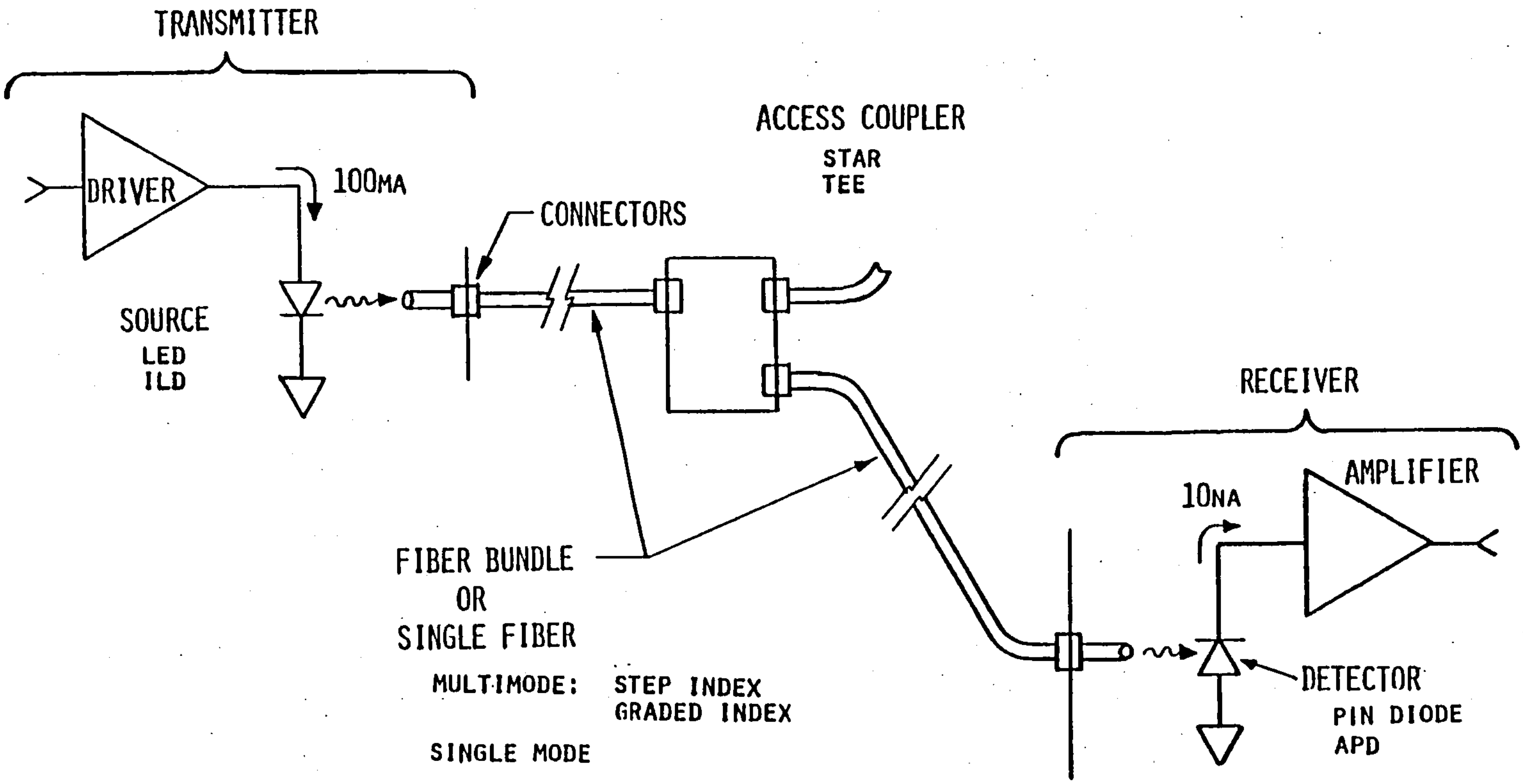
Finally this section addresses some of the reliability issues by listing several failure scenarios and relating problem detection and remedy to the bus structures discussed.

IV.2 SYSTEM REQUIREMENTS

The elements that are required to implement a fiber optic bus (or point-to-point) link are illustrated in Figure IV-1. At the left of this figure a transmitter is shown which consists of driver and a source. The source is usually a semiconductor device that emits light in the near-infrared region (800-1600nm). Semiconductor sources in the form of light-emitting diodes (LED's) and injection laser diodes (ILD'S) are available. The light output is (approximately) proportional to the current suppled by the driver. Thus a modulated light wavefront is emitted by the source with bandwidth of available sources extending to the GHz region. A drive current of 100ma is typical.

FIBER OPTICS SYSTEMS ELEMENTS

Figure IV-1



The light emitted is coupled into a glass fiber which is approximately 100 microns in diameter. Light is an electromagnetic radiation and as such the glass fiber can be viewed as a dielectric waveguide and Maxwell's equations apply. The light propagates down the waveguide (guided modes) with loss mechanisms due to scattering (mode conversions to radiation) and absorption (heating). An astounding feature of modern fiber is low loss on the order of a few dB/km for commerically available fiber cable and less than a dB/km for laboratory grade fibers.[3]

In general, means of connecting and disconnecting the fiber from modules, passing through bulkheads and joining fibers to fiber are required. Thus, connectors comprise another system element. These, due to imperfect alignment, contribute a loss at each connector of 1 to 2 dB. Note this is equivalent to about 1 km of fiber. For longhaul systems or in other systems in which low inline loss is important, permanent splices with losses on the order of 0.1 dB are used. This precludes rapid system reconfiguration or ease of transportability, which should not be a problem for an aircraft platform.

If a passive bus is utilized, then optical access couplers are required to divide the optical power among the terminals on the bus. There are two general types: tee couplers and star couplers. The tee-couple is possibly better called a Y-coupler. It is a three-port device that divides the input power to one port between two output ports. Star couplers divide the power from input ports equally (in most cases) among a number of output ports. Obviously, the optical access couplers are not required for a point-to-point bus implementation.

The receiver serves the function of detecting the modulated optical signal and amplifying it to a usable electric signal. The detection process is accomplished for most fiber optic links with a semiconductor device. Both pin diode detectors and avalance photodiode (APD) detectors are available. The APD provide an advantage in gain at the expense of requiring a high voltage supply and having poor temperature stability. In the 10Mbps region, the amplifier must be capable of accepting and processing signal currents on the order of 10 μA.

The present state of the art is such that point-to-point links from low bit rates to several hundred Mbps are being routinely applied for data transmission, especially in telecommunication, but also for commuter interconnects, industrial process control and numerous other applications. Bus systems are in the advanced development stage. Recent developments in optical access couplers and bus receivers with large dynamic range have advanced the state of the art so that multiterminal passive optical buses are now practical.

A number of additional optical components are in various stages of development that may allow more esoteric configurations. These include wavelength multiplexers and demultiplexers, optical switches and other integrated optics devices.

The components that we will consider in more detail in the course of this section are summarized in Figure IV.2.

IV.3 COMPONENT DESCRIPTION AND PROPERTIES

IV.3.1 Transmitter

SOURCES. As indicated in the discussion above, presently there are two devices types that are suitable for light sources for fiber optic communications: the LED and ILD. Both are produced using GaAs semiconductor technology.

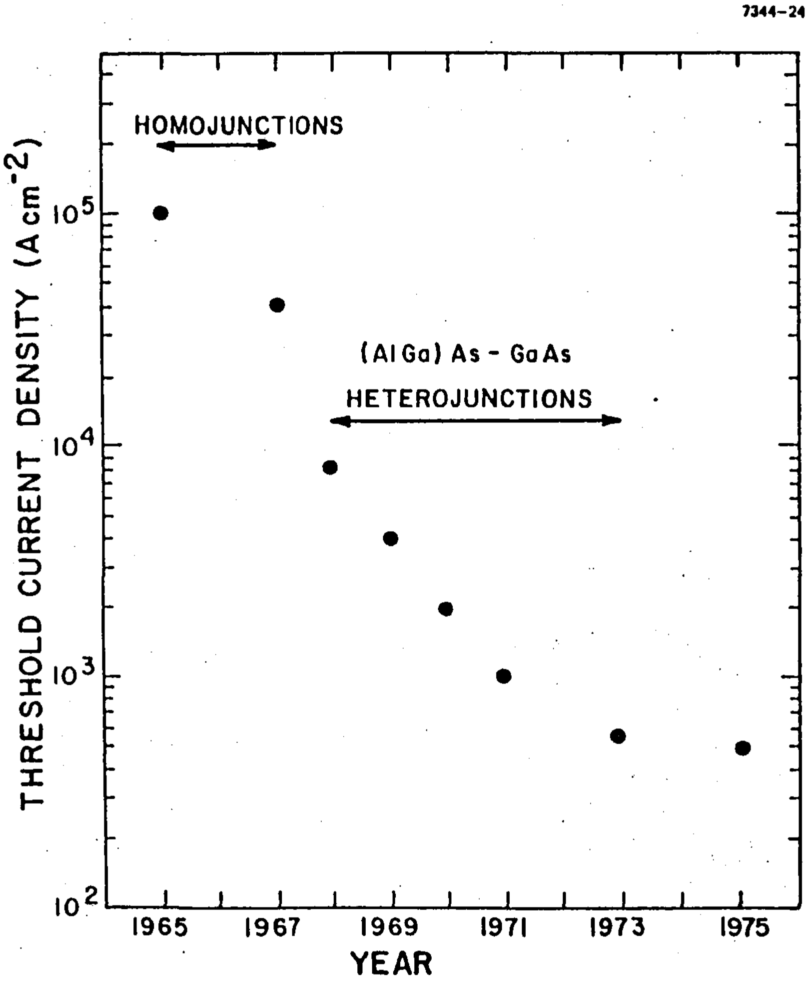
Figure IV-3 shows the improvement that was made in threshold current density for ILD, making the device practical for room temperature operation with extended lifetimes.

Dopants are employed to control the output wavelength. Currently output wavelengths in the range between 800 and 1600 nm are available with devices in the range between 800 and 900 nm being most mature. The manufactured wavelength that these devices emit has been selected to match the minimum in fiber attenuation that has been changing as fiber technology matures.

FIBER OPTIC COMPONENTS

Figure IV-2

- OPTICAL FIBERS
- CONNECTORS/SPLICES
- SOURCES/TRANSMITTERS
- DETECTORS/RECEIVERS
- OPTICAL ACCESS COUPLERS
- WAVELENGTH MUX/DEMUX
- OPTICAL SWITCHES
- OTHER INTEGRATED OPTICS


7344-24
HOMOJUNCTIONS
(AlGa) As - GaAs
HETEROJUNCTIONS
THRESHOLD CURRENT DENSITY (A cm^{-2})
10^5
10^4
10^3
10^2
1965
1967
1969
1971
1973
1975
YEAR

The LED's are either edge emitters or surface emitters. Etched-well surface emitters are sometimes referred to as "Burrus"-type LED's.[4] The edge emitter output is contained in a 120°-by-40° beam. Surface emitters radiate a lambertian pattern, while the Burrus-LED radiates a modified-cosine pattern. The spectral width is 40 to 50nm. A sketch of an LED Burrus etched-well emitter is shown butt coupled to a fiber in Figure IV-4.

The source optical power is the total amount of optical power emitted. This is typically 50 to 100W/cm^2-steradian at a drive current of 150 mA. The area of emission is typically 10^{-5} cm^2. Unfortunately, only a small portion of this power is coupled into the fiber. This coupling loss, to be discussed below, is between 10 and 20 dB.[5] The surface emitter, due to its uniform radiation pattern, has about a 5 to 6 dB greater coupling loss than the edge emitter. This is approximately offset by a higher radiative power. The Burrus diode, due to its small emission area and modified-cosine radiation pattern, suffers the least light loss in coupling to the fiber.

LED's exhibit reasonable linearity and may be either amplitude modulated or pulsed.

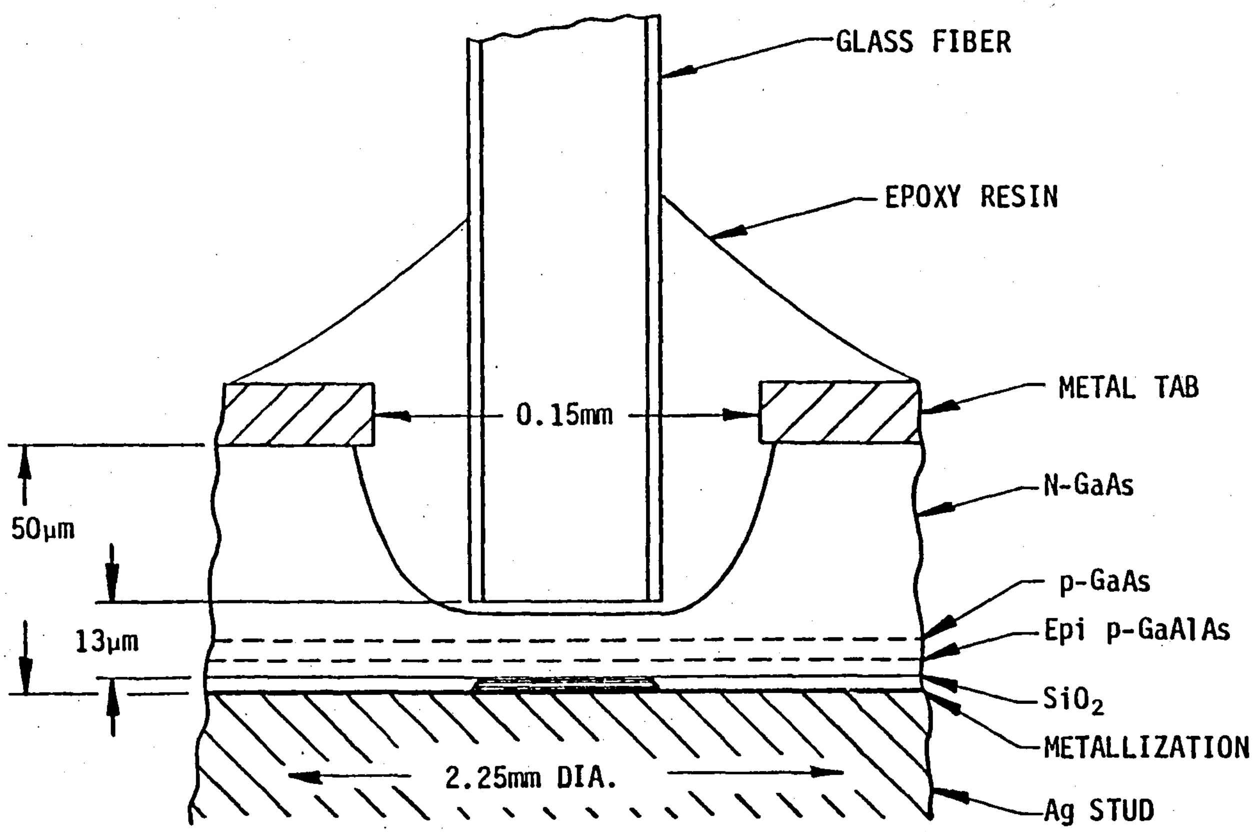
Data rates are limited by diode response time. To first order, with diode current constant, the optical power output is related to the modulation angular frequency ω by

$$P(\omega) = P_0[1 + (\omega\tau)^2]^{-1/2}$$

where τ is the minority carrier lifetime. This ranges between 1 and 30 ns depending on material and doping levels. Circuit parasitic elements can further reduce the modulated power. High speed diodes require short minority carrier lifetime, but short minority carrier lifetimes are obtained at high doping levels. These create a high density of nonradiative centers, lowering the quantum efficiency of the diode. So a compro-

LED
BURRUS ETCHED WELL EMITTER

Figure IV-4



mise is required to obtain good quantum efficiency (10%) and fast response time (nanoseconds).

The basic failure mode of the LED is a gradual degradation of the externally measured quantum efficiency created by nonradiative center formation in the radiative region where electron-hole pair recombination occurs. Center formation appears to be a function of crystal dislocations, active region edges and strain introduced during assembly. Typical LED lifetimes are greater than 10^6 hours.

Laser diodes potentially have many advantages. They emit coherent light with peak power on the order of watts. The spectral width is narrow (1 to 1.5 nm) and the beam pattern is confined to about 8°. Due to the narrow beam, fiber coupling losses are small -- only about 1 to 3 dB.[6] They are high-speed devices and allow modulation to 1 GHz. However, they presently suffer lifetime shortcomings and sensitivity to temperature and time as well as modal instabilities. The sensitivities to temperature and time require feedback circuitry to adjust the laser bias to compensate for the varying optical output. Laser diodes, depending on geometry, are either single mode or multi-mode devices. The single mode devices are extremely linear; the second harmonic distortion is less than 1% with useful modulation depths. Their narrow spectral width will undoubtedly be required for wavelength division multiplexed systems.

A comparison summary of LED versus ILD is presented in Figure IV-5. For many system designs, the high power launch, narrow spectral width, and linearity of the ILD may offset its disadvantages of poor temperature stability and higher cost.

DRIVERS. The LED or ILD drivers present no particular electronic problems. On-off current switches for digital modulation formats are straightforward to implement as are analog modulators. Light output from the source may be sensed and used to control a feedback loop to stabilize the output if required. This added complexity is usually only warranted for critical analog systems.

LED vs ILD

Figure IV-5

	LED	ILD
POWER LAUNCH	LOW	HIGH
TEMPERATURE SENSITIVITY	FAIR	POOR
LINEARITY	FAIR	GOOD (SINGLE MODE)
SPECIAL WIDTH	WIDE	NARROW
LIFETIME	GOOD	FAIR (IMPROVING)
COST	MEDIUM	HIGH (IMPROVING)

IV.3.2 Optical Waveguides

Transmitting the signal source over a spatial distance requires coupling the modulated light from the source into a transparent medium within which it is guided to its termination point. The characteristics and specifications of optical waveguides or fibers are covered in this section.

PHYSICAL CONSIDERATIONS. Mechanical and physical properties are important. There are silica fibers, plastic fibers and plastic-clad silica fibers. The plastic fibers have, generally, very high attenuation and are suitable for links of 50 m or less. Glass fibers are now routinely produced in lengths over a kilometer and are being utilized for most applications.

The waveguide is either a single fiber or a bundle of fibers. The fiber bundles are difficult to install and have been found to be fragile. This is due to glass-on-glass contact in the bundle. With the advances in cabling, a single high-grade fiber is much more rugged than a bundle of low grade (i.e., for economical reasons) fibers in contact with each other. Furthermore, the presence of a number of fibers in one bundle gives rise to gaps between individual fibers and therefore not all light striking the bundle end is coupled.

For these reasons, a single silica fiber cable is recommended. The single-fiber cable is easy to splice and terminate. Typically the fiber is coated, encased in layers of plastic jacket and fiber whipping and finally given a plastic outer sheath for protection. The overall diameter is on the order of 5 mm. These fully protected cables have high tensile strength and are as easy to install as coax. The several layers of padding protects against micro bends in the fiber which cause radiated light loss (see below).

Several (2 to 10 or more) independent fibers may be configured in a single cable. This cable includes non-conducting strength members to provide rigidity and absorbs loading forces to protect the fiber. The overall cable diameter for a seven fiber cable with two strength members is also only 5 mm.

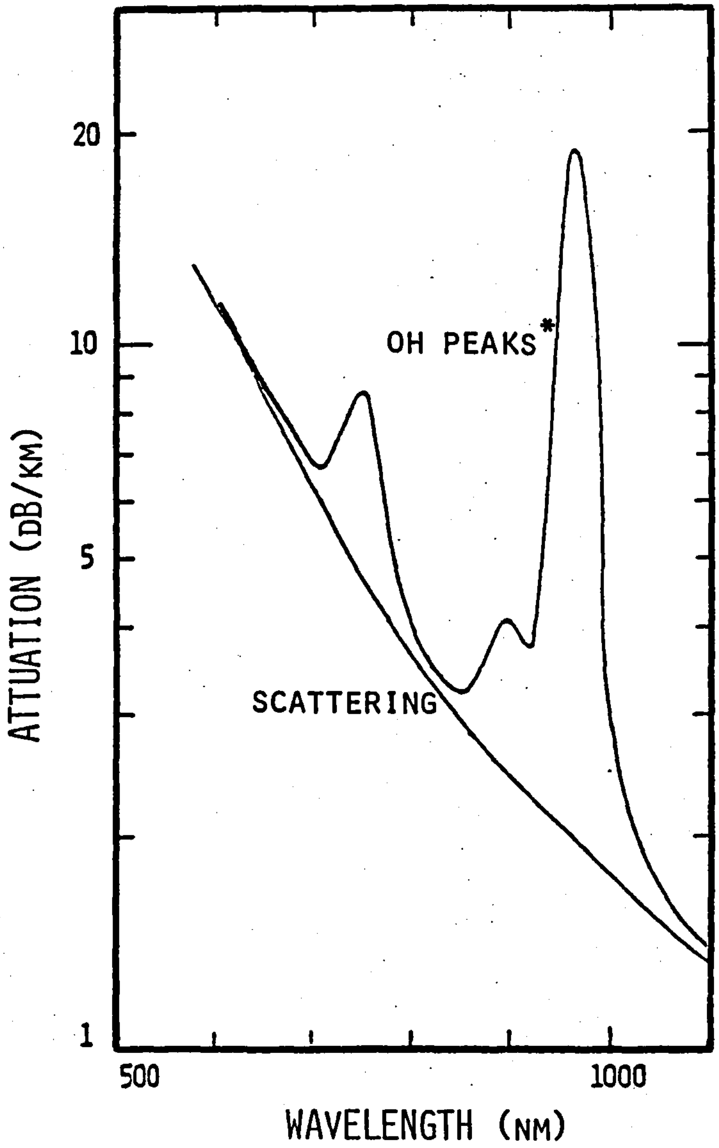
OPTICAL CONSIDERATIONS. The most important optical properties of the fibers are numerical aperture, attenuation, propagation mode and dispersion. These properties interrelate, therefore each is briefly introduced and then discussed in detail in relation to the other properties.

NUMERICAL APERTURES. The numerical aperture, NA, is an expression of the light-gathering power of the fiber. In order for the light to be captured and transmitted along the fiber, the light must lie within the cone of the critical angle of acceptance.

ATTENUATION. Attenuation expresses the fiber losses, usually in dB/km, and range from 1000 dB/km to 1 dB/km depending on the quality of the cable and the wavelength of the source. The losses are caused by both impurities (scattering losses) and absorption. Figure IV.6 shows an optical fiber attenuation plot as a function of wavelength. The OH absorption band at 950 nm is a ramification of vestigial water in the fiber manufacturing process. This figure is representative of an "outside-grown" fiber. New, "inside-grown" fiber manufacturing techniques produce fibers with attenuation characteristics that are approximately due to scattering alone.

MODE. Fiber optic waveguides presently in production are specified as step-index multimode, step-index single mode and graded index. This specification characterizes the construction of the fiber and its radial index of refraction distribution which in turn determines the light wave propagation mode.

DISPERSION. Pulse dispersion, expressed in ns/km, arises from three main effects: propagation mode, material and waveguide. The effect of dispersion is to widen the pulse and therefore is one of the factors that limits the data rate for a given length link.



(* ELIMINATED IN MODERN FIBER PRODUCTION)

HUGHES

FIBER LOSS CHARACTERISTICS

Figure IV-6

Figure IV-7 shows the relationships between the NA and the indices of refraction for a step-index fiber. A ray with an angle greater than the critical will radiate from the fiber and will not propage along the fiber. The major portion of the optical power is propagated by meridonal rays, so rays that do not pass through the optical axis are usually ignored. The NA is specified by the fiber manufacture and typically range from 0.1 to 0.4 (with large plastic fibers having NAs of 0.5 to 0.6).

The pulse disperion depends on the NA of the step-index fiber. The greater the NA, the greater the allowed difference in path-lengths between the axial rays and rays internally reflected at the allowed angles. This spreading in arrival time due to path length difference is known as modal dispersion. It is easier to launch power into a high NA fiber, but a price in decreased bandwidth must be paid for this increased power from a given source when using a step-index fiber.

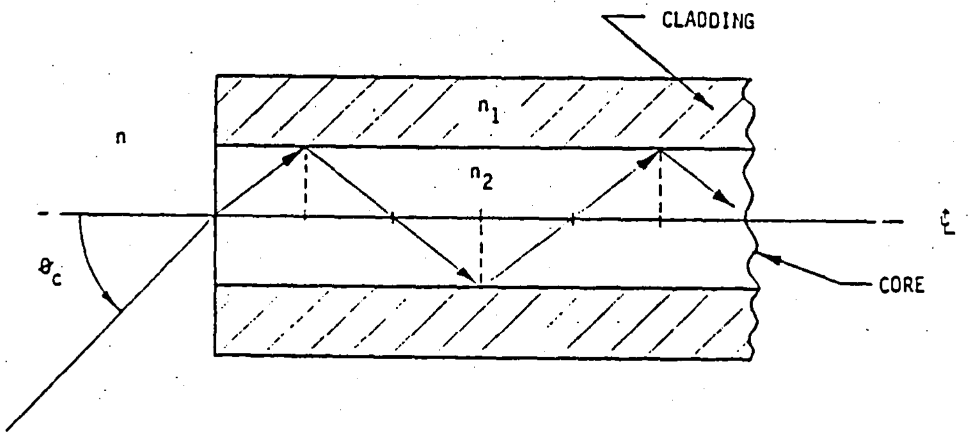
Graded-index fiber is an optical waveguide with a gradually varying index of refraction (usually parabolic). The index of retraction decreases with radius (about a 1% difference), hence the light rays are continuously refocused by refraction. This profiling reduces the spread of the group velocities for the various propagating modes and, therefore, the graded-index fibers have very low disperion (about 5 ns/km with LED sources and less than 1 ns/km with laser sources).

The step-index fiber has a core with a high index of refraction surrounded by a lower index cladding. The abrupt change of index of refraction gives rise to the name use. These may be either single-mode or multi-mode fibers. The single-mode fiber has an extremely small (3-10 μm) core and an index difference of 0.25 to 0.5 percent. The core diameter, d, and wavelength, λ , meet the following criteria to qualify as a single-mode fiber:

OPTICAL FIBERS
NUMERICAL APERATURE

HUGHES

Figure IV-7



NA = numerical aperture = $n\phi_c$

where

n = index of refraction of the medium external to the fiber (usually air for which $n = 1$).

ϕ_c = critical angle

Then, if n_1 and n_2 are the cladding and jacket indices of refraction respectively,

$$NA = n \sin \phi_c = \sin \phi_c = (n_2^2 - n_1^2)^{\frac{1}{2}}$$

$$\frac{\Pi d(NA)}{\lambda} < 2.4$$

The small core size is on the order of the wavelength of the source, hence only a few modes are propagated. A laser source is required to launch power into these fibers. The laser plus single mode propagation leads to very small dispersion, hence extremely large bandwidths are possible.

The multi-mode step-index fiber is identical in construction to the single-mode fiber except the core diameter is much larger. Typical core diameters are 50 to 75 μm, with sizes up to several hundred μm also in use. Core to cladding index of refraction differences range from 0.7 to 2%. The modal dispersion due to the larger core limits the bandwidth. Typically there is a dispersion of 50 ns/km/percent of core-cladding index difference, limiting the bandwidth to about 20Mb/km. Figure IV-8 summarizes the fiber types, while Figure IV-9 illustrates the difference between step index and graded index mode propagation and shows how the large bandwidth is achieved by the graded index profile.

The coupling losses of light into the fiber are of two types: one caused by unequal cross-sectional areas and one due to the optical constraints (i.e., NA) of the fiber itself. For a lambertian source and a graded index fiber, the fractional power launched into the cable is given by

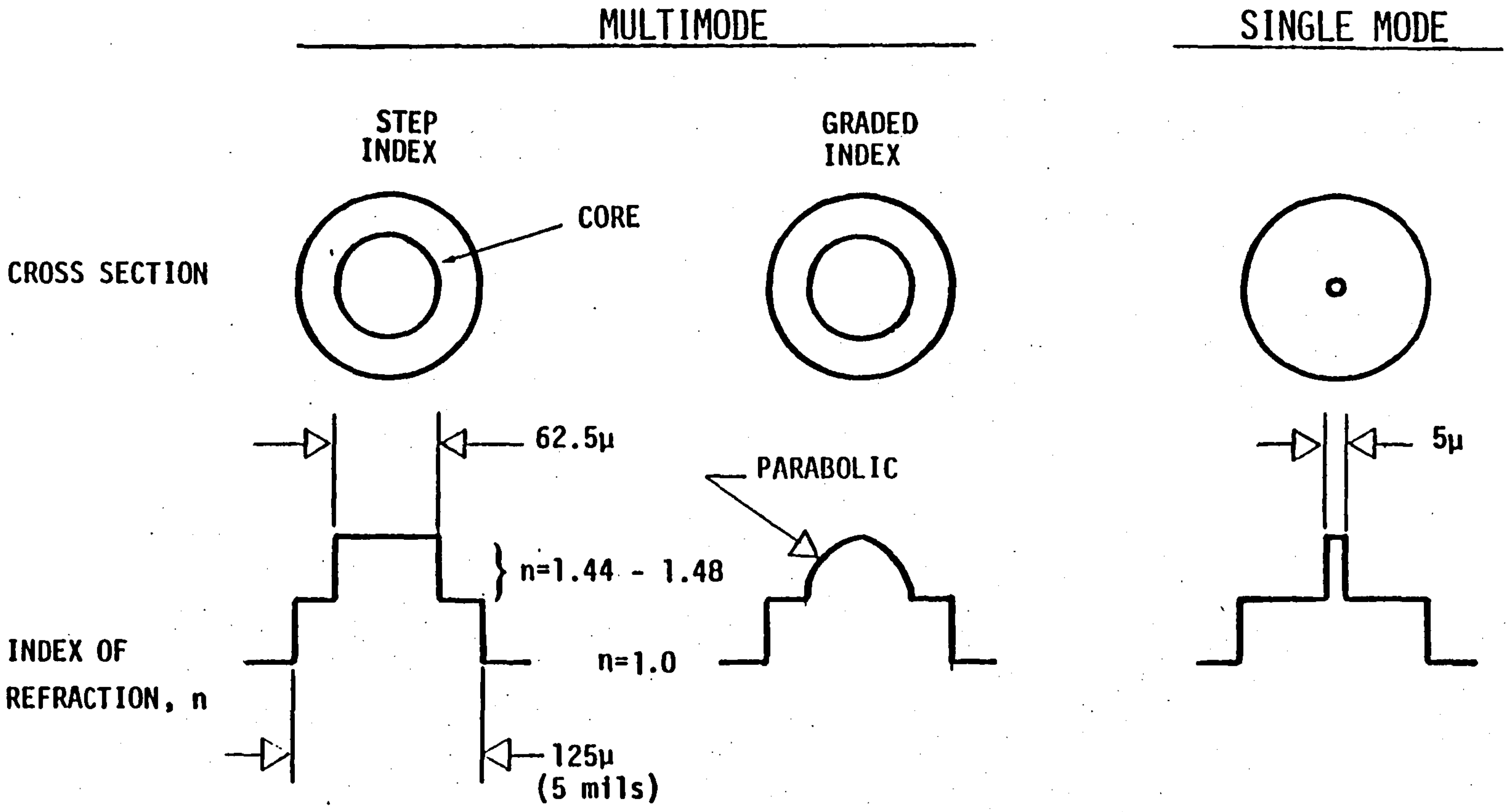
$$\frac{P}{P_O} = \frac{A_C \, (NA)^2}{2 \, A_S \, n_O{}^2}$$

where A_C and A_S are the core and source areas respectively and n_O is the index of refraction of the medium between the source and the waveguide. The core area is generally less than or equal to the source area and the fiber is simply butted against the source. Lenses could be employed. Coupling losses range from 10 to 20 dB.

OPTICAL FIBERS

HUGHES

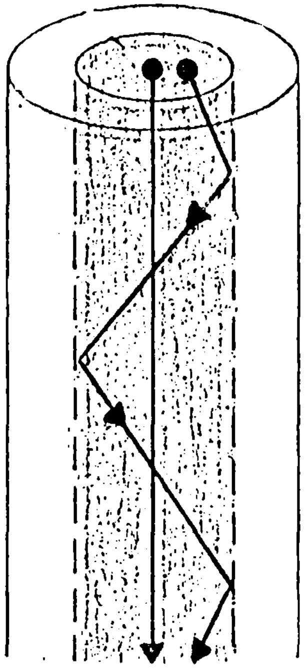
Figure IV-8



TRANSMISSION BANDWIDTH

Figure IV-9

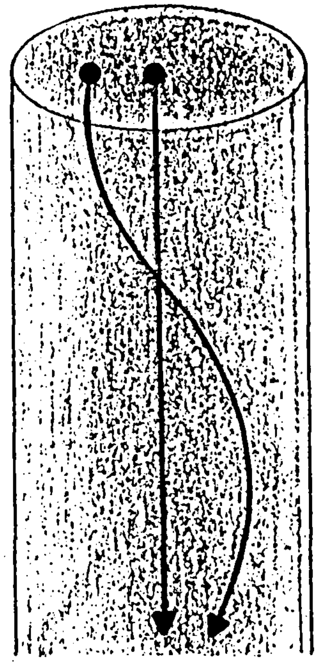
STEP INDEX



OFF-AXIS MODES TRAVEL
AT SLOWER VELOCITIES

LIMITED BANDWIDTH

GRADED INDEX



ALL MODES TRAVEL
AT THE SAME VELOCITY

LARGE BANDWIDTH

A power of -10 dBm launched into a 0.2-0.3NA fiber by an LED provides a good baseline estimate for present off-the-shelf components.

The main factors that influence pulse dispersion are multimode propagation, waveguide and material effects. The multimode effect related to different path lengths have been discussed above. For NA's between 0.1 and 0.3 the step-index fibers have delay spreads of 10 to 50 ns/km, while graded index fibers have delay spread of 0.1 to 1 ns/km. The waveguide effect is generally negligible. Material properties lead to dispersion effects that depend on the wavelength of the source and on the spectral distribution of the light. An impulse is broadened due to the differential delay of the various wavelengths. For LED sources, this chromatic dispersion is approximately an additional 5 to 10 ns/km.

For very long fibers, there is indication that the dispersion does not grow linearly with length. This is due to mode coupling and after equilibrium is reached (about 1 km) the dispersion grows with approximately the square root of the distance. An approximate rule-of-thumb is that, for intensely modulated signals, the bandwidth is limited to about .35/dispersion over the link length. For pulse-modulated transmission the reciprocal of the bit rate approximately sets the allowable dispersion.

The attenuation of the fiber depends on absorption by transition-metal ions and hydroxl radicals. The scattering by impurities in the fiber core material also lead to losses. The scattering goes like λ^{-4}, where λ is the light wavelength, and, therefore, there are efforts to produce long-wavelength sources and detectors in the infrared region near 1100 nm.

Microbends cause light propagating near the critical angle to be constantly scattered out of the fiber. This problem is largely cured by the protective layers on the sheathed fibers. During installation, a sharp bend will impose a one-time loss of certain propagating modes, but will be non-recurring (for similar bends) except for the energy restored to these modes by mode coupling during long fiber runs.

Well protected silica fibers with NA's of 0.2-0.3, attenuations of 3-50 dB/km and bandwidth-length products in excess of 20 MHz/km are now routinely produced by a number of manufacturers with prices that are competitive with coax.

IV.3.3 Optical Access Couplers

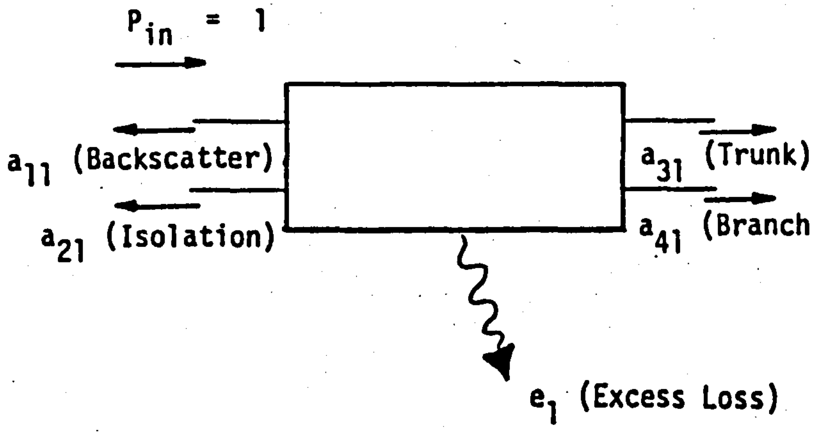
In order to provide an optical bus capability, there must be devices to extract and inject optical power from and to the distribution network. This can obviously be accomplished with active devices consisting of transceiver units; however, here we emphasize passive devices which are referred to as optical access couplers. The availability and construction of these will be discussed in this section.

TEE COUPLERS. The fused-tee couplers are constructed by stretching two single-fibers as they are heated and the claddings fused together. The procedure forms a biconical taper. As light enters the decreasing taper, guided modes are converted to cladding modes. During transmission through the fused region, a portion of the optical power in the cladding modes is exchanged between the fibers. The cladding modes are then converted back to core-guided modes as the taper increases at the output of the junction. During coupler construction, parameters are controlled to yield tap ratios ranging from slightly above 3 dB upward.

Figure IV-10 shows the coupler as a four-port device and defines the variables. The fused-tee coupler is characterized as a four-port device. Ports 1 and 3 are one fiber; ports 2 and 4 are the other fiber. In the ideal case, a_{11}, a_{21} and e_1 would all be zero and the sum of a_{31} and a_{41} would be one. The fractional power output at port j due to an input at port i is denoted a_{ij}. The coupler exhibits loss e_i when power is launched into port i.

The isolation coefficient is a function of the tap ratio and, also, coupler fabrication. The value of -35 dB is a worst case and is noted only for equal power division. This coefficient decreases as the tap ratio increases and reaches a value of less than -50dB for 15dB couplers.

GENERALIZED TERMS FOR A FOUR PORT OPTICAL ACCESS COUPLER WITH EXCESS LOSS



The transfer matrix a_{ij} is shown in Figure IV-11. Experimentally, a_{ij} is found to be approximately equal to a_{ji} as required by reciprocity. The equality of the small elements represented by δ is an approximation for the backscatter and isolation parameters. Furthermore, a good coupler exhibits $a \approx \alpha$ and $b \approx \beta$ due to symmetry and homogenity of excess loss mechanisms. Typical parameters for an equal power division coupler are

$$\alpha = 0.48, \quad \beta = 0.42, \text{ and } \delta = 3 \times 10^{-4}.$$

The measured tap ratio and excess loss for a set of 36 fused-tee couplers is shown in Figure IV-12.

The planar optical access couplers under development at Hughes are based on a proprietary masking and diffusion process. The concept is illustrated in Figure IV-13. The process, which is undergoing intense investigation and development, holds great promise for low cost, well controlled, mass produced, multi-mode optical components. These devices have been demonstrated in the laboratory. The present thrust is two-fold: multiple diffusion process development to match the channel to optical fibers and fiber attachment and packaging.

Since the channel is determined by a masking operation, a wide variety of geometrics may be conceived. The tap ratio of a planar Y with equal area ports is established by the angle between the trunk and branch arm as indicated in Figure IV-14. Ray tracing as well as experimental data have been used to characterize the couplers. The excess loss is found to be small. The transfer matrix for a device may be approximated, where the excess loss and backscatter have been neglected, by A_3 in Figure IV-14. Here X varies in the ray tracing results between 1.25 for θ equal to 1/2 to X equal to 1 for small tap ratios. The calculated excess loss not shown in the transfer matrix is small and will ultimately depend on the quality of fiber to guide matching.

FOUR PORT
OPTICAL ACCESS
COUPLER
TRANSFER MATRICES

$$a_{ij} = \begin{pmatrix} \delta & \delta & \alpha & \beta \\ \delta & \delta & b & a \\ \alpha & b & \delta & \delta \\ \beta & a & \delta & \delta \end{pmatrix}$$

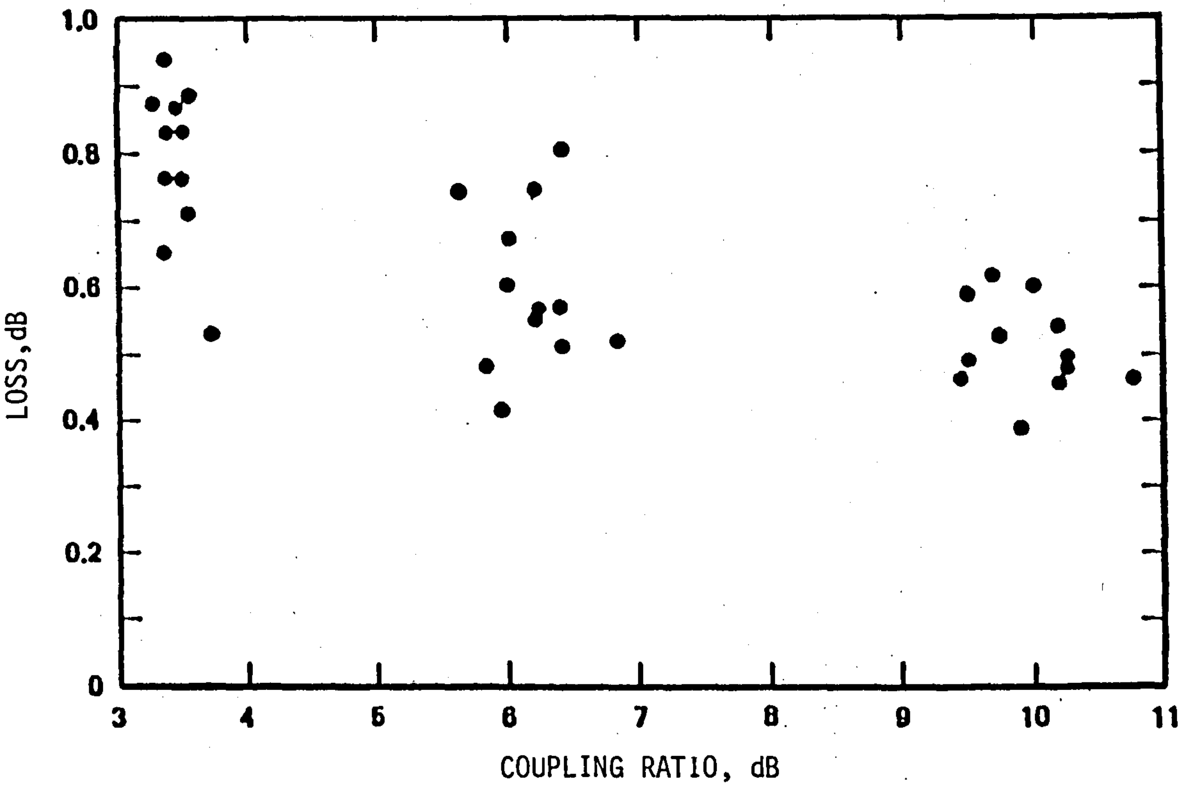
$$a'_{ij} \simeq \begin{bmatrix} \delta & \delta & \alpha & \beta \\ \delta & \delta & \beta & \alpha \\ \alpha & \beta & \delta & \delta \\ \beta & \alpha & \delta & \delta \end{bmatrix}$$

Figure IV-11

FUSED-TEE OPTICAL ACCESS COUPLER

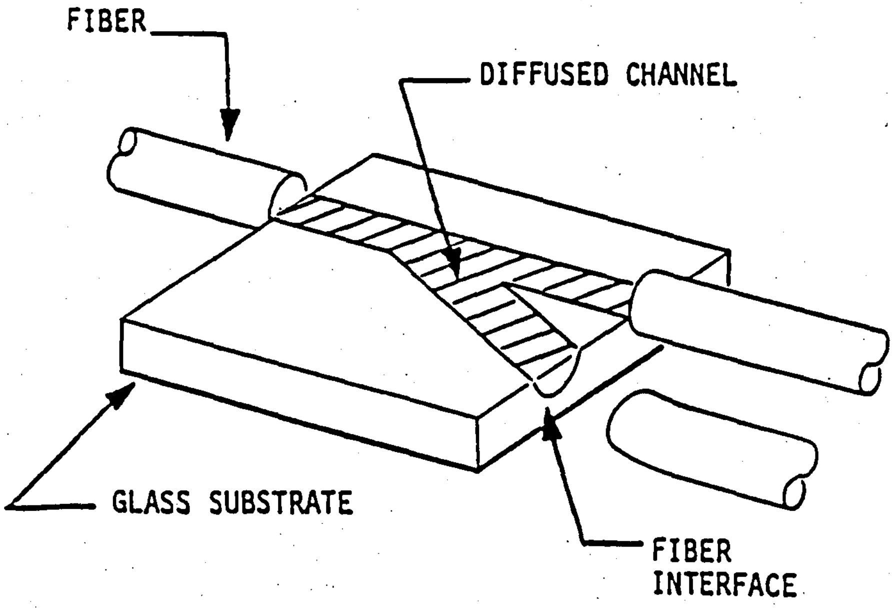
HUGHES

Figure IV-12



PLANAR COUPLER CONCEPT

Figure IV-13

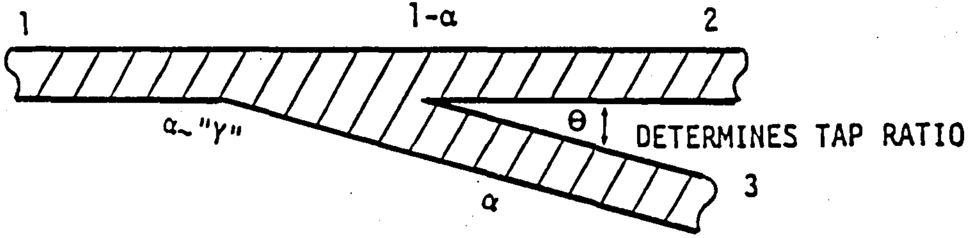


PLANAR Y CHARACTERISTICS

Figure IV-14

HUGHES

$$A_3 \cong \begin{bmatrix} 0 & 1-\alpha & \alpha \\ 1-\alpha & 0 & 0 \\ X\,\alpha & 0 & 0 \end{bmatrix}$$



The basic fused fiber tee or planar Y may be used to make complex access couplers. For example, Figure IV-15 shows bidirectional bus couplers. In A) two fused tee couplers are configured to bidirectionally access the bus. Note this can be produced with two fiber strands and fusing operations. Three Y's are combined in B) to provide a similar function. Future technology should allow complex patterns such as this to be manufactured on the same substrate.

OPTICAL STAR COUPLERS. The optical star or radial coupler concept is shown in Figure IV-16. A number of fibers, in this case seven, are attached to one face of a mixing rod. Light enters the mixing rod which is of such length as to allow the light to become approximately uniformly distributed after being reflected and returned to the fiber faces. Since each fiber is uniformly illuminated, each receives a power launch fraction equal to 1/n, where n is the number of fibers. Unfortunately, this power fraction is not practially obtainable due to the packing fraction and excess losses.

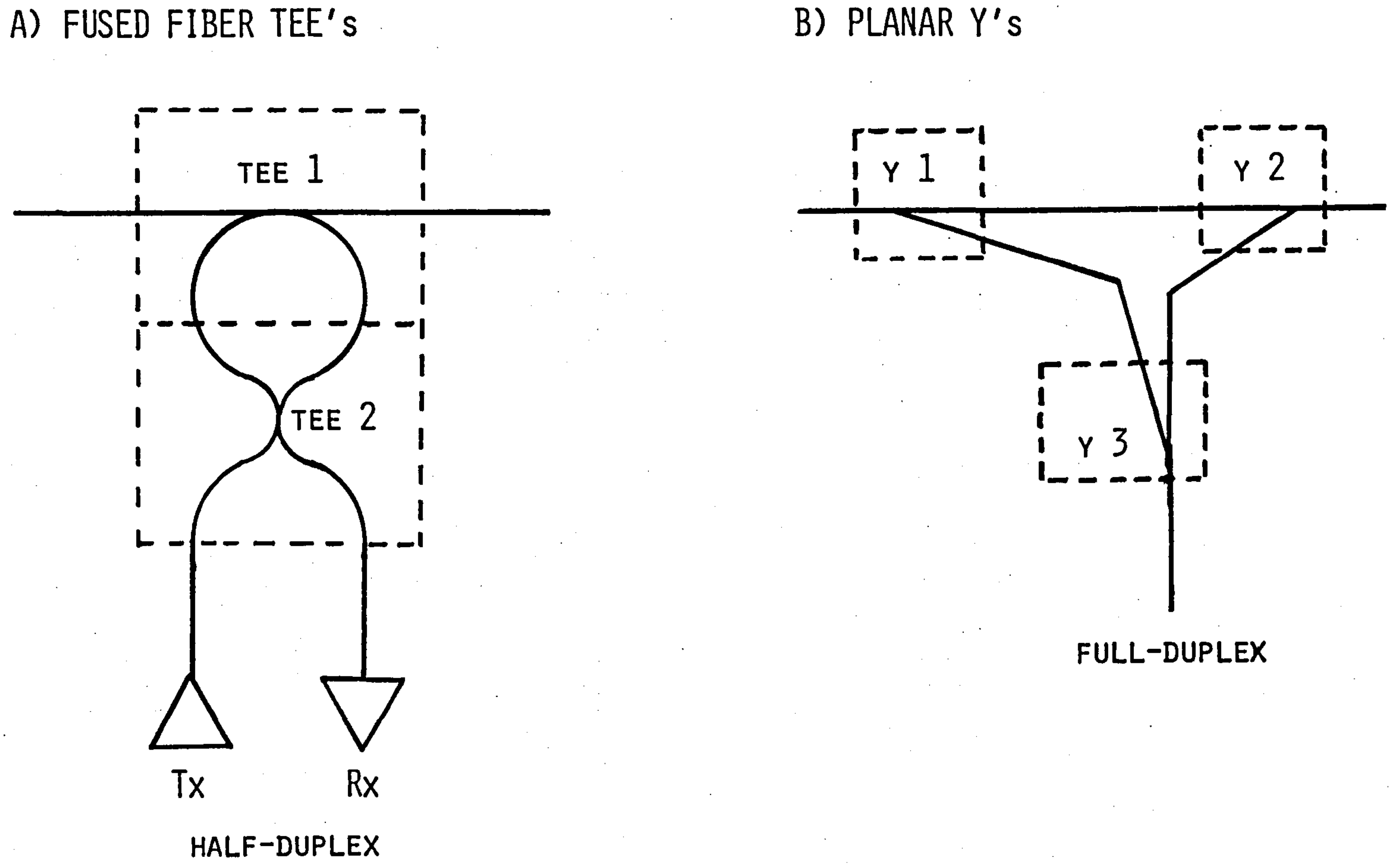
The packing fraction is geometric factor that may be calculated based on the area of core to area of mixing rod. For example, the packing fraction for the hexagonal close-pack is given by:

$$F_{hex} = \frac{N}{N_d^2} \quad \frac{D_{core}^2}{D_{clad}}$$

Where N = the total number of fibers (7, 19, 37, 61)
N_d = number of fibers along the smallest diameter circle containing all fibers
D_{core} = diameter of the core
D_{clad} = diameter of the cladding

BIDIRECTIONAL BUS COUPLERS

Figure IV-15

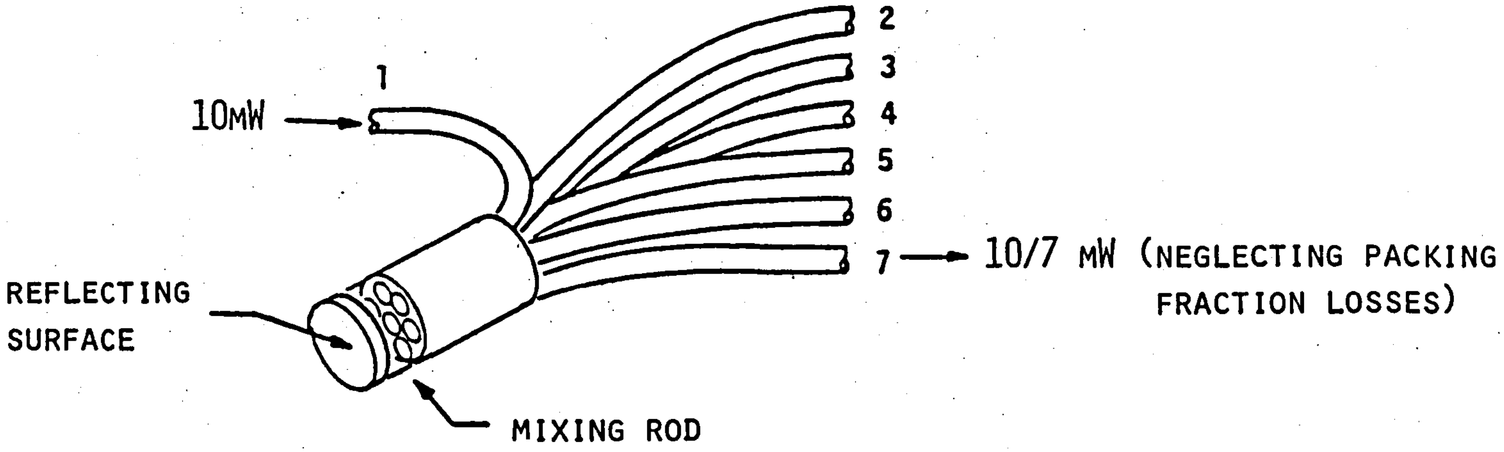


FIBER OPTICS COUPLERS

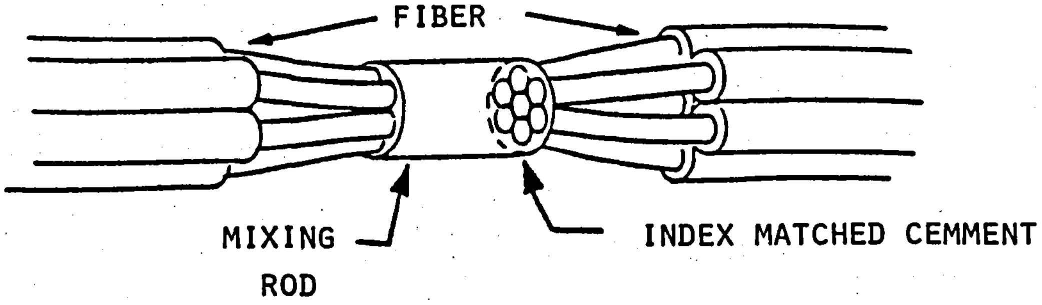
HUGHES

Figure IV-16

- REFLECTIVE STAR



- TRANSMISSIVE STAR



The packing fraction for the linear close-pack is

$$F_{lin} = \frac{\Pi}{4} \quad \frac{N}{1 + (1-N)\frac{D_{clad}}{D_{core}}}$$

Clearly large core-to-cladding diameters or removal of the cladding minimize the packing fraction loss. In the case where D_{clad}/D_{core} is approximately one, the hexagonal close-pack yields a loss of -1.09, -1.19, -1.22, -1.23 dB respectively for 7, 19, 37 and 61 fiber configuration, while the linear close pack is a constant -1.05 dB. Packing fraction losses range from 1.1 to several dB depending on the cladding characteristics.

In addition to the packing fraction loss, there is usually an excess loss related to fiber attachment, mixing rod imperfections and general construction technique. Packing fraction losses coupled with excess losses range between about 7and 10 dB.

The transfer matrix for the relective star may be approximated by

$$a_{ij} = (F_{losses}) \frac{1}{N} \quad i, j = 1, N$$

where

F_{losses} = the fractional transmission due to packing fraction and excess loss

N = number of radial arms.

This transfer matrix is slightly oversimplified. In reality, there are generally variations from element to element due to the fact that the light may not be completely uniform and also due to variations in fiber attachment. In determining receiver dynamic range, these variations are important and must be included.

Another star configuration is the transmissive star shown in Figure IV-16B. Here one side serves as input ports to the mixing rod. The rod must be long enough (several centimeters) so mixing is complete at the output side of the rod.

The transfer matrix for the transmissive star is approximately

$$a_{ij} = (F_{losses}) \frac{1}{N} \qquad i, j = 1, N$$

where F_{losses} is as before and N is the number of output arms.

A major difficulty encountered during fabrication of conventional glass rod couplers is maintaining angular fiber alignment. Any angular misalignment results in excess insertion loss.

The alignment problem may be overcome completely by construction of transmissive stars by techniques identical to those used for fused-tee construction. In fact, the fused-tee (somewhat of a misnomer) is in actuality a 2 x 2 port transmissive star.

In order to produce an N X N port transmissive star, N fibers are twisted and fused while stretching. The result would be similar to Figure IV-16B with the mixing rod replaced by the conical region of melted and fused fibers. For low values of N, results to date show low excess loss for the star on the order of 2 dB (connectors not included). Port-to-port variations of 1 dB can be achieved. Performance data for a 5 X 5 fused star is shown in Figure IV-17.

An alternative to conventional star coupler design uses the planar geometry where the many advantages of planar processing technology apply. A schematic of a reflective planar star coupler design is shown in Figure IV-18.

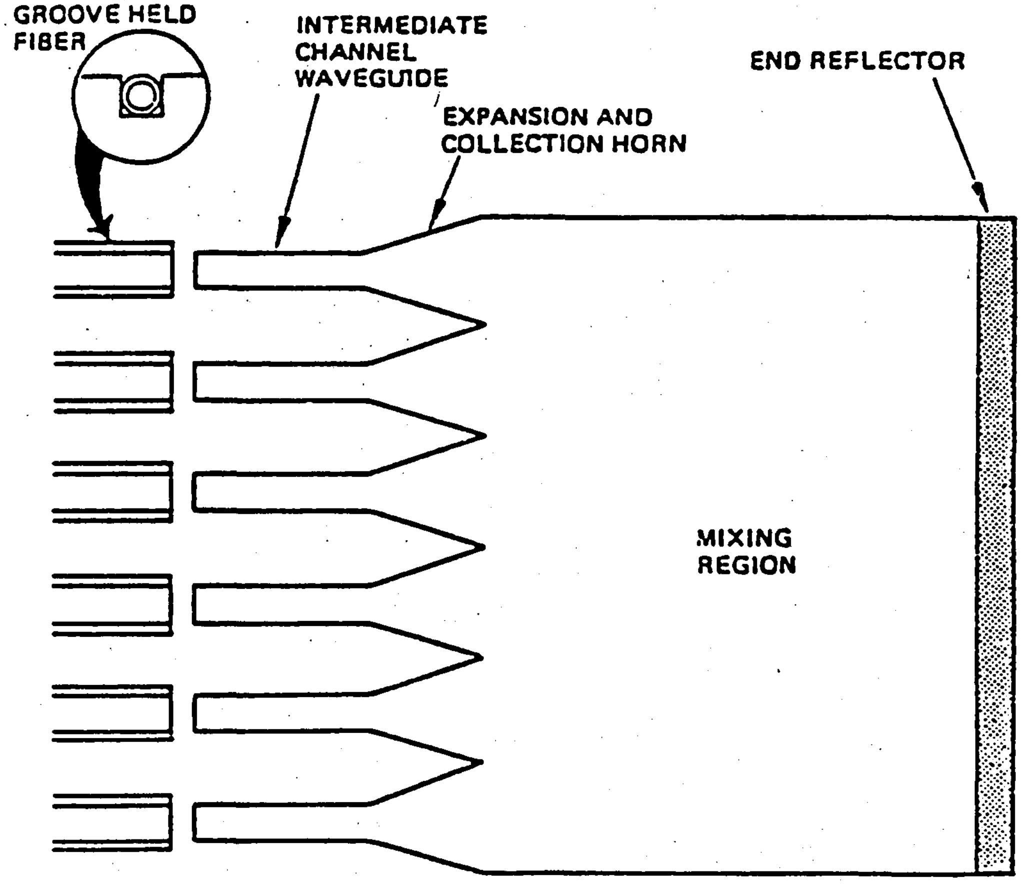
FUSED FIBER STAR PERFORMANCE DATA

Figure IV-17

		OUTPUT PORTS INSERTION LOSS (db)					EXCESS LOSS (db)	PORT TO PORT UNIF. (db)
		1	2	3	4	5		
INPUT PORTS	1	8.8	9.7	9.6	9.4	9.7	2.4	0.9
	2	9.6	9.0	9.5	9.6	9.7	2.5	0.7
	3	9.5	9.6	8.9	9.5	9.6	2.5	0.7
	4	9.5	9.7	9.7	8.9	9.8	2.5	0.9
	5	9.6	9.6	9.7	9.7	9.3	2.6	0.4

PLANAR STAR CONCEPT

Figure IV-18



Multimode fibers are held in alignment grooves formed by selective etching or embossing techniques. Due to the high precision and reproducibility with which photolithographic and embossing techniques can be carried out, these alignment grooves afford the coupler design with a degree of alignment accuracy very difficult to attain with a conventional approach. In addition, each fiber may be readily examined and individually adjusted without disturbing the other fibers. The fibers are butted closely to channel waveguides which serve as interconnecting links with the mixing region. Each channel guide is expanded into the mixing region to allow a rapid mixing of the radiation fields of the different channels and to efficiently collect the radiation reflected from the mirrored end surface of the mixing region.

If properly designed, the packing fraction loss of this type of structure should be zero. The horn structures are designed to effectively couple the radiation reflected from the reflector surface.

A transmissive star may be produced by replacing the end reflector at the right of Figure IV-18 with a mirror image of the pattern.

The transfer matrices for the planar star configurations are identical in form to those given above. As noted, the transmission term F_{loss} is larger (less loss) for the planar star due to horn structure and precision fiber alignment techniques. Furthermore, the variation from port to port is also smaller due to the precision fiber alignment.

IV.3.4 Other Optical Components

Other optical components that should prove useful to bus design that are under development include wavelength demultiplexers and multiplexers and also optical switches.

Wavelength demultiplexers make use of chomatic dispersion or filtering to extract a wavelength or color from an optical spectrum. These devices are discussed in greater detail in conjunction with the hardware development tasks of this program. The approach here is development of a miniature spectrometer, although an off axis Fresnel lens or other optical techniques also offer promise. Key parameters required for detailed bus analysis include optical power loss and number of wavelength channels that can be demultiplexed while maintaining a desired level of crosstalk isolation. Filters are a potential method of isolating and selecting a single wavelength. Sharp, narrow band (10's of nm) filter would probably be prohibitively expensive, however there is the possibility of development of electronically tuned filters. Lasers will probably be required as sources due to their narrow optical bandwidth. Wavelength stability of sources and demultiplexers or filters will be required to achieve a large number of channels with low crosstalk. Wavelength reproducibility in source production will be required in order to match factory-aligned demultiplexers or filters.

Wavelength multiplexers may be obtained by inverse use of a reciprocal demultiplexer. An alternative approach is to use a star coupler to mix the wavelengths by use of "different color" source at each input arm. The output arms then each contain roughly equal power from each source. This method is, of course, best suited for systems where a star distribution system is appropriate.

Optical switches may be fabricated by employing optoelectric phenomena in various materials. Single-mode switches utilize mode-interference effects, however switches that rely on grazing-incidence reflection will support a large number of TE and TM modes to result in a multimode optical switch. Presently, there are quite high losses (10dB or more) associated with these switches as will requirements for relatively high switching voltages (several hundred volts).

Optical switches have also been fabricated using mechanical switching methods. This approach may yield much lower loss, however switching speeds are, of course, considerably slower than the optoelectric devices which can operate in the (sub)nanosecond region.

IV.3.5 Connectors

Connectors for fiber optics are precision items due to the small fiber size. There must be accurate transverse alignment of fiber ends and only a small longitudinal gap between ends. A liquid or a solid may be used to fill the void and match the index of refraction. There is approximately a 3 dB loss if the fibers are offset about one core radius and 0.2 dB loss if there is a 0.2 core radius offset. A gap of about one core radius leads to a 0.1 dB loss with index matching. Single mode fibers require about 1 μm alignment and therefore the connectors are expensive. Single fiber multimode core, either step-index or graded-index, requirements are less severe. At present, the major problem is fibers have not been standardized among the various manufacturers, and the major connector vendors have only cautiously entered the market. Connectors are available for the most popular fibers with prices on the order of $100 per piece in small quantities. Precision connectors designed to meet military environments may run as high as several hundred dollars.

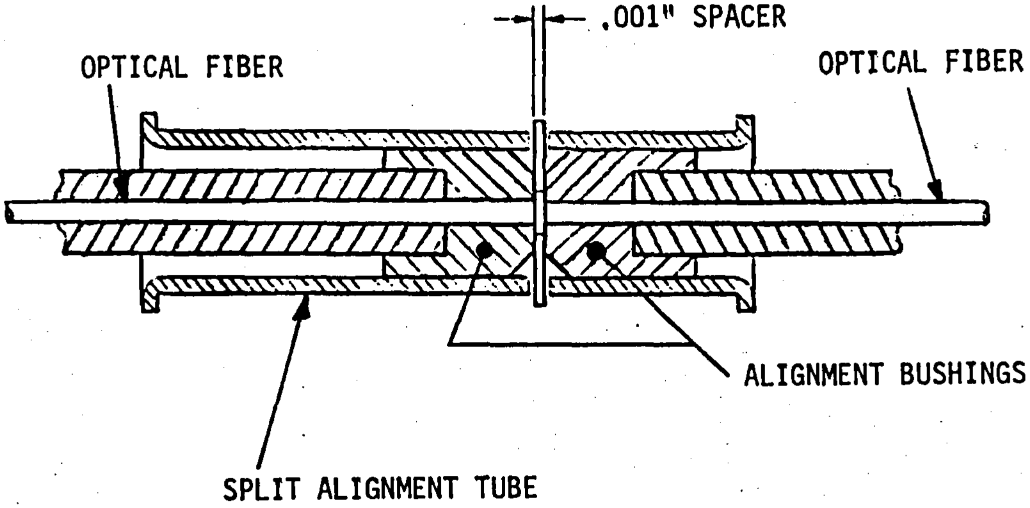
The single fiber silica cables are relatively easy to connectorize. The cable is striped of the protective outer sheaths and the fiber protective coating is chemically dissolved. The fiber is then scored and broken under controlled radius and tension in a fixture. This results in a surface that requires no further preparation or polish. The commercial connectors automatically align the fibers and a matching fluid is used if desired. The resulting loss is 1 to 3 dB depending on the connector quality and care of workmanship. An alignment mechanism is shown in Figure IV-19. Cable strength members must also be picked up and properly terminated (not shown in the figure) in order to keep stresses from the fiber optic strand.

IV.3.6 Receivers

FUNCTIONAL REQUIREMENTS. The function of the receiver is to convert the received optical signal to an electronic signal compatible with its

FIBER OPTIC CONNECTOR

Figure IV-19



terminal requirements. The fiber optic receiver is made up of two elements, a detector and an amplifier. The fiber optic receiver to be employed for use in multiplex bus applications must have a low noise, wide bandwidth performance and must be capable of operating over the required minimum and maximum signal range (dynamic range). The optical power levels and dynamic range that will be experienced by bus receivers are determined by analysis of the network paths. The required Bit Error Rate (BER) establishes the Minimum Usable Signal (MUS) for which the receiver must be designed.

DETECTORS. The solid state detectors generally used for optical telemetry are p-i-n and avalanche photodiodes.[7] These devices are intentionally constructed with a large, reverse biased junction that creates free charge carriers when illuminated. The spectral output of the source and the fiber spectral losses when folded together give rise to a transmitted spectrum that is well matched by these semiconductor devices.

The p-i-n diode is an improved pn diode and consists of an almost intrinsic n region, i, sandwiched between the p and n junction; hence, the name p-i-n. This structure decreases the capacitance and decreases the response time over a simple pn junction. The intrinsic region is a large, high field-depletion region where incident photons produce charge carriers which are rapidly swept away by the high electric field. The length of the intrinsic region is a compromise between good quantum efficiency ($\sim$40-60%) obtained with a large depletion region and fast response time (nanoseconds) from a small depletion region. The p-i-n diode exhibits good linearity and is therefore equally useful for analog and digital transmission formats. Responsivity is approximately 0.5 A/W. Typical photoelectron currents due to the received signal depend on bit rate but are on the order of a few nanoamperes and require care to process electronically.

Avalanche current multiplication is exploited in the avalanche photodiode (APD) in order to obtain higher output currents. The APD consists of another p layer between the n and i layers of the p-i-n structure. At large (100-400V) reverse voltages, this extra p region is a very high electric field region (larger than the depletion region). Charge carriers passing through this region receive sufficient energy to release lattice electrons in subsequent collisions while traversing the crystal. These additional electrons are accelerated and also suffer collisions causing avalanche multiplication of the carriers to occur. Therefore, APD's are generators of large photoelectron currents and are, in general, more sensitive detectors. The multiplication yields an internal gain of about 100. Since the avalanche process is fast, APD's possess short response times. However, the avalanche mechanism is temperature dependent and the multiplication also causes amplification of noise. The excess shot noise requires the gain to be optimized to achieve maximum sensitivity. Of course, the greater output from the APD means that subsequent amplifier noise figure requirements are less demanding than those used with p-i-n diodes. The temperature sensitivity and the high bias voltage required for multiplication make the APD more difficult to use than the p-i-n diode. A comparison between p-i-n and APD detectors is made in Figure IV-20.

AMPLIFIERS. A receiver figure of merit is the minimum (optical) power required to meet a given performance level. For analog signals, this is a signal-to-noise ratio (SNR); for digital signals, a bit error rate (BER). This depends on the subsequent amplifier performance as well as the detector. Commonly accepted performance levels are on the order of 40 dB signal to noise for analog signals and 10^9 bit error rate for digital signals.

The noise source is analyzed by a model of parallel current sources that arise from dark current noise, surface leakage current noise, quantum noise and amplifier noise. The p-i-n diode receiver sensitivity is limited almost entirely by the thermal noise of the amplifier for wideband applications. A transimpedance amplifier with input transistor setting the noise figure provides a good amplifier for fiber optic receivers up to about 100 MHz.

P-I-N DIODES

- ~ .5 A/W
- LINEAR
- LOW VOLTAGE BIAS
- LOW NOISE (RECEIVER FRONT-END CRITICAL)

APD

- GAIN
- LINEAR
- HIGH VOLTAGE BIAS
- TEMPERATURE SENSITIVE
- RECEIVER FRONT-END LESS CRITICAL

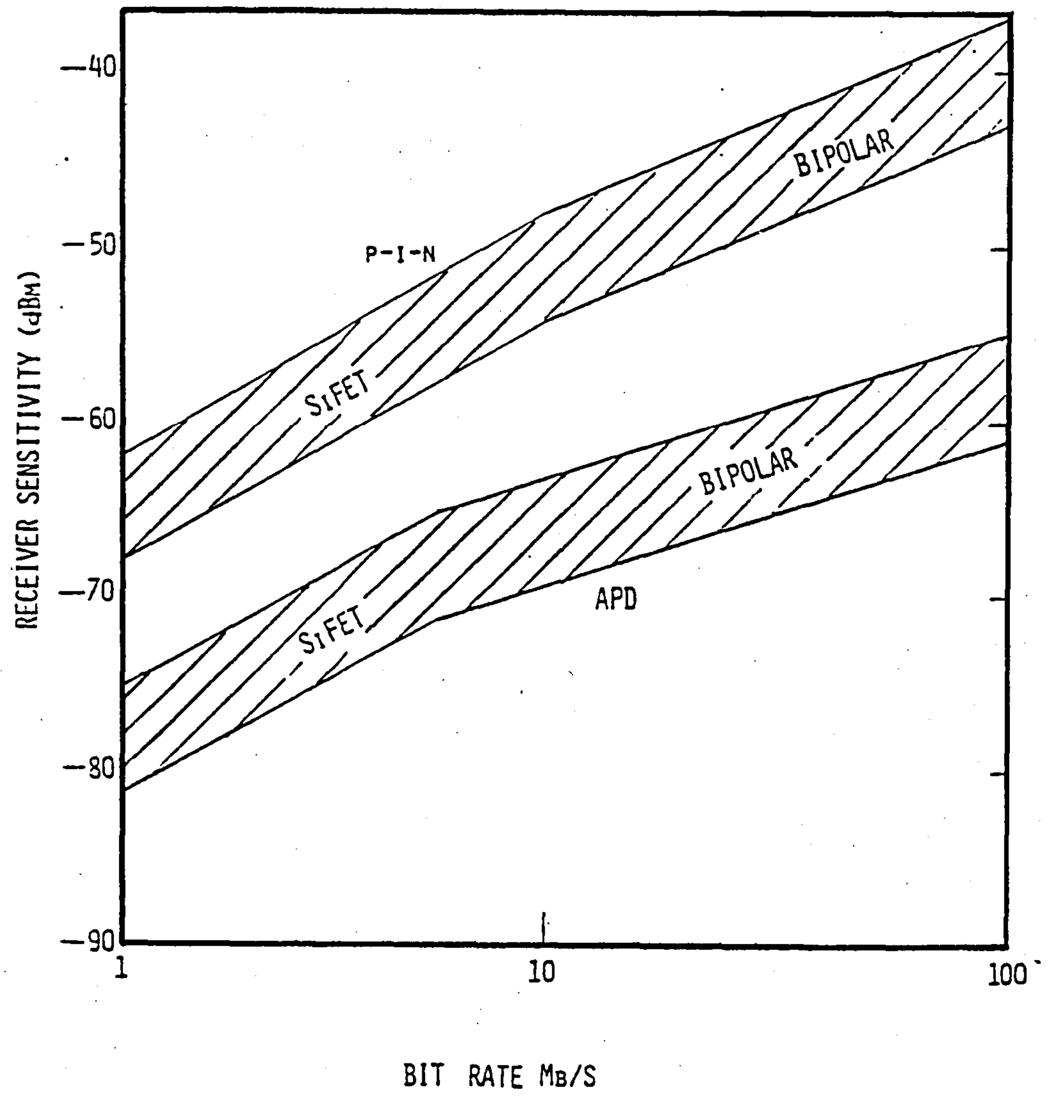
Point-to-point digital communication links do not require receivers with wide dynamic range. A single source is used to transmit a continuous bit stream to a single receiver. Therefore, a receiver with a conventional, slow acting AGC to set the detection threshold and a PLL to obtain precise timing for coherent detection is easily implemented for maintaining optimum operation. Figure IV-21 indicates the sensitivity of p-i-n and APD receivers which achieve high performance. Both FET and bipolar integrating amplifiers with subsequent equalization stages are shown. The widebands take into account component and implementation variations.

Two conflicting design requirements for fiber optic bus receivers present a significant technical challenge. Because of the relatively low launch power of optical sources and the losses encountered in optical fiber connectors and optical access couplers extremely high sensitivity is required of the receiver. These losses may also result in a very wide intermessage dynamic range (IMDR) of received signals; e.g., high level signal from a near terminal followed immediately by a low level signal from a distant terminal. High sensitivity coupled with wide IMDR is very difficult to achieve in a receiver design. A serial topology generally results in a high dynamic range requirement for the receiver due to the in-line losses of the bus. A star architecture tends to equalize the losses along all paths and hence minimizes the dynamic range. A dynamic range requirement of 10 to 20 dB is typical of a star topology. For greater dynamic ranges, reflections on the bus may begin to become comparable to the minimum signals.

The receiver must be able to operate over this dynamic range such that bus efficiency is not degraded by receiver design. The intermessage gap time required by the receiver should not be greater than that required by the bus protocol. For example, an integrating front-end receiver which offers maximum sensitivity generally has poor overload recovery characteristics. A conventional AGC may require sensing a bus deadtime period after which the sensitivity is reset to be ready for the next message

RECEIVER SENSITIVITY

Figure IV-21



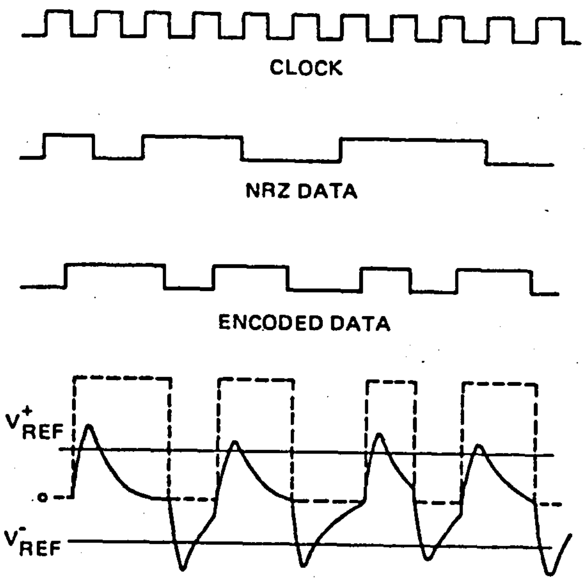
which could be of minimum amplitude. If the next message is a strong signal, time (conditioning bits) may be required for the AGC action to take effect and alleviate the overload transient effects. Receiver sensitivity, dynamic range, and recovery time as well as timing jitter are interrelated parameters.

The problem caused by the dynamic range for bus receivers is due to the unipolar nature of the optical signal. Unlike a wireline signal which may rest at zero volts and then swing above and below zero when a signal exists, a fiber optic bus signal can only be off or positive. Because of photodetector dark current and other sources of DC offset, it is usually necessary at some point to AC couple the amplified receiver signal. When no signal is on the bus, the output side of the coupling capacitor rests at zero volts. When a signal first arrives at the receiver, the output voltage swings positive from zero and then begins to discharge. As the input signal continues to switch on and off, the output signal gradually reaches a steady state quiescent point. If the input data is a strong signal and if this is then immediately followed by a weak signal, the receiver output will again require time to reach a steady state quiescent value. In either case, this causes loss in decoding efficiency, and can cause a large degradation in link performance.

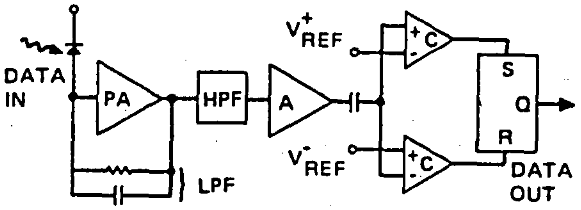
Compromise is required among sensitivity, intermessage dynamic range (IMDR) and message gap time when faced with unipolar light pulses. Some sensitivity must be sacrified for a bus receiver; some of the bit energy may be used in order to produce a pulse that is processed in a practical implementation. The method is similar to a pulse encoded modulation technique in that the bit edges are used to reconstruct the received data. In effect, the receiver differentiates the waveform by bandpass filtering the received data pulses. Figure IV-22(A) shows the effect of filtering 20-Mbps Miller coded data with a bandpass of 7 to 35 MHz.

Figure IV-22B is a block diagram of a receiver employing this technique. The preamplifier accommodates the required optical dynamic range with

A) BANDPASS FILTERED DATA



B) FUNCTIONAL IMPLEMENTATION



HUGHES

BANDPASS

FILTERED

BUS RECEIVER

Figure IV-22

maximum gain consistent with the required high frequency response. High pass filtering follows the preamplifier. Subsequent AC-coupled, pulse-limiting amplifiers provide signals to two comparators. One detects positive going edges and the other detects the falling edges of the optical pulses. The outputs of the comparators toggle a flipflop to recover the full width pulse.

Therefore, we see that there is no one (simple) fiber optic receiver, but that the receiver implementation must be tailored to the system requirements. For example, in a long message protocol, an essentially point-to-point link receiver could be used by slightly degrading the bus efficiency with a header to "condition" the receiver. It is also interesting to note that the APD receivers of Figure IV-21 are only an order of magnatude away from quantum limited (ideal) receivers and therefore future receiver cannot show much greater sensitivity. For purposes of this present analysis and estimates of number of terminals in a passive bus system, it will suffice to take the low sensitivity edge of the bands in Figure IV-21 as the approximate bus receiver sensitivity for a given bit rate; care, however,. must be exercised in a more detailed analysis to include requirements of dynamic range, gap time and timing jitter to obtain a more precise estimate of receiver sensitivity.

IV.4 TOPOLOGY ANALYSES

In this section, analyses are performed to establish the path losses of point-to-point links, star buses and serial buses. The resultant path loss when combined with transmitter launch power and receiver sensitivity will establish the maximum passive network, i.e., the link length for dedicated structures and the number of terminals for a bus structure.

IV.4.1 Point-to-Point Link Analysis

Analysis of a point-to-point link simply sums up the in-line loss factors. The point-to-point link results and definition of the notation for these factors are shown in Figure IV-23. Typically fiber-to-detector coupling loss, D, is on the order of 1dB and the received power, P_R, is essentially a function of fiber and connector losses. For the purpose of discussion, we will assume a power budget of 40dB (i.e., 10 log (P_L/P_R)) which is appropriate for data in the region of 10 Mbps. The exact link length depends, of course, on the fiber loss, connector (or splice) loss, and number; however it is easy to see that links on the order of 10Km are (easily) accomplished. Usually, within the power budget, a contingency of several dB is allowed to account for temperature effects and aging of the components (especially the source) over the system lifetime.

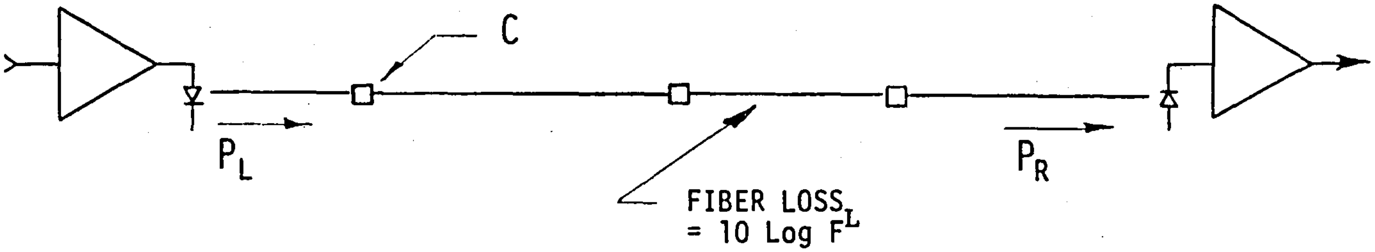
IV.4.2 Star Bus Analysis

A star bus network, as shown in Figure IV-24, is analyzed as essentially two point-to-point links with the additional loss element included for the star. This star loss is made up of two parts: a power division loss and an excess loss denoted by S_{loss}. The power division loss goes like the number of ports. For a transmissive star supporting N terminals the power division is 1/N. For a reflective-simplex network where there is a separate transmit and receive fiber for each terminal, the power division is 1/2N. A reflective duplex network can be configured with an equal power division tee-coupler to allow only N ports at the star and single fiber runs to the terminals. Here the star power division is 1/N, however, the power is halved twice (neglecting tee coupler excess loss) by the tee-coupler for a power division of 1/4N. Note that the reflective-simplex network offers no advantage and, in fact, a 3dB loss with respect to the transmissive star network. The reflective star offers only the advantage of fiber saving in the duplex network, and this saving in fiber costs about 6dB (closer to 8dB when tee-coupler excess loss is included).

Here, of course, the link lengths of the arms of the star are less than can be accommodated by the dedicated structure. For example, a 20-port

LINK ANALYSIS
POWER BUDGET

Figure IV-23



$$P_R = P_L F^L C^N D$$

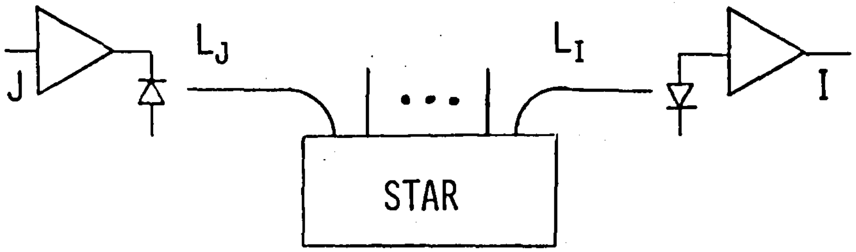
WHERE

P_L = Power launch
F = Fractional fiber transmission/Km
L = Link length in Km
C = (average) fractional connector transmission
N = Number of connectors
D = Fractional coupling to the detector

STAR DISTRIBUTION SYSTEM

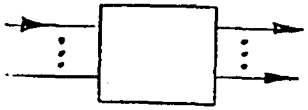
HUGHES

Figure IV-24

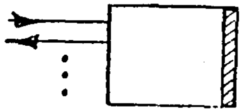


$$(P_R)_{IJ} = D_I L_I A_{IJ} L_J (P_L)_J$$

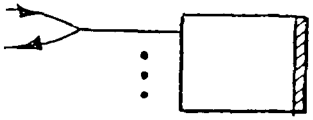
$$= \underbrace{(P_L)_J F^{(L_I+L_J)} C^{(N_I+N_J)} D_I}_{\text{SAME AS POINT-TO-POINT}} \underbrace{\left[S_{loss} \frac{1}{N} \right]}_{\text{ADDITIONAL LOSS}}$$



TRANSMISSIVE $\frac{1}{N}$



REFLECTIVE-SIMPLEX $\frac{1}{2N}$



REFLECTIVE-DUPLEX $\frac{1}{4N}$

star has a power division loss of 13dB; with excess loss and connectors at the star, there would be an insertion loss of about 20 to 25dB. This allows link distances of a km or so depending on connector requirements. Note that the star network is best suited to clusters of terminals near the central star distribution point.

IV.4.3 Serial Bus Analysis

A serial or linear bus is best suited for networking a number of dispersed terminal sites. Here, however, the end-to-end link loss are all in line and therefore with practical power budgets the number of drops in a passive bus is limited. Figure IV-25 shows a simple serial bus where a central is used to communicate with a number of remote terminals. This figure shows either the transmit bus or receive bus for simplex operation. Again, tee couplers could be incorporated at the central and each remote to provide duplex operation at a loss factor of 1/4 plus tee coupler excess loss (about 8 dB). All remote-to-remote transfers must be routed through the central in this network.

An optimized bus would provide equal power received at each terminal from the central transmitter. The figure defines the notation used to analyze in detail this network. Starting at the end of the run, a recursion relation for the coupler ratios may be derived. The result is

$$A_{k-1} = \frac{e_{k-1}\, A_k}{B_{k-1} + A_k} \qquad \text{with} \qquad A_{n-1} = \frac{e_{n-1}\, B_n}{B_{n-1} + B_n}$$

where $A_k = C^2 A_k B_k F_k$

For the ideal case, where there are no losses other than the power division to the branches, the ideal tap ratios are given by:

$$A_n^{(\text{ideal})} = \frac{1}{N+1-n} \qquad n = 1, 2, \ldots, N-1$$

Consider now a more realistic case. Let:

$A_k = Z A_k$

$Z = C^2 Bf$

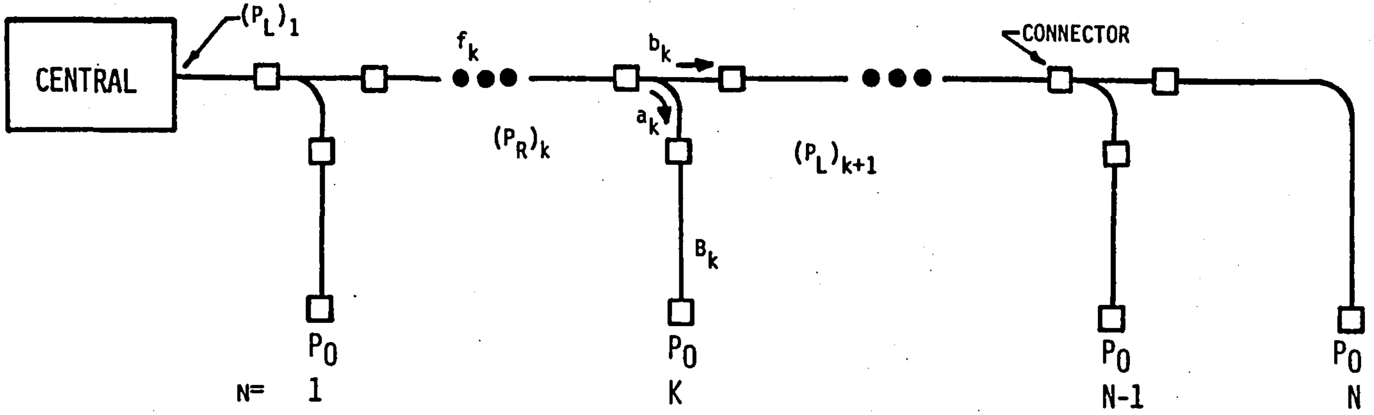
$B_k = B = 1$ (short stubs)

$f_k = f$

$e_k = e$

SERIAL BUS ANALYSIS

Figure IV-25



WHERE:

B_k = fractional transmission of the kth branch

f_k = fractional transmission of the kth link

$(P_L)_k$ = power launched into the kth link

$(P_R)_k$ = power received at end of kth link

a_k = branch coefficient of the kth coupler

b_k = trunk coefficient of the kth coupler

e_k = efficiency of the kth coupler = $a_k + b_k$

C = average fractional transmission of connector

That is, losses are included but all are taken to be equal and fiber stub loss is neglected. In this case, the recursion for the a_k's may be put in closed form, which allows a rapid order of magnitude calculation. With these assumptions

$$A_{n-1} = e/2$$

$$A_n = \frac{e(Ze)^{N-n-1}\ (1-Ze)}{2-(Ze)\ -\ (Ze)^{N-n}}$$

(which reduces to the above for $e = z = 1$, by using L'Hospital rule to take the limit).

In order to investigate the number of terminals that can be supported, we first note in the lossless case that the power received at any terminal is given by $P_R = P_L$ X $_1$ which is proportional to 1/N. This is essentially the same as a star system. (The star would be 1/(N+1) due to requirement for an additional arm for the central.) To include losses, let $C = f = e = 0.8$ (about -1 dB). Results for this case are shown in Figure IV-26. Of course, one would probably choose from a standard set of tap ratios (with some variance) and this would reduce the number of terminals due to lack of optimization.

Another approach to the serial bus design is to use a fixed tap ratio and optimize this. Figure IV-27 compares the two approaches neglecting losses. Here m terminals are being served and the trunk to the right is connected either to the m + 1 remote terminal (R) or a repeater (r). The optimum fixed tap ratio is easily found to be 1/m and the critical path loss 1/[e(m-1)], where here e is the base of natural logirithms. This result holds in the limit of large m. Thus the difference between tailored or fixed tap ratios is about 4.34 dB.

Figure IV-28 illustrates several methods of providing duplex operation. The first and last were noted above and have a difference in power budget of 1/4 or -6 dB, neglecting losses. Two alternative methods are shown. The second uses a 2 X 2 port star (fused fiber "tee") to get on or off

SERIAL SYSTEM WITH LOSSES

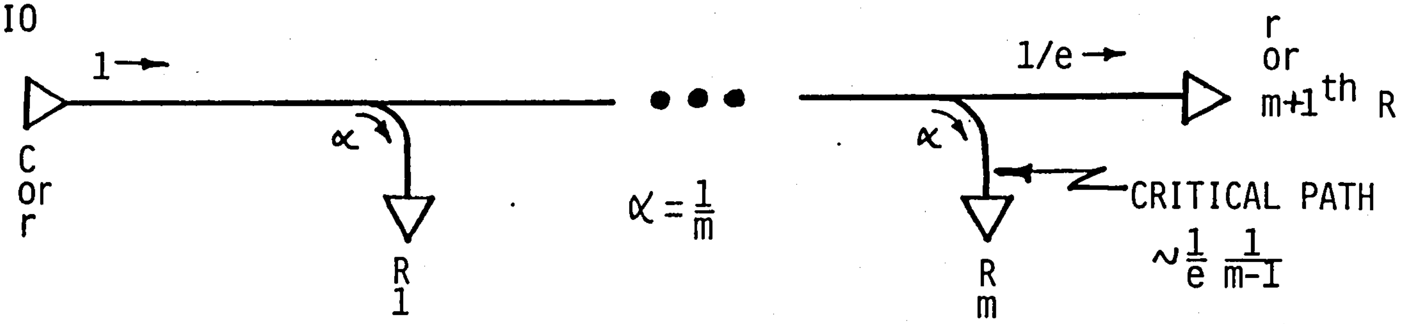
Figure IV-26

NUMBER OF TERMINALS	LOSS (dB)	TAP RATIO (dB)								
		N= 1	2	3	4	5	6	7	8	9
3	13.4	8.7	4.0							
5	20.2	15.7	12.8	8.7	4.0					
10	41.1	36.3	32.4	28.5	24.7	20.8	15.7	12.8	8.7	4.0

BUS ANALYSIS - SIMPLEX (C → R)

Figure IV-27

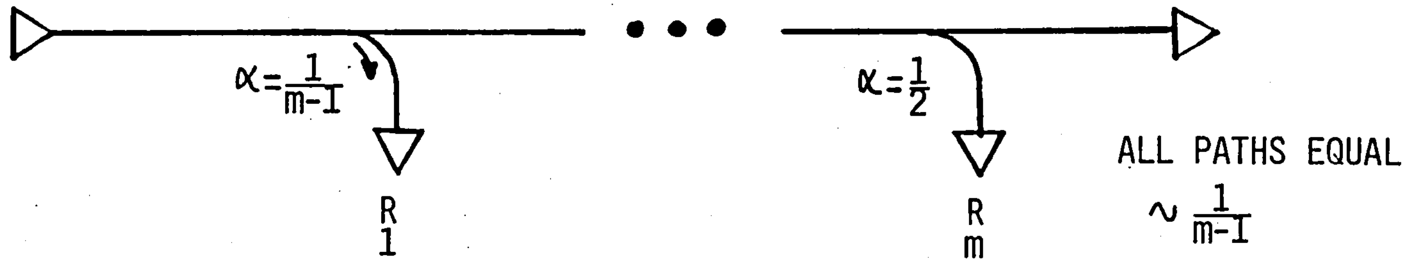
FIXED TAP RATIO



CRITICAL PATH

$\sim \frac{1}{e} \frac{1}{m-I}$

TAILORED TAP RATIOS



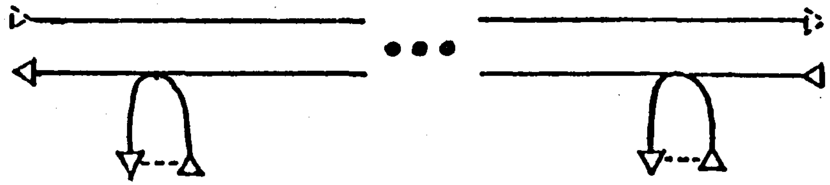
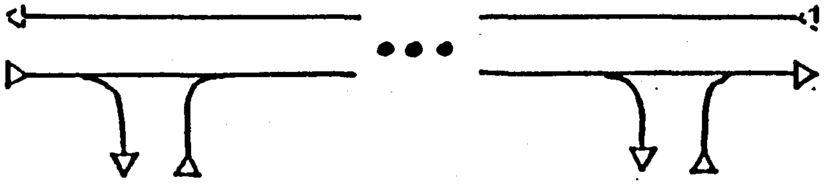
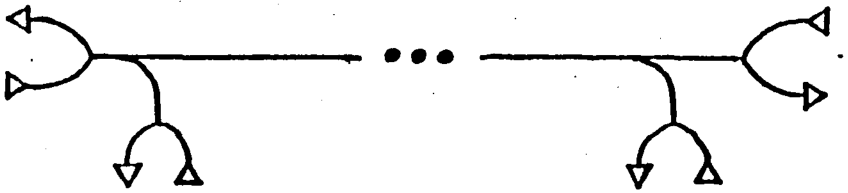
ALL PATHS EQUAL

$\sim \frac{1}{m-I}$

TAILORING IMPROVES ONLY BY e = 2.718... (4.34 dB)

BUS ANALYSIS - DUPLEX (C → R; R → C)

Figure IV-28

CONFIGURATION	RELATIVE
	0dB
	0dB
	-3dB
	-6dB

CRITICAL PATH
POWER
$\sim \frac{1}{m}$

the bus. This has the same relative power budget as the first example but uses half as many taps. Note in this configuration the local transmitter of a terminal is directly connected to the local receiver through the fiber loop and there would be an electrical inhibit denoted by the dotted line joining these functions in the diagram. In this same type of configuration, isolation can be provided by directional couplers. This costs 3dB of power budget and does not appear to have any advantage over the top diagram. In all of these cases the critical path power is proportional to 1/m.

A similar analysis may be made for a serial bus with requirements for direct remote-to-remote data transfers. Figure IV-29 shows the pertinent networks and the relative power budgets, again neglecting losses. Note, however, the very important result that here the critical path power is proportional to $1/m^2$. This means that no matter how much losses are reduced a serial bus with remote-to-remote transfers (as is basic with a star system) will support fewer terminals than a similar loss-reduced star system which has critical paths proportional to 1/m.

Figure IV-30 shows a way that a looped bus with an active repeater may be used to provide 1/m performance. Again with a passive loop the critical path is proportional to $1/m^2$.

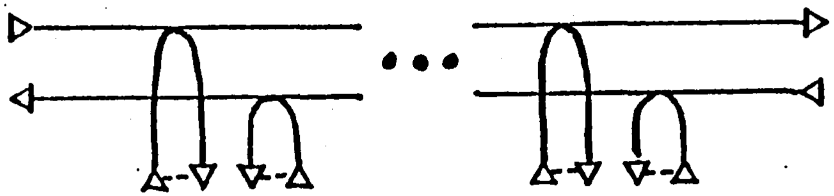
Figure IV-31 shows the number of terminals that can be supported as a function of power budget loss for several examples case of connector loss, $L_c$and excess loss L_e. The link losses are assummed to be negligible. The network is full duplex with remote to remote transfers. Results for other networks can be estimated by modifying the loss by the relative dB factors of the previous figures. Here we see that on the order of 5 to 10 terminals are possible in a passive bus and that use of splices and reduction of tap excess loss allow on the order of 20 terminals.

BUS ANALYSIS - DUPLEX (C → R; R → C; R → R)

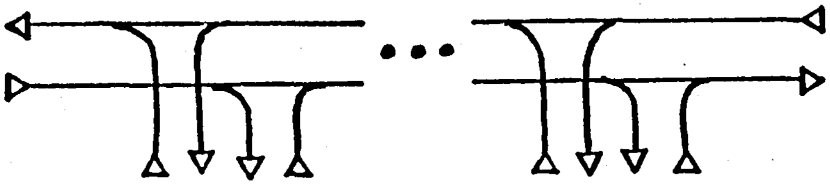
HUGHES

Figure IV-29

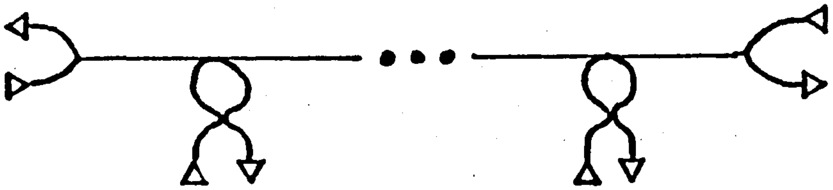
CONFIGURATION | RELATIVE



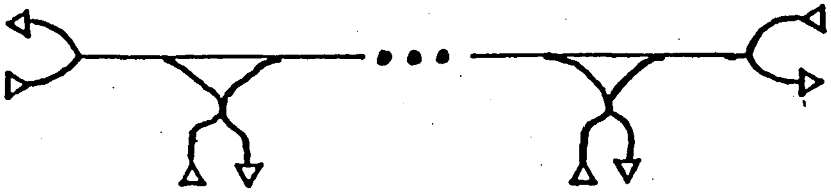
0dB



-6dB



-6dB



-12dB

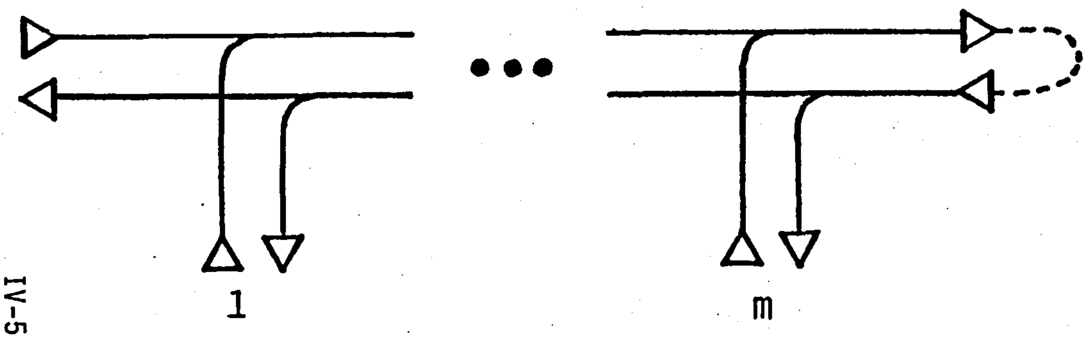
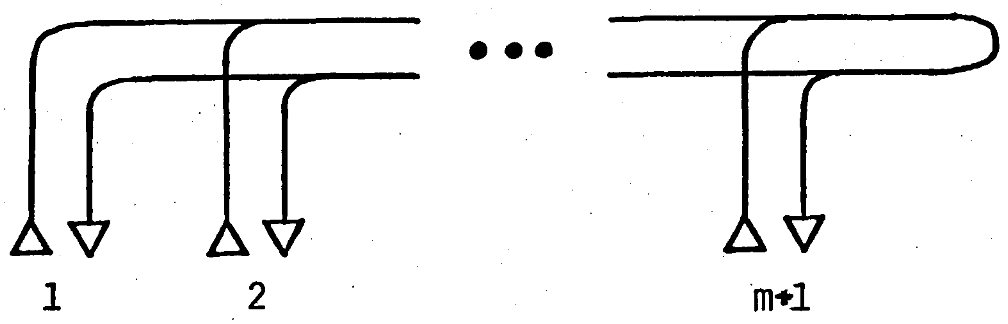
CRITICAL PATH POWER

$\frac{1}{m^2}$

BUS ANALYSIS - DUPLEX (C → R; R → C; R → R)
LOOPED BUS CASE

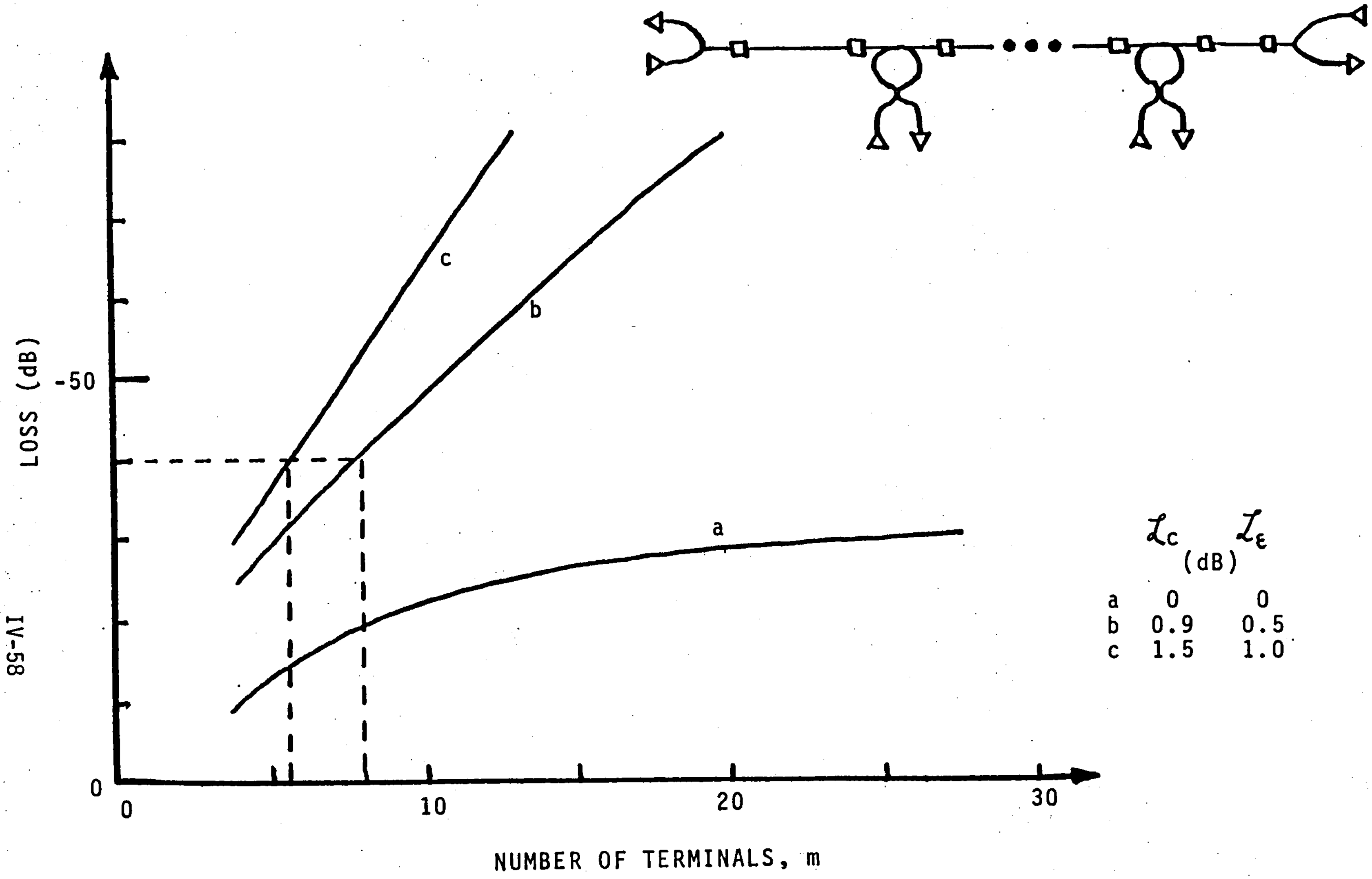
HUGHES

Figure IV-30

CONFIGURATION	CRITICAL PATH
	$\sim \frac{1}{m-1}\,\frac{1}{e}$
	$\sim \left[\frac{1}{m-1}\right]^2\left[\frac{1}{e}\right]^2$

EXAMPLE SYSTEM WITH LOSSES

Figure IV-31



IV.4.4 Comparison

Figure IV-32 compares serial and star networks. It is a sort of "apples and oranges" comparison, since the star best serves clustered terminals and serial best serves distributed terminals with large distances between them. The details of a comparison are dependent on losses assumed and whether direct remote-to-remote transfers are required. If they are not, then the lossless cases are essentially the same. As losses are included, this curve is displaced by the losses for a star; however, for a serial bus it becomes a steeper, more linear relation as indicated.

IV.4.5 Complex Networks

As discussed in Section II, the simple structures analyzed here can be used to comprise more complex networks. However, this analysis indicates that a fiber optic bus system is power budget limited. As an example, star to star to star, etc., passive interconnections would be proportional to the inverse product of their number of ports (i.e., $(1/m)^n$ for n m-port stars). This and several other topologies are summarized in Figure IV-33. Therefore, formation of complex network will probably be accomplished by inclusion of active elements (repeaters or terminal node) between these simple structures.

IV.4.6 Optical Reflections

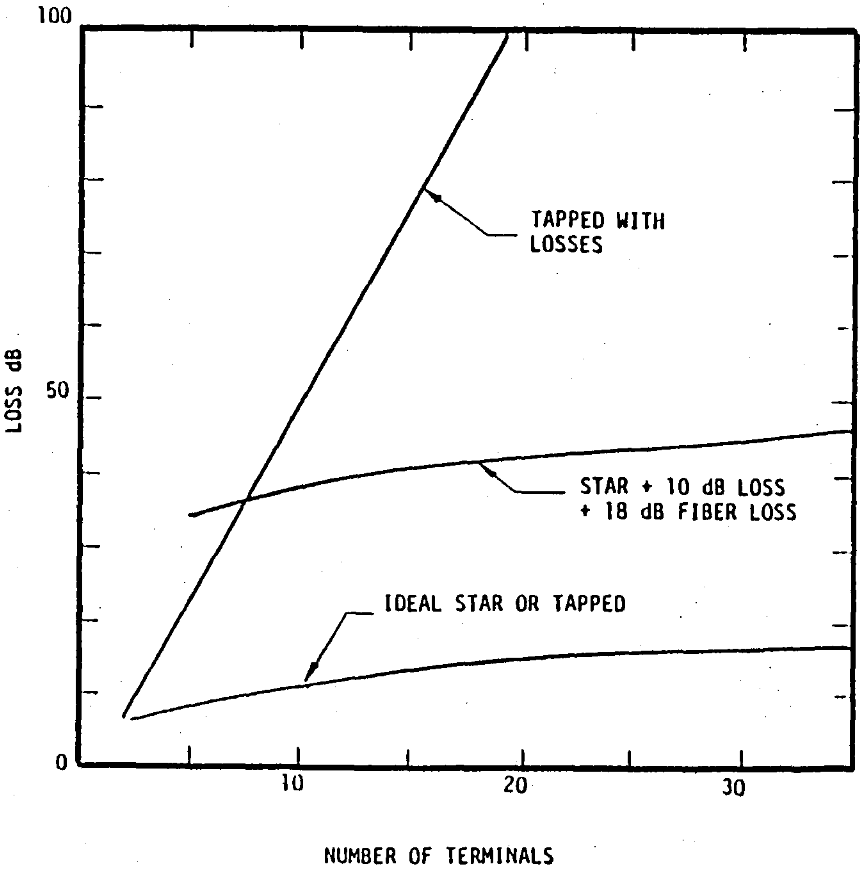
Bus analysis must address interference effects of reflections from air gap (dry, fiber-to-fiber interface) connectors in the system network. The detailed results depended upon the specific topology; however, the basic order of magnitude of the effect can be illustrated by consideration of the simple topologies shown in Figure IV-34. One case is a star topology configured with an N X N port transmissive star with each port connected to a terminal a distance L from the star. The second case is a bidirectional serial bus with a tap in the center of a fiber length of 2L.

SERIAL AND STAR "COMPARED"

Figure IV-32

- "APPLES AND ORANGES"

- DEPENDENT ON LOSSES ASSUMED
  18 dB FIBER BOTH CASES
  1 dB CONNECTORS



OTHER TOPOLOGIES/CONSIDERATIONS

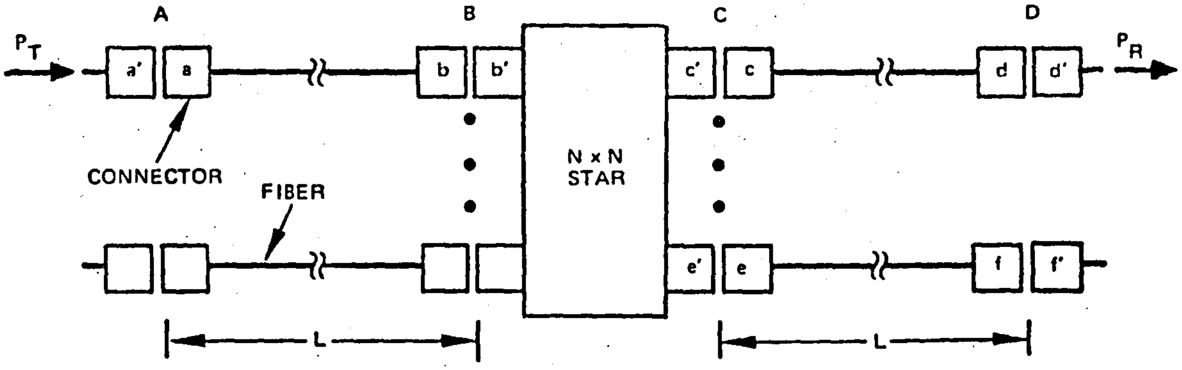
Figure IV-33

- STARS $\sim \prod_{I} (1/M_{I})$
- HYBRID $\sim (1/M)^{2}$ (SERIAL BUS)
- TREE-BRANCH $\sim \prod_{I} (\text{SERIAL BUS})_{I}$

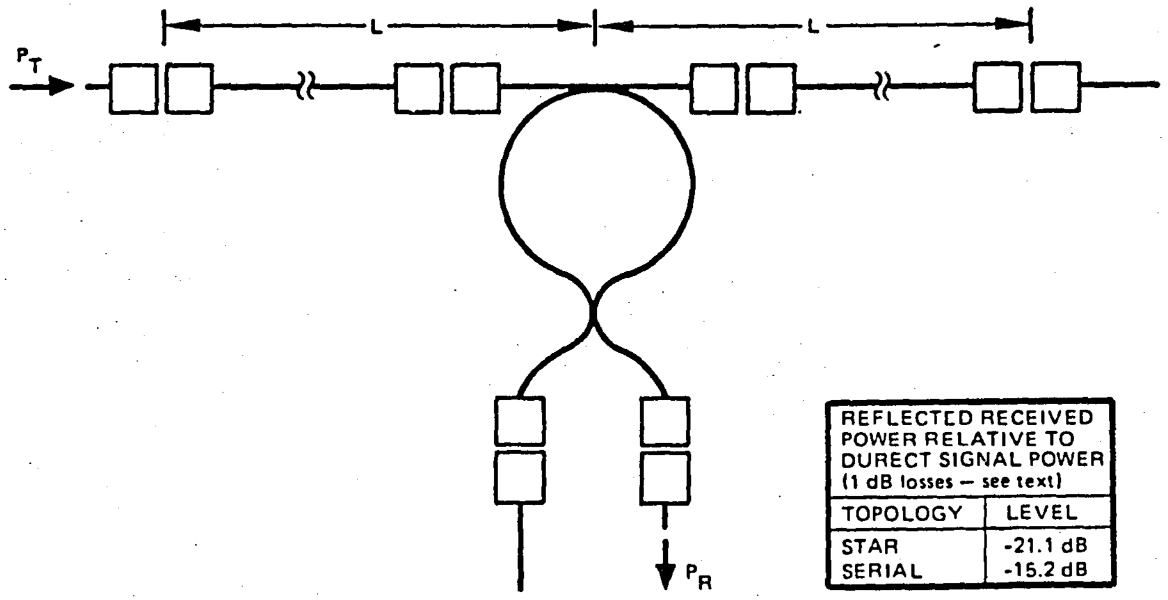
BUS REFLECTION ANALYSIS

Figure IV-34

A) STAR TOPOLOGY



B) SERIAL TOPOLOGY



REFLECTCD RECEIVED POWER RELATIVE TO DURECT SIGNAL POWER (1 dB losses – see text)

TOPOLOGY	LEVEL
STAR	-21.1 dB
SERIAL	-15.2 dB

Reflections occur at air-glass or glass-air interfaces. The fraction of light power reflected, R, depends on the index of refraction. For glass with an index of refraction of 1.4, R is about 4%. The calculation consists of totaling the reflected power that reaches a particular receiver and comparing this to the power that reaches the receiver via the direct path. Practically, we need only consider terms to order F^2R^2, where F is the transmission coefficient for the fiber of length L.

Let P_T be the transmitted power and P_R be the received power. Then

$$P_{REF}^{STAR} = P_R\ (2R^2F^2(1+C^2))^2\ \ (1+e^2C^2)\ .$$

where C is the average fractional transmission for a connector, and e is the fractional transmission (excess loss) of the star coupler. For 1-dB loss connectors, a 1-dB excess loss coupler and a fiber length L with 1 dB loss, the reflected power is 21.1 dB less than the primary received power. For F, C and e approximately equal to 1, the reflected power is only 16 dB below the signal. Similarly, for the serial bus shown in the figure

$$P_{REF}^{SERIAL} = P_R\ (RF^2(1-A)e(1+C^2)+O(R^2F^2))$$

where A is the fractional power tapped from the bus. For A equal to 0.1 and other values as above, the reflected received power is about 15.2 dB below the signal.

The reflected power limits the dynamic range. If the receiver is sensitive to a received power $P_{R\ min}$, then the maximum signal must produce a reflected power of less than $P_{R\ min}$. In practice, the dynamic range may be further limited. If reflected power on the order of magnitude but less than $P_{R\ min}$ is received at the same time as a primary signal of power $P_{R\ min}$, then the SNR will be degraded such that the primary signal will not be detectable.

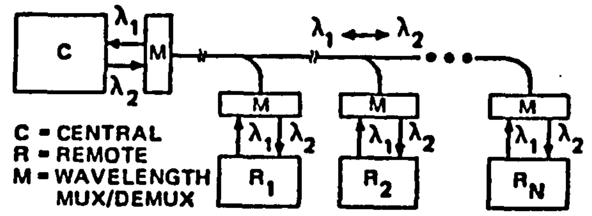
The conclusion is that reflections are not necessarily negligible in a bus system. The star system which minimizes dynamic range requirements has a less severe reflection problem, but care must be taken to exercise a system design that is insensitive to reflections (e.g., receiver sensitivity should not be overspecified). The reflections can be reduced by use of splices or wet connectors; source-fiber and fiber-detector interfaces will still provide reflection points. Antireflective coatings, which are expensive, could also be used to reduce the reflections.

IV.5 WAVELENGTH DIVISION MULTIPLEXING

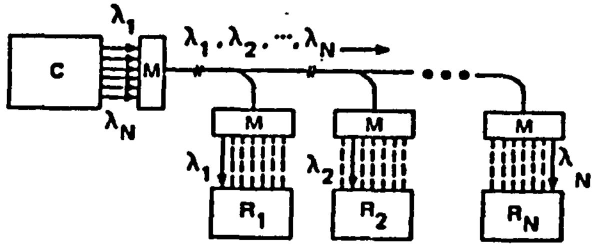
Investigation of fiber optic systems utilizing the advantages of wavelength division multiplexing (WDM) analyzes systems and bus topologies for which WDM may be applicable. The obvious first advantage offered by WDM is the addition of channel capacity.[8] The bandwidth already available would be multiplied by the number of light wavelengths transmitted simultaneously. Presently, it appears feasible to multiplex eight to ten wavelengths between 800 and 900 nm with additional channels in the 1 um region as the technology for sources and detector develop at the longer wavelengths. The separation of channels by WDM offers other advantages. For example, an FDM system must be a linear system, independent of whether the data is analog or digital. If this were not the case, intermodulation distortion products in the transmitter and receiver would cause channel-to-channel interference effects independent of the degree of filtering used at the receiver for each channel.

Many of the basic bus concepts that are addressed may be directly applied to the analysis of transmission of wavelength multiplexed channels. Several examples of WDM topologies are discussed below. Single-fiber, full duplex operation is configured by a system such that remote transmits on light wavelength λ_1 and receives on λ_2 with inverse assignments for the central or main terminal as shown in Figure IV-35A. This allows full duplex operation with no local interference effects, but does not allow direct remote-to-remote transfers. The wavelength of transmission

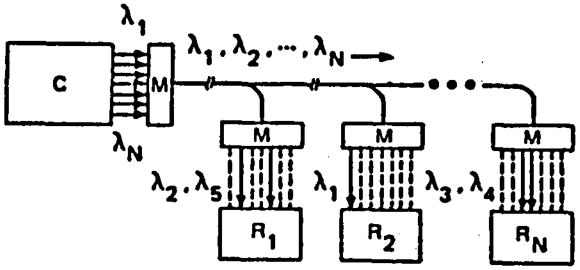
WAVELENGTH
MULTIPLEXED
BUS EXAMPLES



(a) WAVELENGTH MULTIPLEXED FULL-DUPLEX BUS



(b) TERMINALS ADDRESSED BY WAVELENGTH



(c) TERMINALS SUBSCRIBE ONLY TO CHANNELS OF INTEREST

Figure IV-35

may be used as a terminal address as shown in Figure IV-35B. Figure IV-35C illustrates distribution of several channels of independent data and each terminal subscribes only to those channels of interest. This case may be viewed as several independent buses where WDM has been employed to place the several channels on the same physical fiber. Note that a disadvantage of this approach is that the optical power of each wavelength is extracted by the optical access coupler whether the terminal at that tap uses that wavelength or not. Thus, in an already power-limited network, the advantages of wavelength multiplexing may be lost by the fewer number of total terminals serviced. In a high-capacity network, the electronics to pick off the channels to which the terminal subscribes are replaced by the optical multiplexing device. This could provide benefits in a high data rate system where TDM of the several independent channels would require (sub)nanosecond gating and hence sophisticated, high speed circuitry at each remote terminal. The tradeoff is between complex electronics and optical multiplex-demultiplex devices. In a pure distribution system, the demultiplexers potentially could be narrowband filters to extract the desired wavelength. At the central (or any other) wavelength multiplex transmission site, the source element must be attached at the correct wavelength position and its output wavelength carefully controlled for temperature or ageing effects to maintain compatibility with the demultiplexers. A star could provide the wavelength multiplexing function if it is compatible with system topology. The channels from remotes to central could be on another (WDM) bus or full duplex could be used in the same bus as discussed above.

IV.6 OPTICALLY SWITCHED BUSES

Optical switches are in preliminary development stages and as yet it is too early to assess their full impact on multimode fiber optic bus system architecture. The loss must be reduced for viable deployment. Furthermore, for an electro-optic switch under dynamic control, there must be some sort of "terminal" at the switch to activate it under command. In addition to the electro-optic type switch, one could also envision low-loss mechanical switches (either electrically or manually operated).[9-11]

An obvious use for optical switches is construction of a reconfigurable network. Here, one would divide the requirements into static and dynamic reconfiguration. The static case encompasses reconfiguration that is semi-permanent, while dynamic reconfiguration would be on a real-time, message-to-message basis. In the former case, mechanical switches could be suitable, while in the latter case opto-electric (or other) technology would be required to provide adequate switching speed. Figure IV-36 illustrates a simple reconfiguration. In the top illustration, optical switches control the message routing to the boxes which represent computer terminals. If the system software is distributed among several computers and is dynamically redistributed, it may be convenient to automatically cause the functional buses to be reconfigured. Of course, this can be accomplished by other methods, such as fixed terminal serving a functional bus, processing the message traffic and routing it appropriately via a computer interconnect bus not shown. Note in this case loss of that computer terminal would cause loss of that functional bus. Redundant buses would protect against this type of single-point failure. However, switched buses will clearly enhance the reliability due to the greater number of options available to circumvent a failure. In the electrical switched bus example in the lower half of Figure IV-36, a function identically to the above optical switches can be accomplished electronically. Note the control is not even necessary since the software can merely ignore messages from the functional bus if responsibility for that bus is not allocated to that terminal. The disadvantage is the additional number of drops that must be made from the bus.

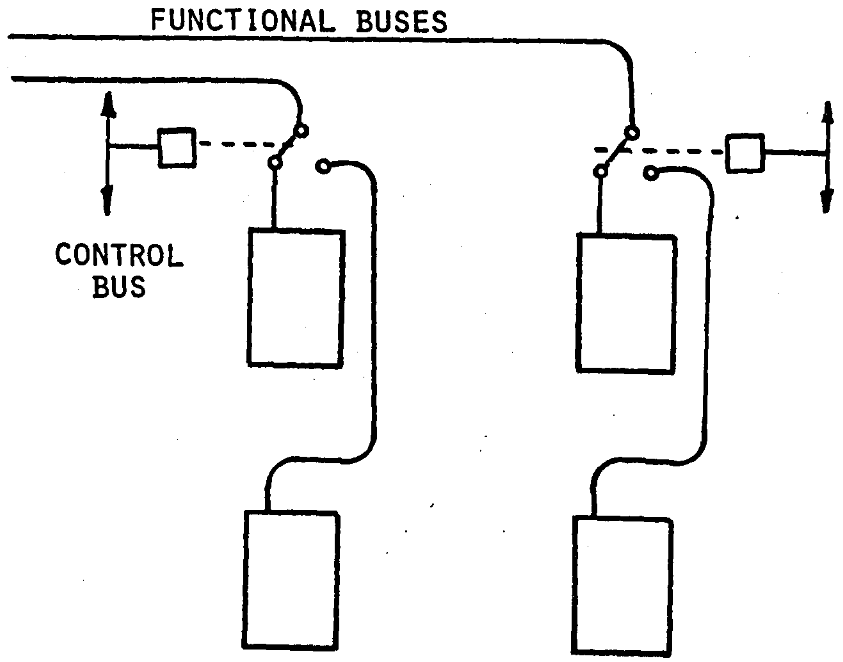
In a similar vein to this example, redundancy could be built into each terminal in terms of multiple sources and detections (the present weak links in reliability) with optical switches used to select alternates in case of failures. As above, optical couplers may be used to perform the same function, again at the expense of power splitting resulting in a reduced power budget.

In discussion of point-to-point links, it was noted that complex bus structures could be formed by terminals passing the message along the bus; for example, the ring structure of Figure II-4. Here, loss of

HUGHES

SWITCHED BUS EXAMPLE

- OPTICAL



- ELECTRICAL

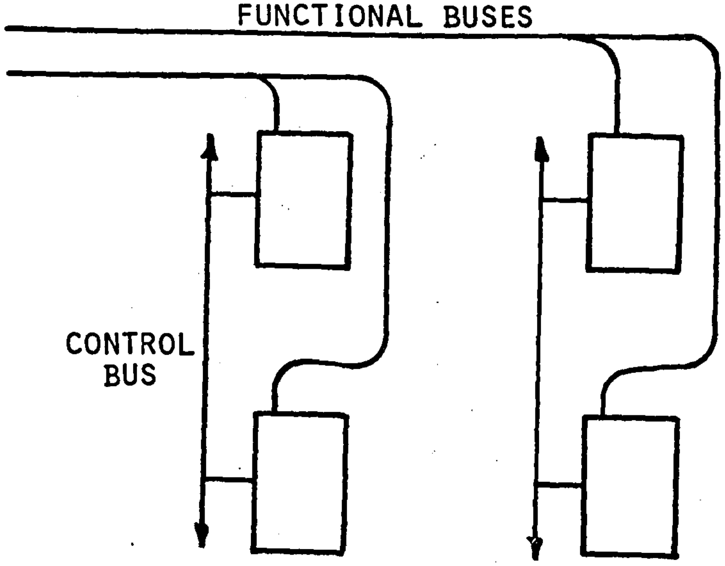


Figure IV-36

a terminal causes loss of that bus. If the link power budgets would allow a two-link run plus a switch loss, then a terminal bypass switch could be installed at each terminal for routing the traffic around the terminal in case of failure.

Another use for switches in a bus system is to use the switch as modulator. Here there would be a single high-power laser source and in-line at each terminal a modulator as indicated in Figure IV-37. This reduces the number of sources and also may reduce the power requirements at each terminal since the source require a substantial fraction of the fiber optic transceiver power requirements. Redundancy of the several centrally located, environmentally protected sources could also increase overall system reliability.

IV.7 BUS PROTOCOLS

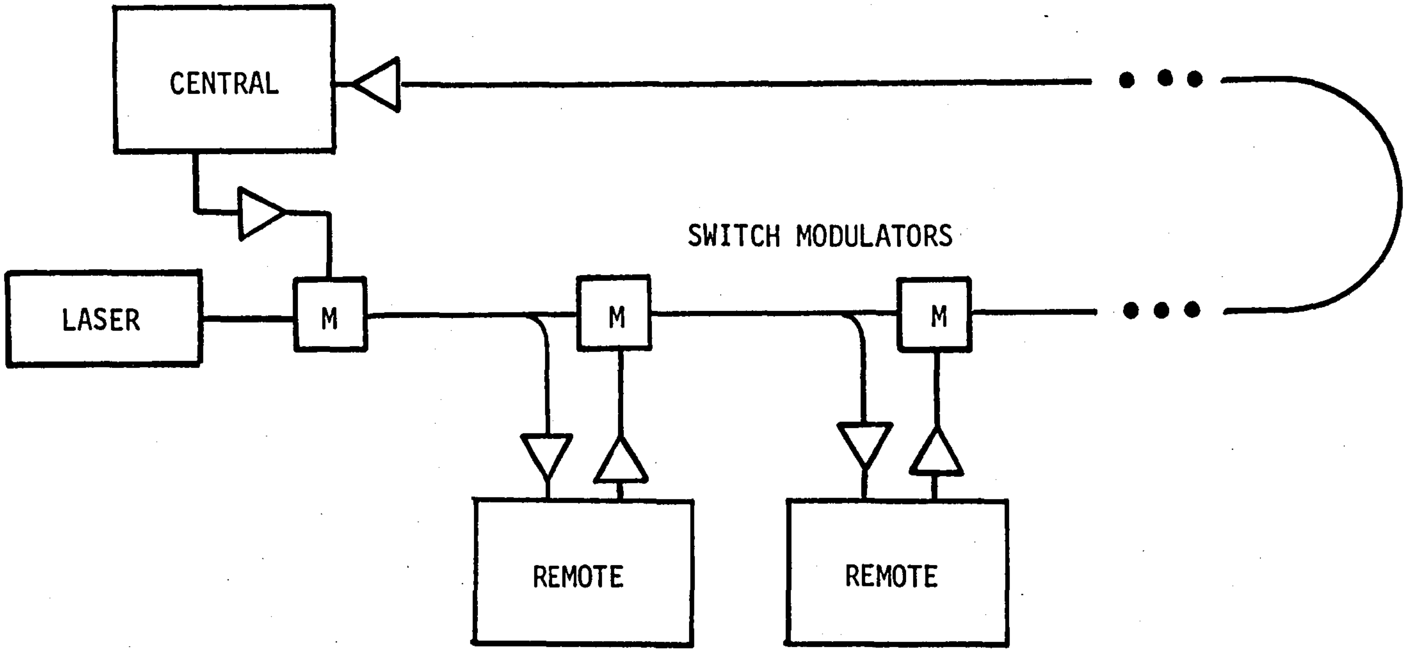
As indicated above, we have simply divided protocols into line protocols and system protocols. The former refers to the details of optical modulation format while the latter refers to the terminal-to-terminal communication format.

IV.7.1 Line Protocol

MODULATION. Three common techniques are presently considered for optical modulation: trilevel, full-width bilevel and pulse-encoded bilevel. The techniques and the results are summarized in Figure IV-38. For the trilevel method, the dc background of light from the N terminals on the bus increase the detector shot noise at each receiver. The exact value of the dc light bias depends on the bus configuration and losses. An extreme case results when N-2 terminals each with maximum power of the dynamic range are received by a terminal and a signal at the minimum power must compete with their background bias light. For thirty terminals and a 20-dB dynamic range, the sensitivity of a p-i-n receiver is reduced by about 15 dB at 10 MHz as compared to a zero bias light condition. The increased shot noise negates any advantage in gain an APD

SWITCH MODULATED BUS CONCEPT

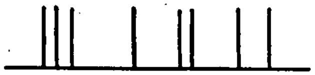
Figure IV-37



OPTICAL MODULATION TRADEOFFS

Figure IV-38

HUGHES

METHOD	ADVANTAGES	DISADVANTAGES
TRI-LEVEL 	EMULATE WIRED SYSTEMS MINIMIZE TRANSIENT EFFECTS IN AC COUPLED RECEIVERS FIXED DECODING THRESHOLD	CONTINUOUS SOURCE OPERATION TRANSMITTERS MUST CONTROL SYMMETRIC SWING DC LIGHT LEVEL DEGRADES RECEIVER SENSITIVITY
FULL-WIDTH BI-LEVEL 	SIMPLE SOURCE DRIVER NO CODE CHANGE	SEVERE TRANSIENT EFFECTS IN AC COUPLED RECEIVER COMPLEX TECHNIQUES REQUIRED TO PROVIDE WIDE IMDR
PULSE ENCODED BI-LEVEL 	RECOVERY BETWEEN PULSES ALLOWS AC COUPLED RECEIVER WITH NO TRANSIENT EFFECTS PULSES EASILY PROCESSED BY LIMITING TECHNIQUES TO PROVIDE WIDE IMDR	HIGHER BANDWIDTH REQUIRED INCREASED PULSE CURRENT DRIVE REQUIRED TO MAINTAIN EQUIVALENT BIT ENERGY AT THE RECEIVER

offers. This loss in sensitivity coupled with transmitter control complexity and continuous operation of the LEDs which expends lifetime allow one to conclude that tristate modulation for digital buses is not viable.

Aside from a few dB variation with bit rate and temperature, theoretical performance of the pulse-encoded method can be made equivalent to the full-width modulations by providing equal bit energy through increased LED drive for the short pulses. The major disadvantage is lack of data for LED lifetime with high peak power drive; however, receiver implementation is considerably simplified.

LINK OVERHEAD. At the line level, one must usually incorporate into the message structure some information in addition to the user data. This would include sync bits, start of message, terminal address, end of message, and other information. Also, in order to increase the receiver sensitivity, line conditioning may be employed. Here one would affix a preamble to each message in order to allow transient effects to settle and also establish bit timing. These approaches at the link implementation level impact bus efficiency and therefore could affect system design.

IV.7.2 System Protocols

Choice of a system protocol may impact the network design. Here, we cannot delve with detail into protocol, but will illustrate this statement with an example. A protocol known as "Listen Then Talk" is basically a type of polled protocol where control is passed from terminal to terminal. In the case of a serial network, an automatic start-up and reconfiguration (when a terminal is added or deleted) orders the terminal number on the bus and thus minimizes the bus cycle time to a twice the linear delay (plus message traffic). This results in a very efficient bus. In a star configuration, the bus cycle time is proportional to the number of terminals. Here, for a large number of terminals and short messages, the network can greatly reduce the bus efficiency. The major point is that detailed design and trade-off among various approaches cannot be made without considering the system as a whole.

IV.8 RELIABILITY

Reliability is a major issue for civil avionic systems. Data on fiber optic implementations is only beginning to emerge. Some estimates are given in the appendix to this report for component reliability. A summary is presented in Figure IV-39. The electronics would seem to offer no extraordinary challenge; the fiber and optical access couplers are passive devices and should be able to exhibit the required degree of reliability. The opto-electric components, however, are much less certain. The detector being a simple diode structure should ultimately be in the same class as semiconductor electronics. Sources are a separate problem. Here, high power sources are required to provide a suitable bus power budget; on the other hand, small size is required to match the lumination to the small fiber core. This implies a high current density which is not compatible with high reliability. Improvements in processing have taken semiconductor laser from liquid air-cooled devices to devices that operate at room temperature with lifetimes of 10^5 to 10^6 hours. Additional improvements will undoubtedly occur over the next several decades, but not at such a dramatic rate. Thus, it would be reasonable to assume that in order to obtain reliability on the order of 10^{-9}/hr., the sources will have been operated in a derated mode at the expense of power output. Hence, reliability and available power budget are two parameters that are very closely tied to one another.

In Figure IV-40A, source reliability is further discussed. The parallel reliability model shows the improvement expected by redundancy, however massive redundancy may be required to achieve failure rate times consistent with the expected required times even for a derated source. Figure IV-40B shows a potential solution. Here a bus interface unit (BIU) is

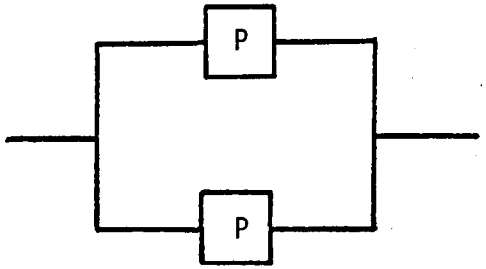
QUALITATIVE RELIABILITY ASSESSMENT (10^9 HR.)

Figure IV-39

COMPONENT	RELIABILITY	COMMENTS
ELECTRONICS	EXCELLENT	"MANY" WITH 10^9 HR. LIFETIME
SOURCES	POOR	CURRENTLY 10^5-10^6 HR.
DETECTORS	FAIR/GOOD	REQUIRES MORE TESTING - LIFETIME SHOULD BE SIMILAR TO ELECTRONICS WITH MATURATION
COUPLERS	GOOD	PASSIVE COMPONENT; REQUIRES EXTENSIVE TESTING
CABLES	GOOD/EXCELLENT	PASSIVE; MORE TESTING; SIMILAR TO ELECT. CABLES
CONNECTORS	FAIR/GOOD	PASSIVE; MORE TESTING; LONG TERM SMALL VIBRATIONS; CLEANLINESS AT INTERFACE CRITICAL (Sealed Connector)
WDM/SWITCHES	FAIR	EARLY TO MIDDLE STAGE OF DEVELOPMENT; MATURATION AND TEST REQUIRED; NO SIMILAR ELECTRONIC COMPONENTS

SOURCE RELIABILITY

Figure IV-40



PROBABILITY ONE SURVIVES

$$1-(1-P)(1-P)=2P-P^2=P(2-P)$$

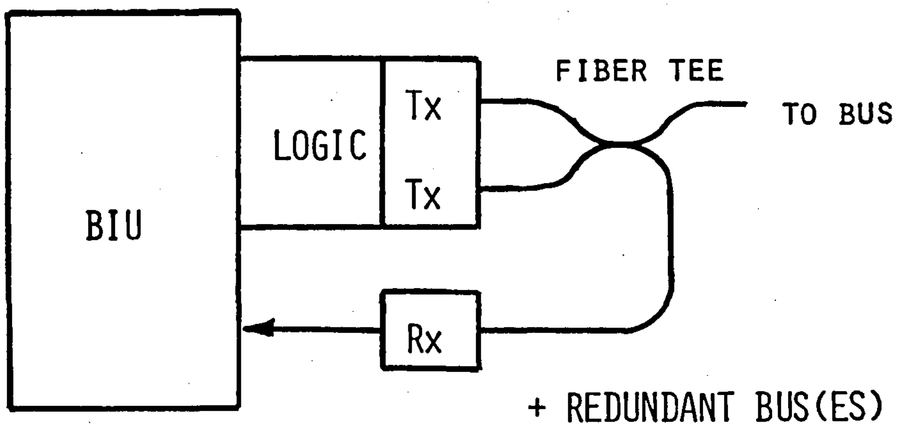
SOURCE FAILURE STATISTICS NOT WELL KNOWN

ASSUME CONSTANT FAILURE RATE MODEL (ae^{-at})

a is 10^{-5} to 10^{-6}

TWO PARALLELED SOURCES FAR FROM $T=10^9$ Hr

MAYBE



+ REDUNDANT BUS(ES)

ONE Tx (SOURCE) OFF UNTIL Rx DETERMINES FAILURE. THEN BIU AND LOGIC SWITCH TO SECOND Tx.

(STILL HAVE MTBF DUE TO VIBRATION, OXIDATION,...)

implemented with two fiber optic transmitters. These feed a 2X2 star. One output arm of the star is connected to the bus, the other is interfaced with a fiber optic receiver at the BIU. One transmitter source is off until the BIU determines failure of the other source via the fiber optic receiver. Then the BIU and logic switch to the secondary fiber optic transmitter. The bus would also be duplicated to provide the redundancy required by other considerations. This solution assumes that source MTBF due to vibration, oxidation, etc., in the off state is sufficiently high to meet the requirements.

Several kinds of system level failures are indicated in Figure IV-41. System design would rely on use of the good set of redundant buses once a failure was detected. Reconfiguration may be used to dynamically "repair" the problem (e.g., simple reconfiguration per Figure IV-40B to massive reconfiguration via optical switches). Additional buses, possibly wavelength multiplexed on the same fiber, could be used to disable a babbling terminal.

IV.9 SUMMARY

In this section, a number of general considerations for fiber optic bus design have been made. The various areas discussed have been related to each other. Detailed analysis of the three simple networks (dedicated links, star buses and serial buses) from which more complex networks were made and compared. Each has advantages and disadvantages that must be weighed in relation to the specific system design. Wavelength multiplexing allows superimposition of several independent buses within the same physical structure (i.e., fiber) which may offer advantages in terms of increased data rates or simplified electronics, supporting separate functions or multiple protocols and providing special functions such as high-speed interrupt lines, disabling "babbling terminals," etc. Switched buses were briefly considered. Their advantage appears to be the ability to provide reconfiguration in event of fault or reallocation of (software) function location in an integrated, distributed computer system.

SYSTEM FAILURES

Figure IV-41

FAILURES	DETECTION METHOD
BABBLER	TIMEOUT
DEAD UNIT	TIMEOUT
SEVERED BUS	HANDSHAKING
TRANSMISSION ERRORS	PARITY CHECKS
BAD DATA	VOTING

V EXAMPLE IMPLEMENTATIONS OF FIBER OPTIC BUSES

V.1 INTRODUCTION

In Section III, we described a "1553" baseline that could be representative of next generation systems. The simplified configuration is shown in Figure V-1 where there are a number of independent buses shown to the left, each with its own subsystem computing power. Thus, the processing is distributed. These independent subsystem buses are redundant to the degree required by reliability for the function. The subsystems are loosely connected by a higher order system (HOX). Thus, each function can be optimized in distribution, communication protocol, reliability and maintainability.

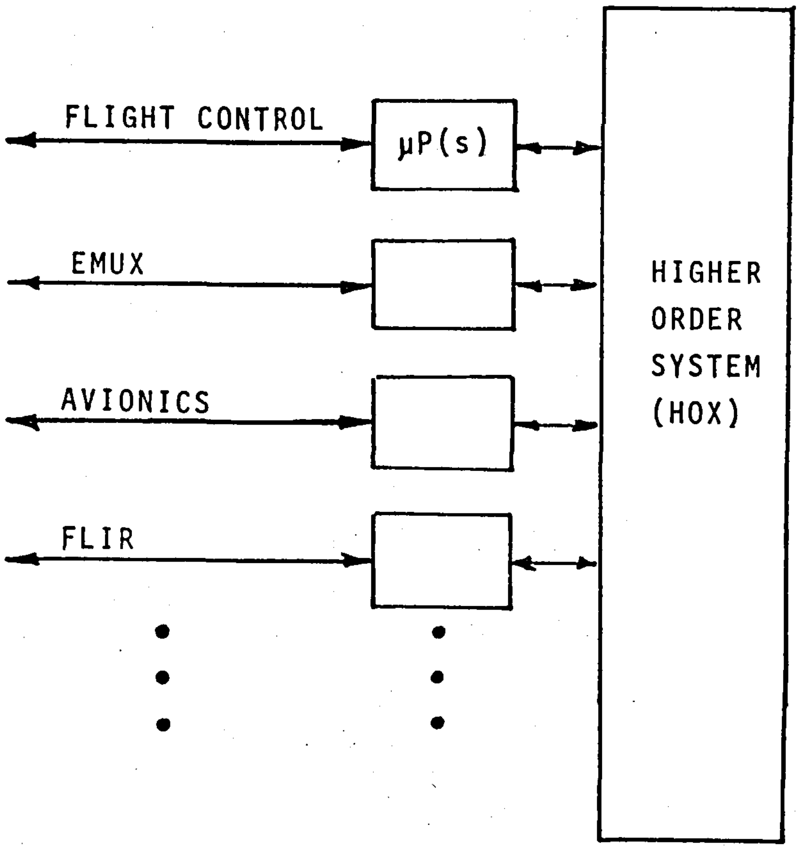
The baseline also established a set of functional requirements and approximate physical locations. These are shown simplified in Figure V-2. Also shown in this figure are a partitioning of the aircraft into zones of NOSE, WING and TAIL and two avionic bays with fault-tolerant computers in each zone. This is the six-bay configuration of the CSDL report[12] which appears to be the best partitioning of computer resources among the multi-bay systems that they considered in terms of their trade-off parameters.

We may now evolve from the baseline of Figure V-1 to the architecture shown in Figure V-3, where there is partial integration of the system. The buses, to the left, are still separated by function. However, here each zone of the aircraft is bused separately. This minimizes the number of taps or star ports. The buses each terminate at the appropriate zone bay and one or more other zone bays as required by redundancy. The fault-tolerant computer system is distributed over the six bays. (Only three are shown.) These communicate with each other on a computer control bus (CCB). The software functions serving a particular bus may be located either in the computer located in the bay at the head of the bus or elsewhere depending on the fault-tolerant computer design. This

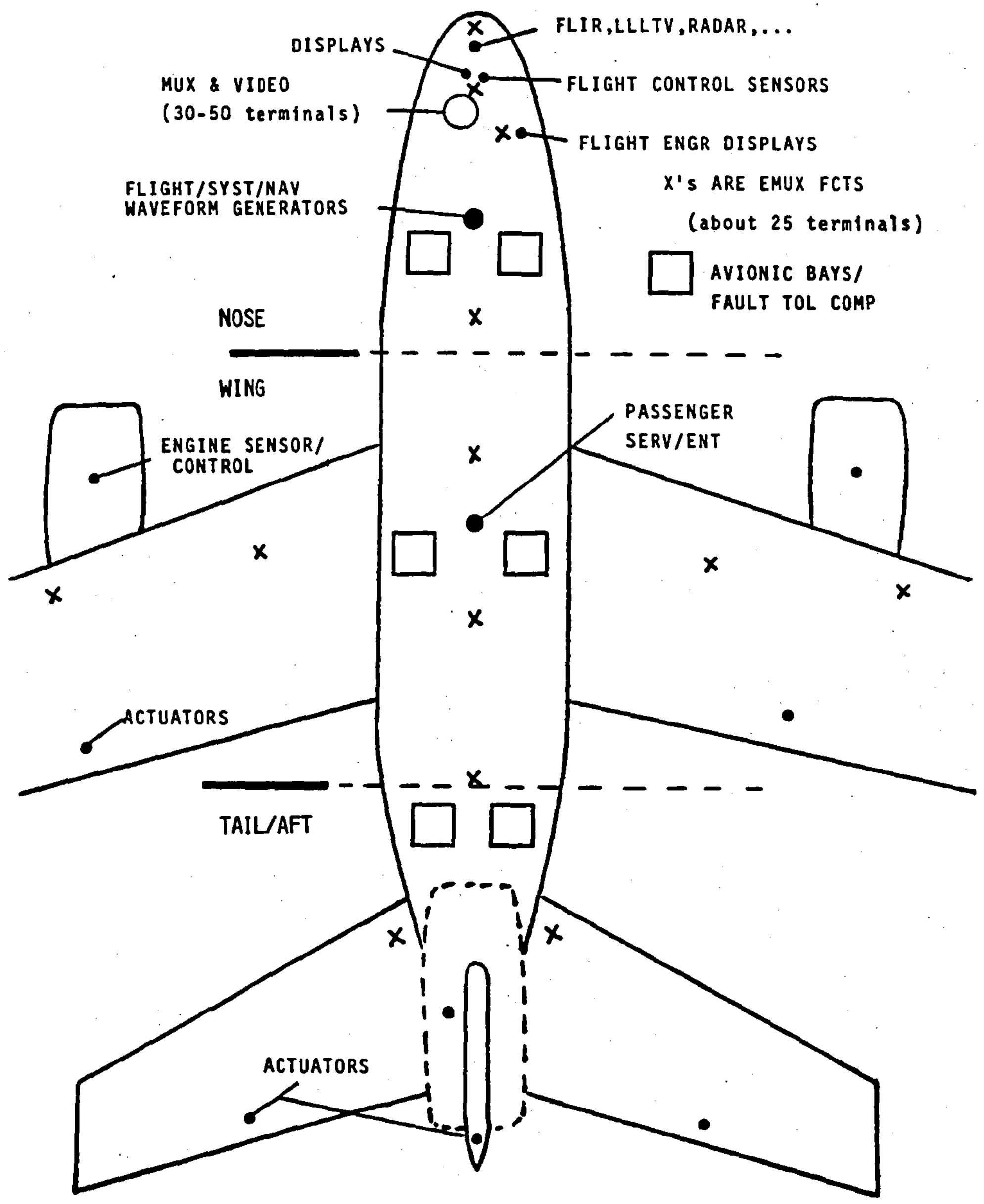
"1553" BASELINE
(THIS GENERATION +1)

Figure V-1

HUGHES



- REDUNDANT BUSES (NOT SHOWN)
- DISTRIBUTED PROCESSING
- INDEPENDENT FUNCTIONAL BUSES
- LOOSE INTERCONNECT VIA HOX
- OPTIMIZE EACH FUNCTION
    DISTRIBUTION
    PROTOCOL
    RAM



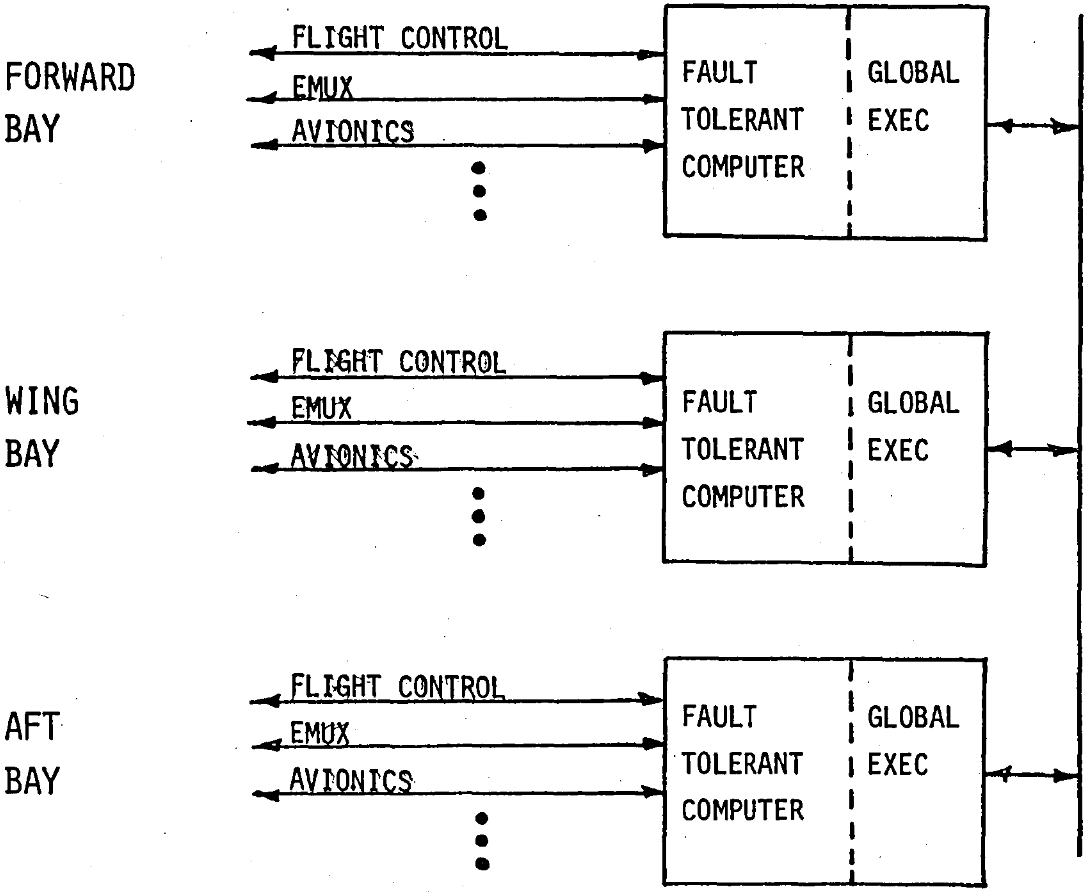
HUGHES

SIMPLIFIED FUNCTIONAL REQUIREMENTS

Figure V-2

PARTIALLY INTEGRATED SYSTEM

Figure V-3



- REDUNDANT BUSES (NOT SHOWN)
- MULTIBAY FAULT TOLERANT COMPUTERS
- INDEPENDENT FUNCTIONAL BUSES (MINIMIZE TAPS OR STAR PORTS)
- INTEGRATED BY CCB
- CCB TOPOLOGY MAY BE DRIVEN BY PROTOCOL (TBD)
- WDM ON CCB
- SOME FUNCTIONAL RAM OVERLAPS

introduces some functional RAM overlaps. The functions (e.g., flight control) of each zone are integrated via the CCB. The CCB topology will be a strong function of the fault-tolerant computer design, which may require high traffic rates, interrupts, clocks, etc. This multiple-signal, high-speed buse should provide an area where wavelength division multiplexing will provide extreme advantages.

The next step in the process of integrating the system is shown in Figure V-4. The difference between this network and the previous one is combining functions on the buses. Although only one bus is shown carrying all the functions, probably several buses would be used, each routed to a subarea of the aircraft zone being served. This could serve to minimize the number of taps. Here wavelength division multiplexing could be employed on the integrated buses in order to separate functions (functionally equivalent to Figure V-3) and allow use of optimize protocols for each function.

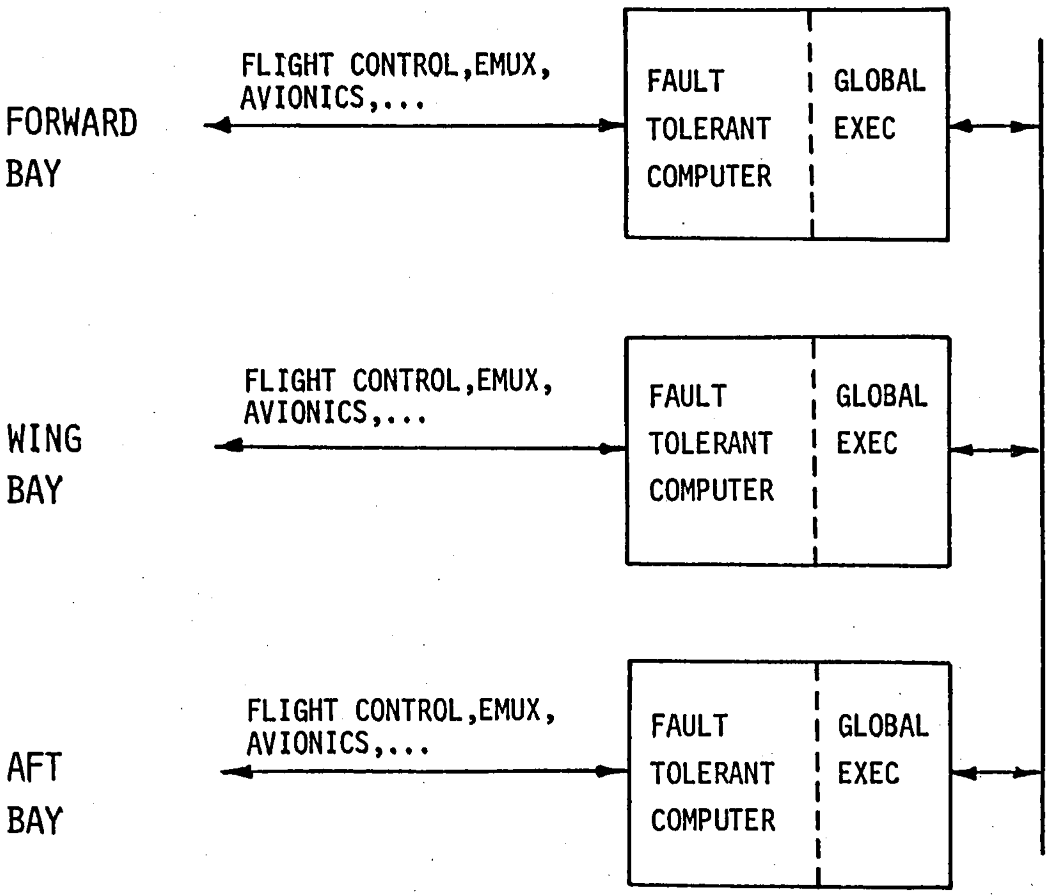
V.2 GENERAL COMPARISON AMONG STRUCTURES

The dedicated link structure shown in Figure V-5 does not support wavelength multiplexing except for duplexing the communication path. Only one of the required redundant links is shown (the dashed line). The point-to-point implementation is the most practical today since it requires no optical access couplers. It would also provide the greatest system reliability because each link is independent. However, in terms of fiber and connector requirements it is inefficient. Also for N terminals, there are 2N transceivers required (not including redundancy).

Figure V-6 shows a single wavelength system with a star optical access coupler dedicated to each function. If functions are mixed on the bus, then one loses choice of protocol for each function. Use of a bus cuts down the amount of fiber and number of connections, especially if the terminals are clustered. Here only one coupler (the star) is required to serve N terminals. Star implementations are practical today for N on the

FULLY INTEGRATED SYSTEM

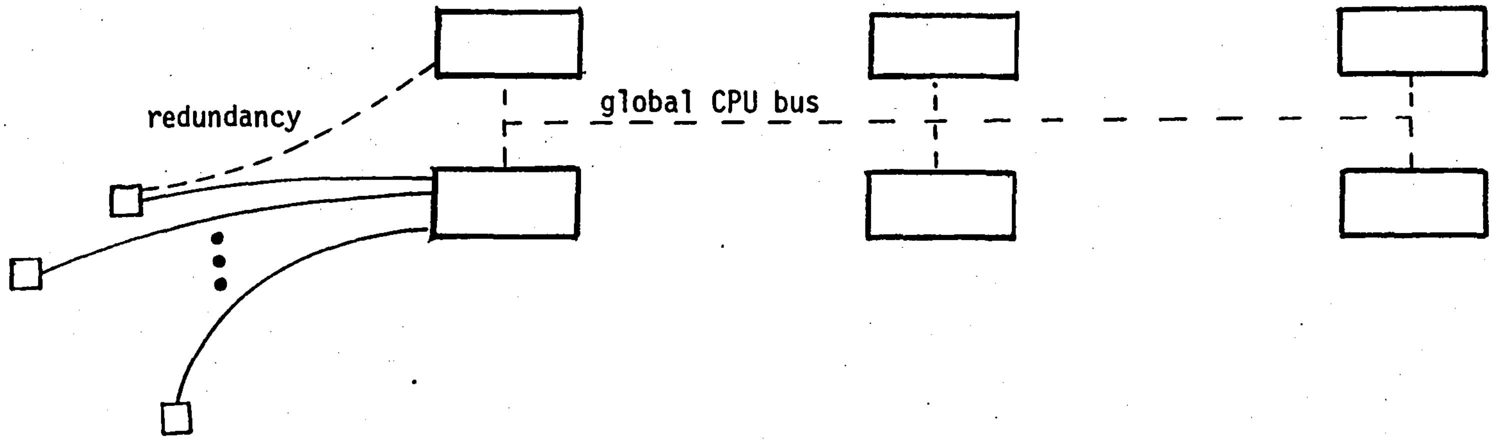
Figure V-4



- REDUNDANT BUSES (NOT SHOWN)
- MULTI-BAY FAULT TOLERANT COMPUTERS
- MULTIPLEXED FUNCTIONAL BUSES (λ-MUX TO SEPARATE FUNCTIONS)
- INTEGRATED BY CCB
- CCB TOPOLOGY MAY BE DRIVEN BY PROTOCOL (TBD)
- WDM ON CCB
- COMPLETE FUNCTIONAL RAM OVERLAP

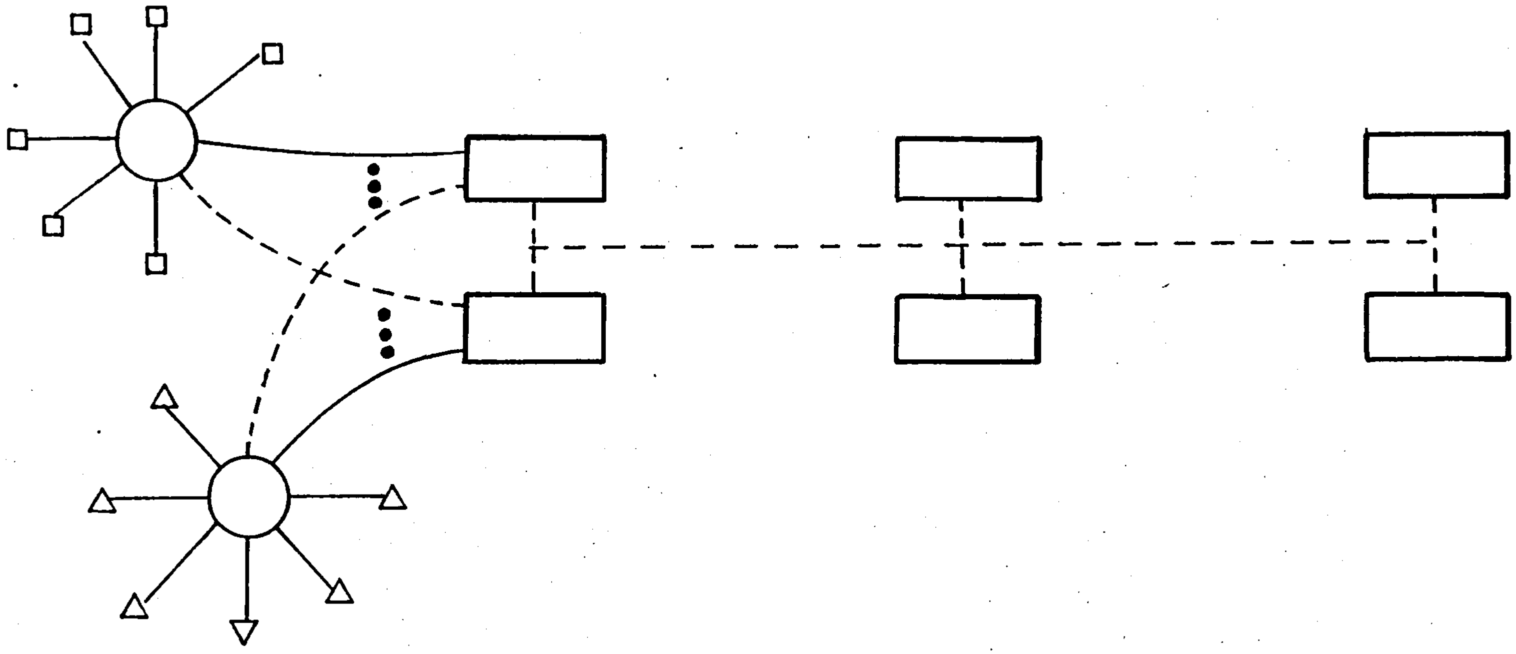
DEDICATED LINKS

Figure V-5



SINGLE WAVELENGTH - STAR DEDICATED TO EACH FUNCTION

Figure V-6



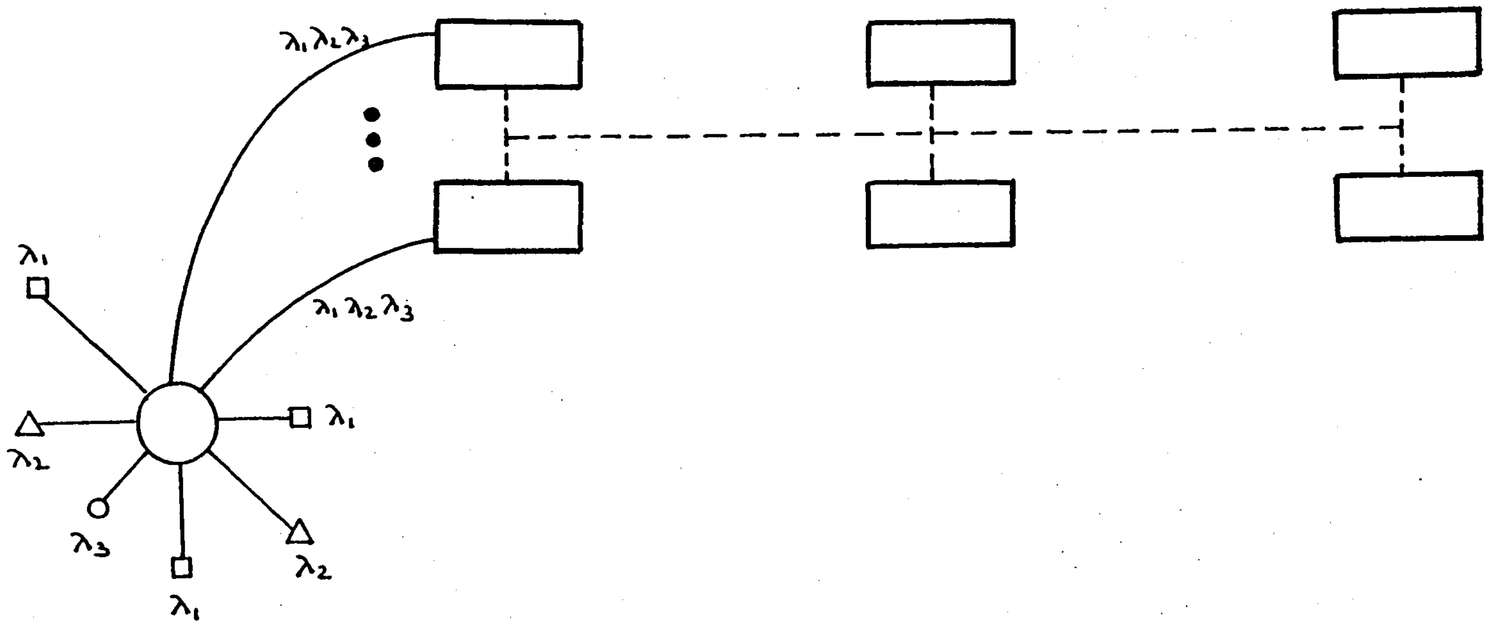
order of 30 for multi-megabit data rates. The number of transceivers is N + 1. Reliability is also good. It is similar to the point-to-point links in the sense that single-point failure affects only that function except in the case of the central terminal star-to-link loss or star failure. The pasive star should provide excellent reliability when properly packaged. If wavelength multiplexing is employed, the configuration shown in Figure V-7 results. Here the number of transceivers increases by the number of additional wavelengths multiplexed, so that N + M transceivers are required where N is the number of terminals and M is the number of wavelengths. This allows each function to communicate with an optimum protocol. Fiber and connector requirements are similar to previous case, however by mixing functions advantage can be taken of clustered terminal groups. Here also, the system reliability may be slightly better because with mixed functions there would be fewer buses to meet the functional requirements. Since wavelength multiplexes are still under development, practicality of implementing more than a several-color bus is low.

The serial buses shown in Figures V-8 and V-9 are identical in requirements for number of transceivers. The fiber requirement is significantly less than the previously discussed networks. In-line losses would require the taps be spliced in the system making installations and maintenance a potential problem and may, in some cases, reduce the practicality of today's implementation. The 2N couplers also increase system cost (trade-off against reduced fiber cost). Reliability is reduced from a star implementation by virtue of a trunk loss (coupler, fiber or splice) severing communications to multiple terminals.

The results of this top level trade-off are summarized in Figure V-10. Each implementation has advantages and disadvantages. We would anticipate that the complex networks required would be built up of combinations of all three. For example, a serial bus could have a few taps located near equipment clusters. An active repeater would be located at each tap. Distribution to the equipment cluster would be via a star. This

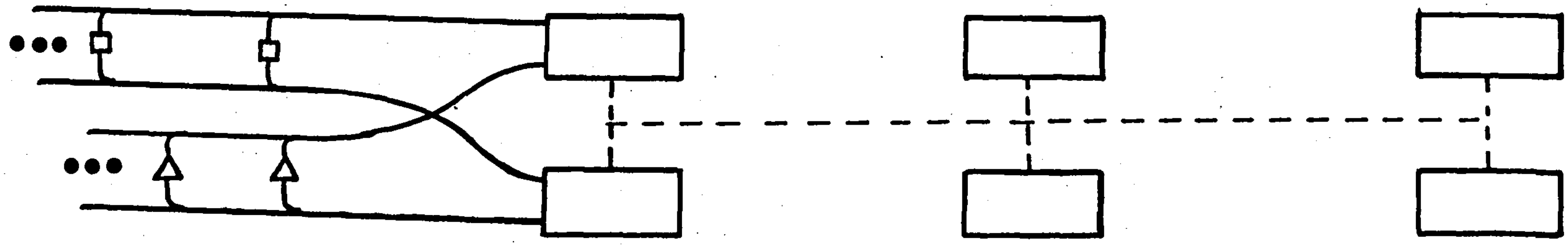
WAVELENGTH MULTIPLEXED - STAR DISTRIBUTION

Figure V-7



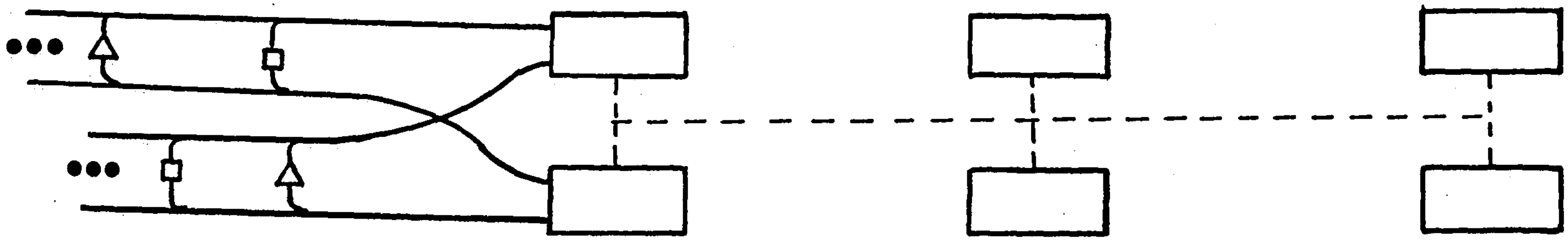
SERIAL BUS - UNMIXED SIGNAL TYPES

Figure V-8



SERIAL BUS - MIXED SIGNAL TYPES

Figure V-9



TOP LEVEL TRADE-OFF
(REDUNDANCY NOT INCLUDED)

Figure V-10

	POINT-TO-POINT	STAR		SERIAL	
		NO WDM	WITH WDM	NO WDM	WITH WDM
NUMBER OF TRANSCEIVERS	2N	N+1	N+M	N+1	N+M
FIBER/CONNECTOR RQMTS	MOST			LEAST	
NUMBER OF COUPLERS	0	1		2N	
PROTOCOL FREEDOM	-	NO	YES	NO	YES
RELIABILITY	1	3	2	5	4
PRACTICALITY (TODAY)	1	2	3	3	4

active repeater reduces reliability. Thus two (or more) wavelengths would be sent on this bus to provide repeater redundancy. Additional redundant buses would guard against central terminal and mechanical link failures. Such a network is shown in Figure V-11.

V.3 WING TOPOLOGY EXAMPLES

Using the specific functional requirements established of Section III, seven topologies are established for the wing area. These are the same as the last section with the explicit addition of multiple stars and serial buses. These are shown in Figures V-12 through V-16. Figure V-17 lists assumptions used for subsequent calculations, while Figure V-18 shows available power budgets for various source, detector, and fiber combinations. A calculation for various topologies is detailed in Figure V-19. Here the minimum allowed source, detector, fiber (SDF) configuration is shown. The tradeoff resulting from this calculation and other considerations discussed above results in the tradeoff matrix for the wing section given in Figure V-20. The serial buses are most attractive with drawbacks in practicality and reliability. Progress in these areas would make this the "optimum" bus structure for future wing implementation. Wavelength multiplexing would be used as required for functional separation. Optical switching could be employed to switch the head of the bus among different bays if required.

V.4 SPECIFIC TOPOLOGIES

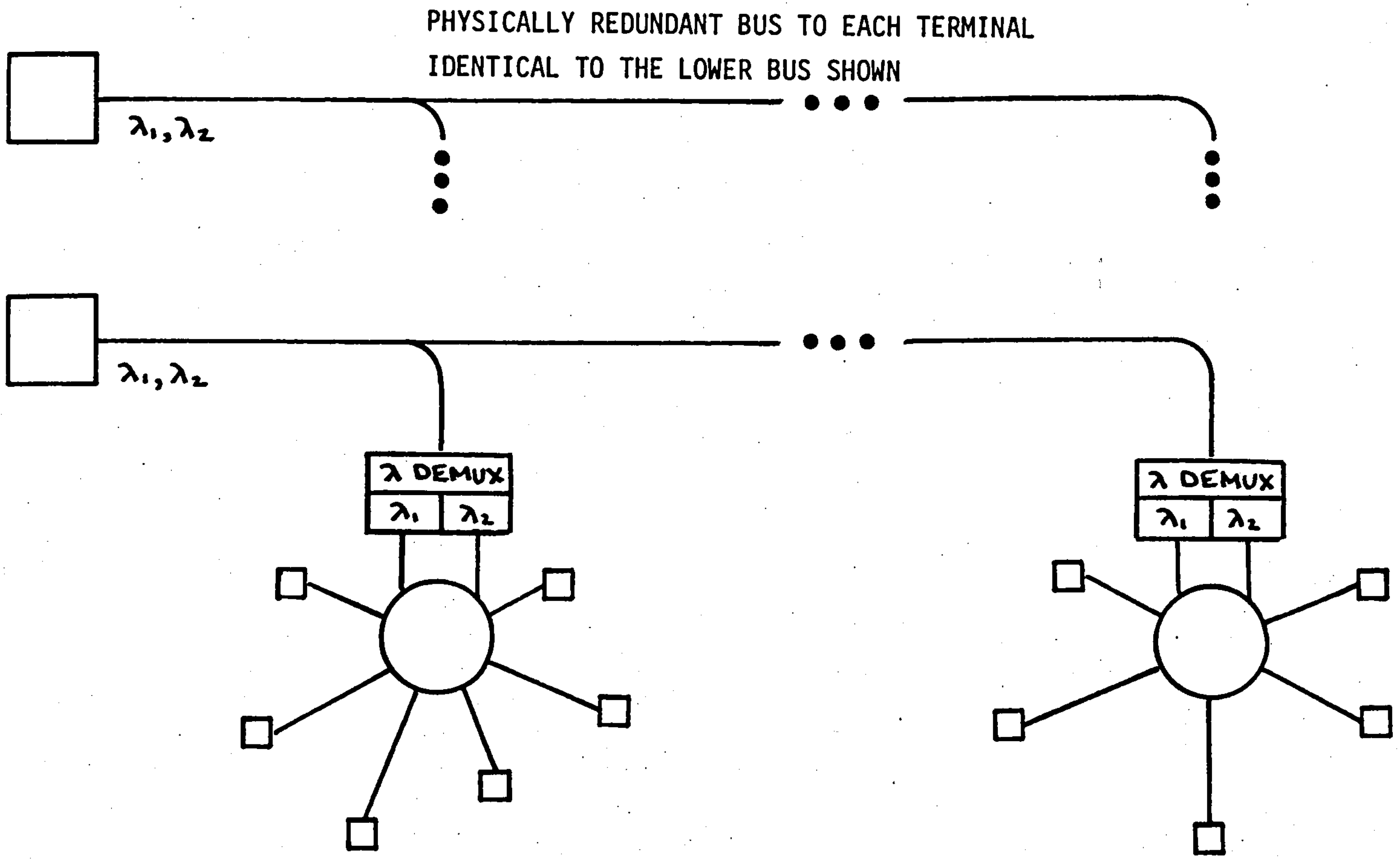
In a similar manner, the other areas of the aircraft were analyzed to establish a potentially optimum topology.

Figure V-21 shows a hybrid bus serving clusters in the nose section of the aircraft. Here approximately a dozen taps are required on the serial bus. Stars are used to distribute to the clustered instrument panels. In order to accommodate the power budget, active repeater as discussed earlier and shown in Figure V-11 would probably be required. Each

HYBRID BUS WITH REPEATERS
WDM FOR RELIABILITY

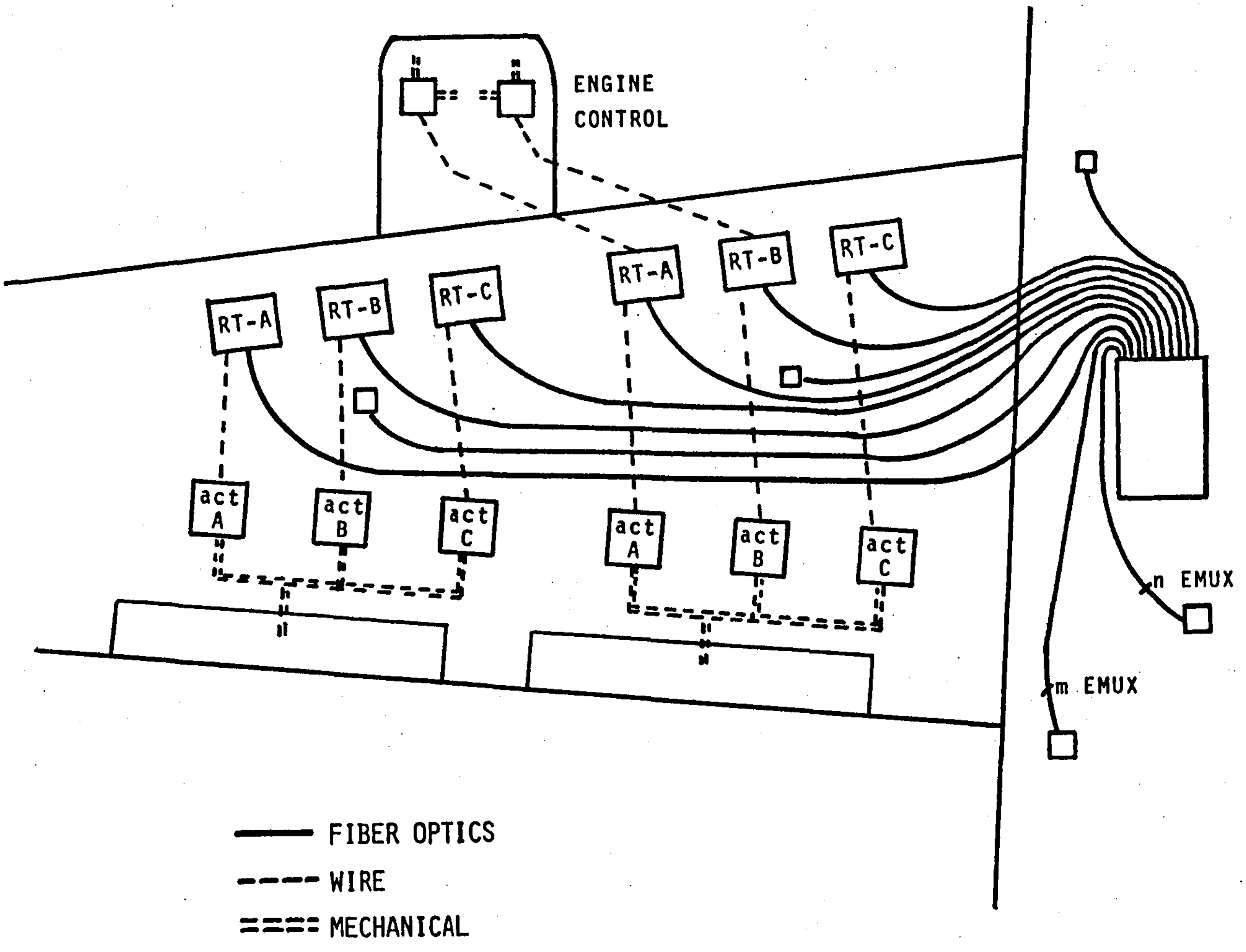
Figure V-11

HUGHES



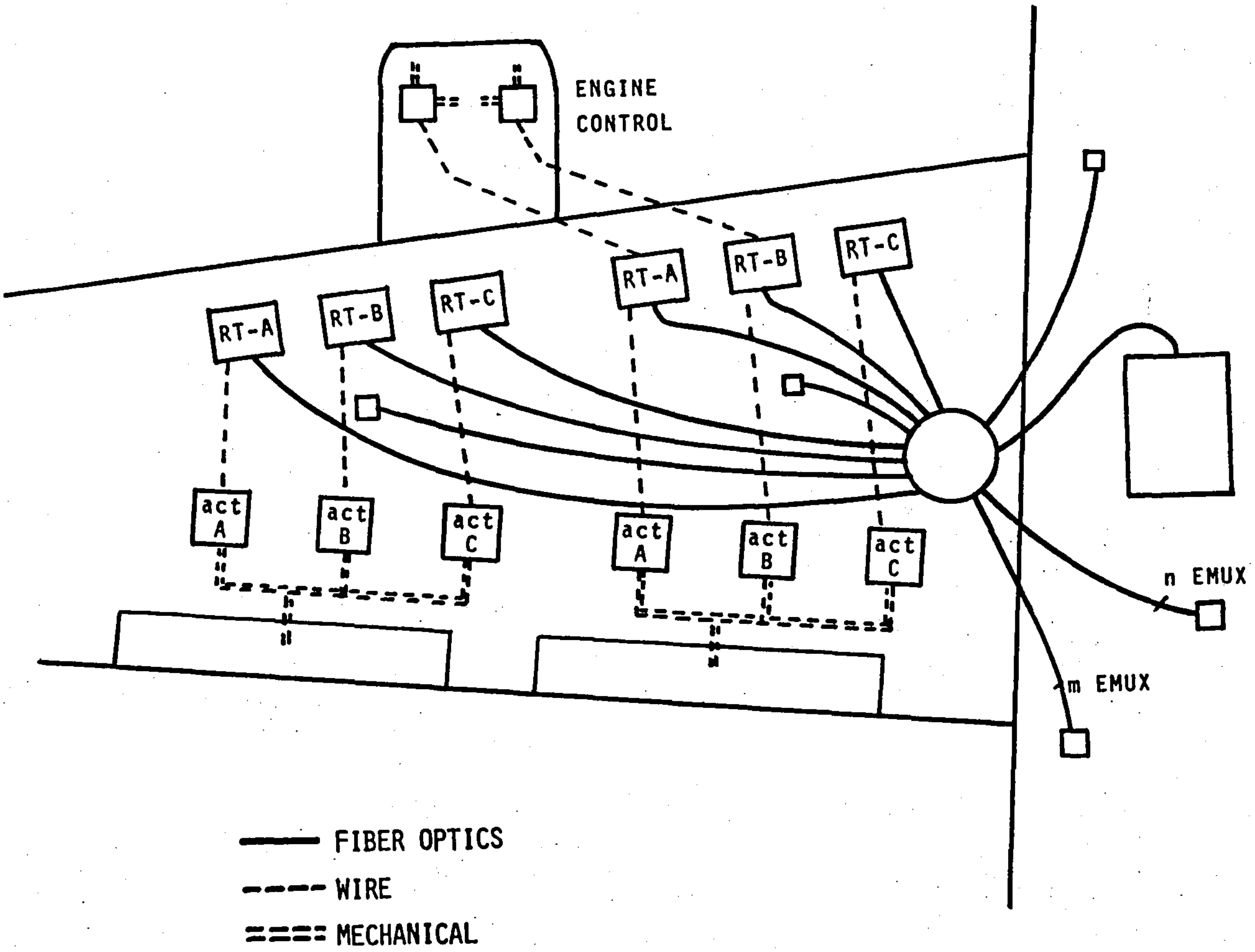
DEDICATED LINKS

Figure V-12



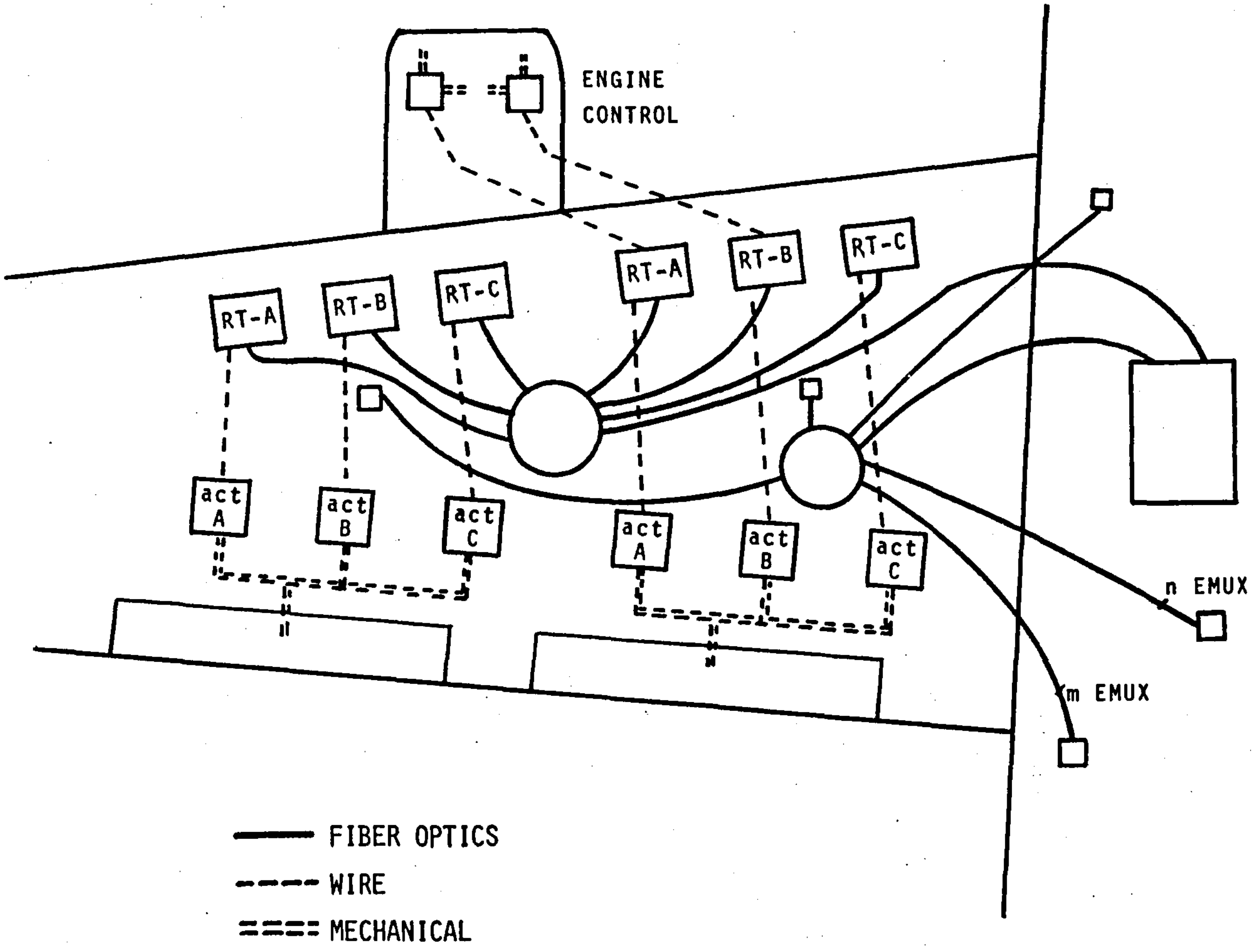
SINGLE STAR

Figure V-13



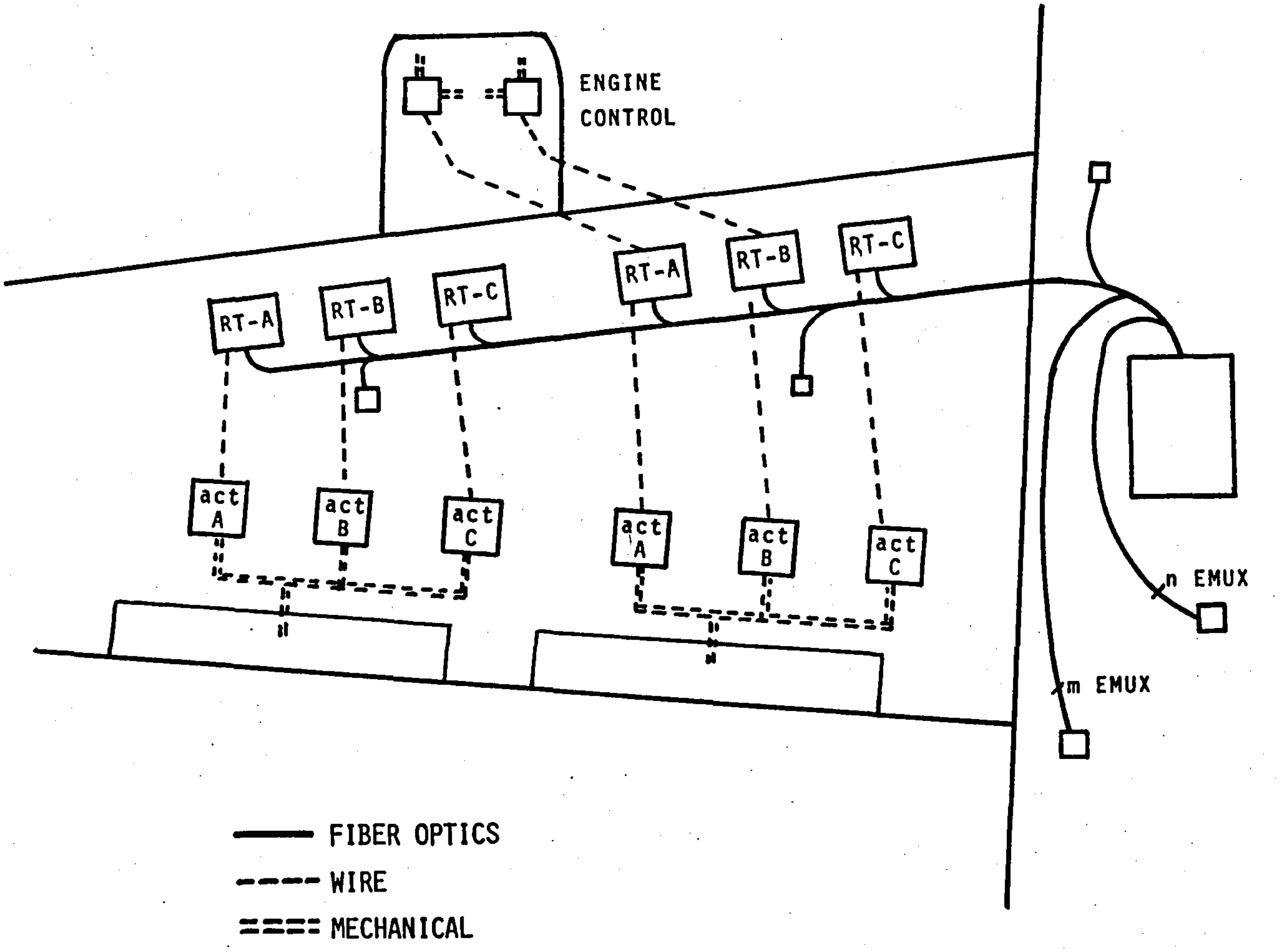
MULTIPLE STARS

Figure V-14



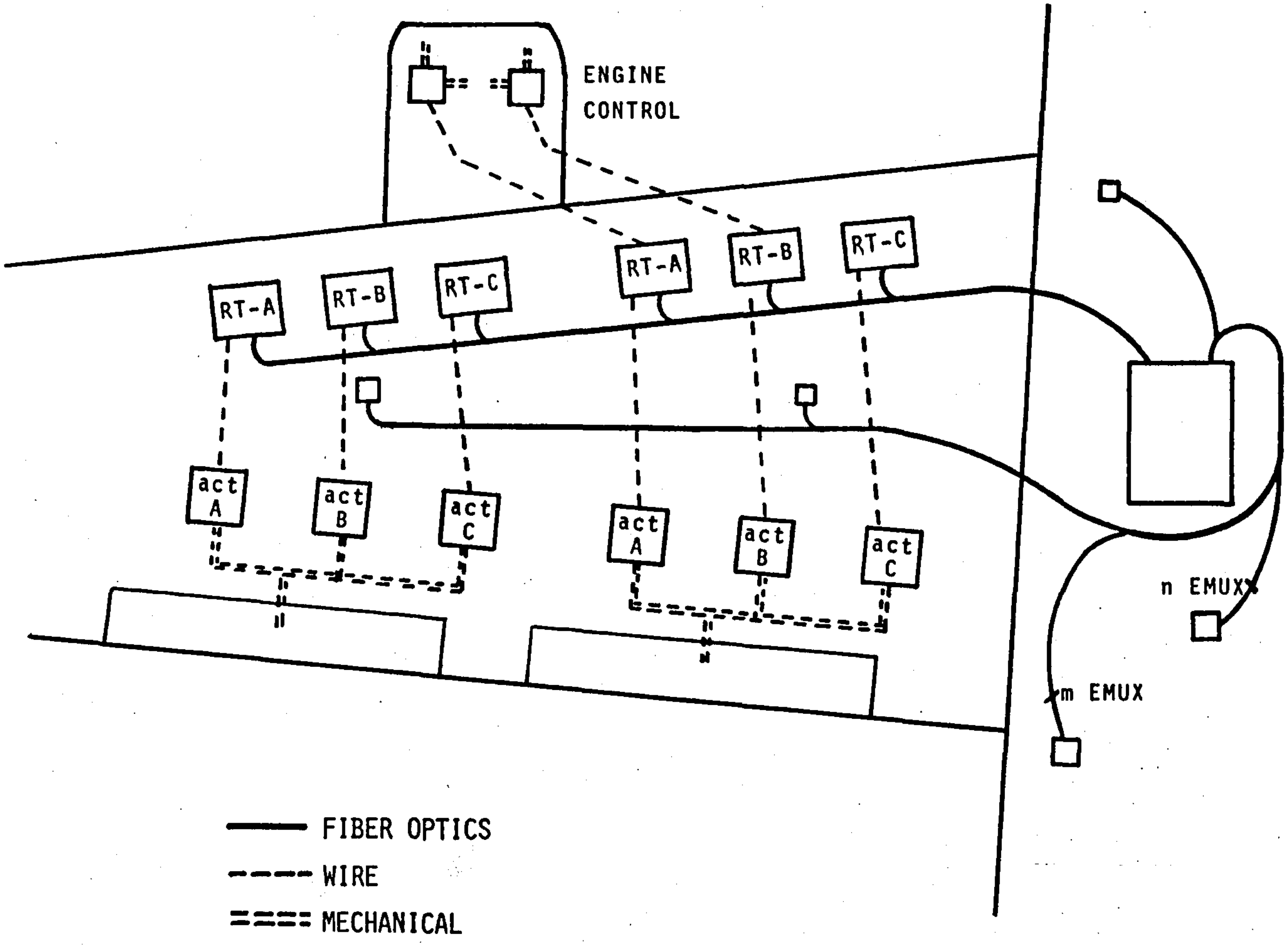
SINGLE SERIAL

Figure V-15



MULTIPLE SERIAL

Figure V-16



ASSUMPTIONS

Figure V-17

- NEED CALCULATE ONLY HIGHEST LOSS PATH
  (NEXT ORDER CALCULATION D. R. / REFLECTIONS NEED TO BE CONSIDERED)
- STAR EXCESS LOSS @ 2.5 DB
- T'S EXCESS LOSS @ .5 DB AND LOW TAP POWER
- LONGEST CABLE LENGTH - 50 METERS
  (FIBER LOSS = 4 db/km → 0.2 db FOR FIBER (EXACT LENGTH WILL NOT BE IMPORTANT)
- CONNECTORS @ 1.5 DB/CONNECTOR → 1 DB FOR 140 µ FIBER

  SPLICES @ 0.2 DB/SPLICE
- 5 BULKHEADS @ 3 DB/BULKHEAD
  MAY NEED ITERATION/INVENTION
  I.E., BULKHEAD MOLDING AROUND FIBER IN HARNESS FOR 0dB

Rx BASELINE REQUIREMENTS

Figure V-18

- BANDWIDTH 1-20 MHz FOR BUSES
- MANCHESTER FORMAT
- DETECTOR OPTIONS

	SENSITIVITY	
PIN DIODE	-40 dBm	10^{-8} BER
APD DIODE	-55 dBm	

(NOISE LIMITED - MINIMAL IMPROVEMENTS ONLY IN FUTURE)

- SOURCE OPTIONS

	LAUNCH POWER 55 μ CORE	140 μ CORE
LED	-10 dBM	0 dBM
LASER	+3 dBM	10 dBM

(SOURCE POWER NOT LIMITED BY LAWS OF PHYSICS)
(REFLECTIONS MAY COME INTO PLAY FOR SOME BUS TOPOLOGIES)

- POWER BUDGETS

LED PIN 55μ	LED PIN 140μ	LED APD 55μ	LED APD 140μ	LASER PIN 55μ	LASER PIN 140μ	LASER APD 55μ	LASER APD 140μ
30dB	40dB	45dB	55dB	43dB	50dB	58dB	65dB
A	B	D	F	C	E	G	H

OPTICAL POWER BUDGET - WING SECTION (15 TERMINALS)

Figure V-19

CONFIGURATION / LOSS CONTRIBUTION	1 PT-PT	2 SINGLE STAR	3 SERIAL	3 SERIAL/ (Splices)	4 DUAL STAR	5 DUAL SERIAL	5 DUAL SERIAL/ (Splices)
FIBER	0.2	0.2	0.2	0.2	0.2	0.2	0.2
COUPLERS (EXCESS + POWER DIVISION)	--	14.8	22.7	22.7	12.5	7.0	7.0
CONNECTORS (BULKHEAD)	15.0	15.0	15.0	15.0	15.0	15.0	15.0
CONNECTORS AT LRU (COUPLERS AND TR'S)	3.0	6.0	45.0	3.0	6.0	27.0	3
SPLICES AT "T" COUPLERS	--	--	--	5.0	--	--	3.6
TEMPERATURE AND AGEING	6.0	6.0	6.0	6.0	6.0	6.0	6.0
TOTAL	24.2dB	42.0	88.9	52.5	39.7	65.2	44.8
MIM ALLOWED SDF CONFIG	A	C	-	F	B	H	D

WING TOPOLOGY TRADEOFF

Figure V-20

TOPOLOGY / PARAMETER	1	2		3	4		5
	DEDICATED LINK	SINGLE STAR	WDM SINGLE STAR	+ STARS	SERIAL	WDM SERIAL	DOUBLE SERIAL
NO. OF TRANSCEIVERS	2N	N+1	N + M	N + 2	N + 1	N + M	N + 2
NO. OF FIBERS/CONNECTORS	2N	2(N+1)	N + 1	N + 2	2 + STUBS	2 + STUBS	4 + STUBS
NO. OF COUPLERS	0	1	1	2	2N	2N	2N
NO. OF OPTICAL DEMUX	0	0	N + 1	0	0	N + 1	0
MIXED PROTOCOL	NO	NO	YES	"YES"	NO	YES	"YES"
RELIABILITY	1	3	2	2	4	3	3
PRACTICALITY	1	3	4	2	4	6	4

HUGHES

HYBIRD BUS - NOSE
(FUTURE)

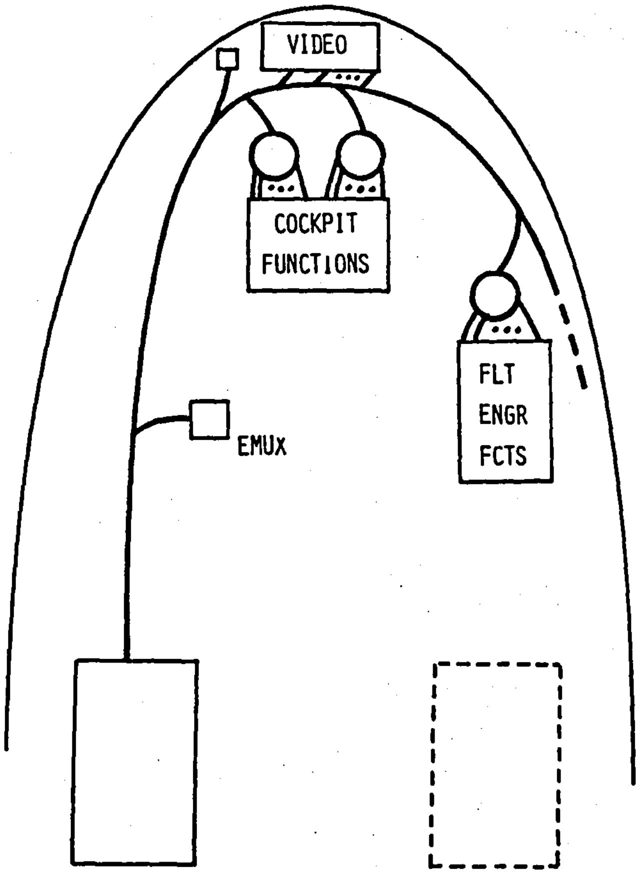


Figure V-21

high-speed video channel would be a separate wavelength on the fiber bus. An alternative network shown in Figure V-22 would bus each star passively to the computer bay and use a serial bus for EMUX. The video functions would be color multiplex by a star in the nose. A low data rate serial serial bus using a single wavelength could provide uplink control signals for the video if required (not shown). This more conservative network uses more fiber, but yields a power budget that is practical for next generation implementation.

Figure V-23 shows a serial bus for the wing section and a separate serial bus for central cabin functions. Here the number of drops would require use of splices at the taps. Wavelength multiplexing could be used to separate flight control, EMUX, and other functions of the bus.

A tree-branch network is shown in Figure V-24 for the tail section. This minimizes fiber, however again active repeaters may be required in some of the branches. Similar to the discussion for the nose section, several serial or star buses could be installed to overcome present power budget limitations.

In each of the above examples, redundant buses are provided as required to meet reliability specifications. In the case of the critical flight control buses, triple or greater redundancy may be required. A detailed analysis may show that this redundancy is required due to electronic reliability and that physical damage to link contribute little to failure rate (collision). In this case, wavelength multiplexing can provide multiple electronic redundancy over a single fiber. Thus two such wavelength multiplex buses may prove to have adequate availability.

A network to interconnect the six computer bays is shown in Figure V-25. Here a doubly redundant star topology is shown. Traffic analysis is not yet definitive for these computer interties, however multiple stars could be used for both the primary and secondary buses to accommodate high data rates, clocks, interrupts, etc. An alternative (which could also have

HUGHES

MULTIPLE BUSES - NOSE
(TODAY)

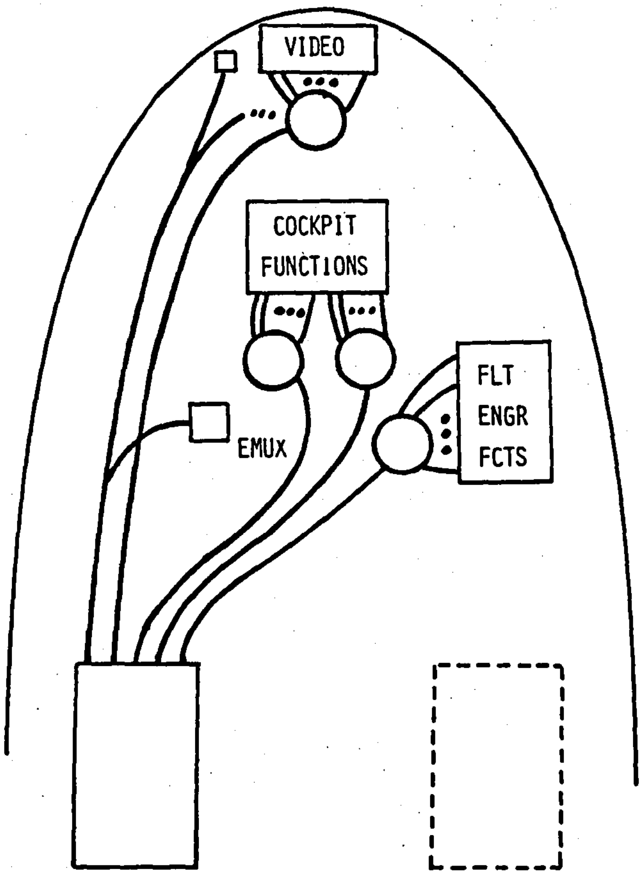
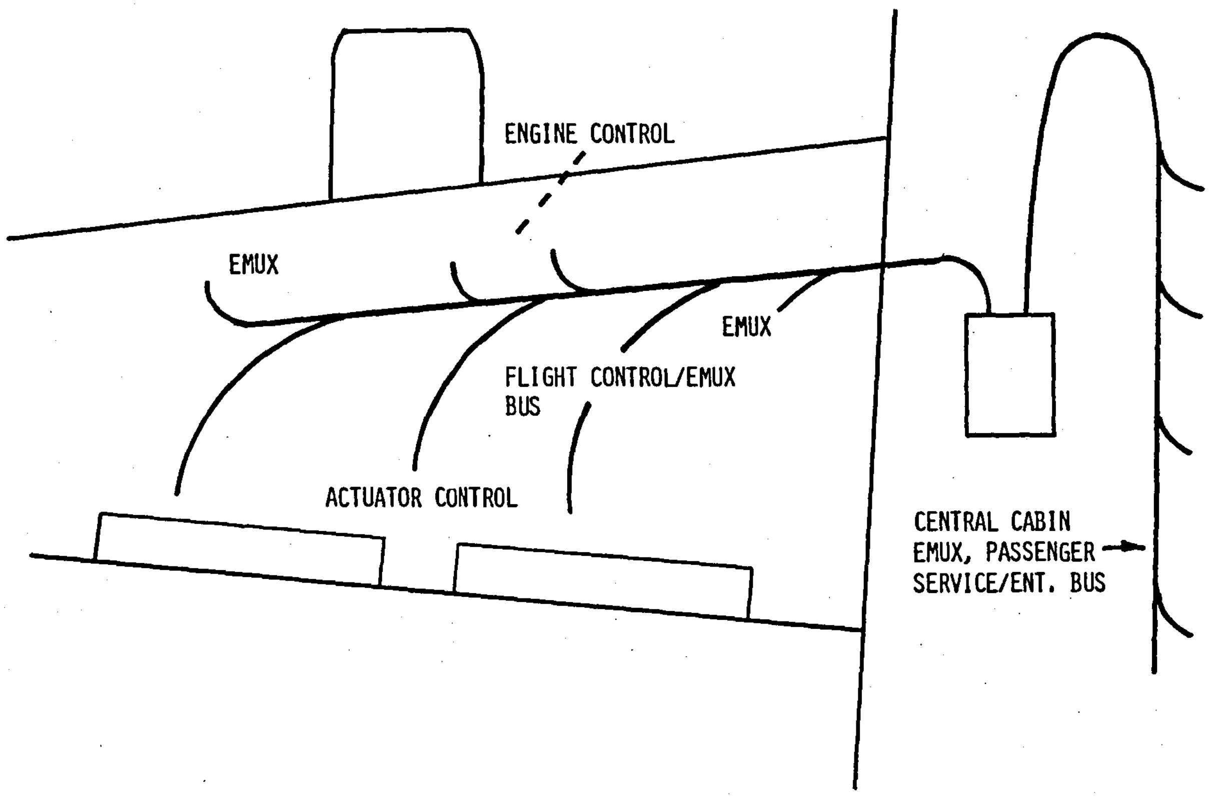


Figure V-22

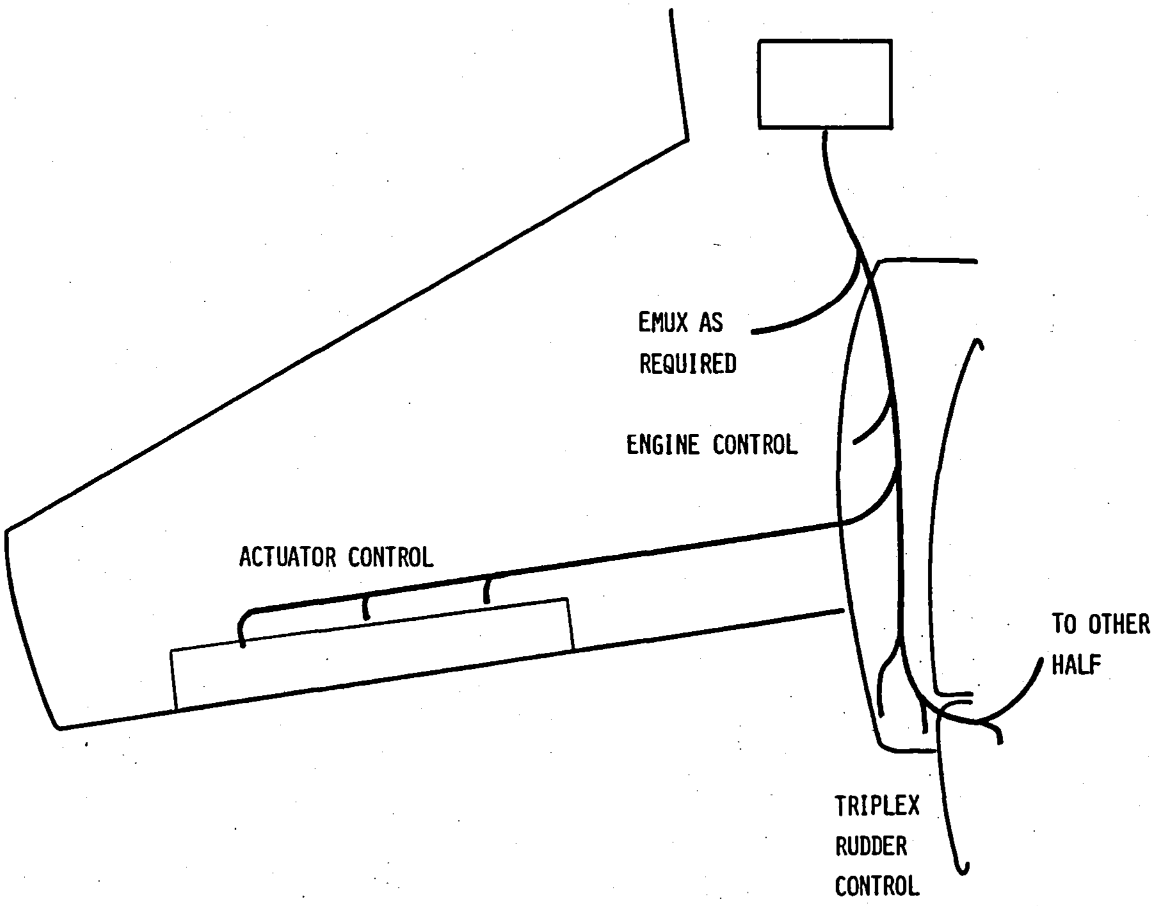
SERIAL BUS - WING & CENTRAL CABIN

Figure V-23



TREE BRANCH TOPOLOGY - TAIL

Figure V-24



STAR
COMPUTER
INTERCONNECT

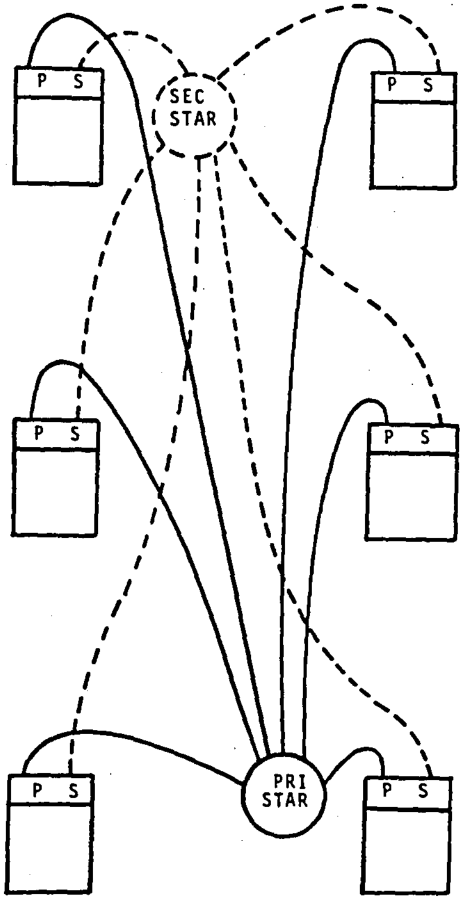


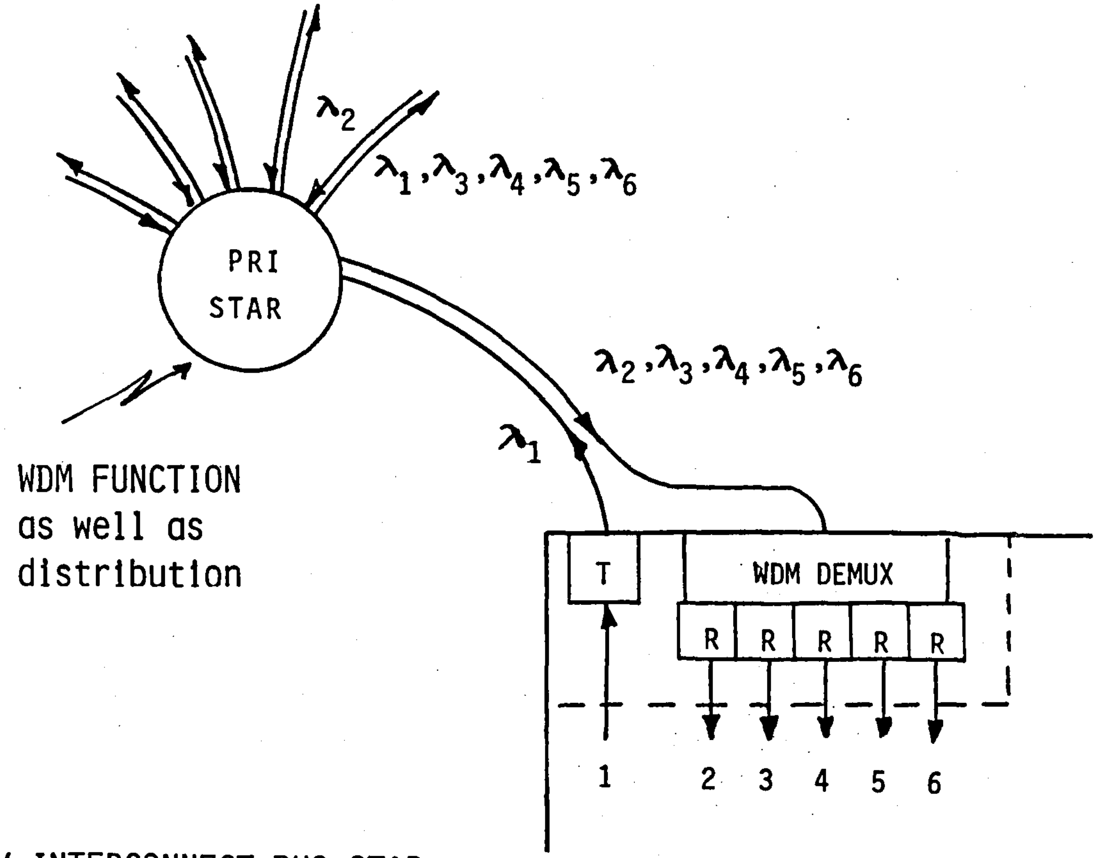
Figure V-25

multiple stars if required) is to employ wavelength multiplexing as shown in Figure V-26. This particular scheme allows simultaneous communication among all six computers. As in the single wavelength case, additional identical networks could be used to accommodate clocks, interrupts, etc. As wavelength multiplexing technology matures, sufficient wavelength may be available to stack clocks and interrupts on the same bus (24 colors).

Similar networks can be configured with serial buses, however the star is advantageous since it serves as both wavelength multiplexer and optical power distributor.

WDM COMPUTER INTERCONNECT DETAIL

Figure V-26



WDM FUNCTION
as well as
distribution

"CPU#1" AND PRIMARY INTERCONNECT BUS STAR
SHOWN

VI SUMMARY

This six man month level-of-effort results in a foundation for specific detailed fiber optic bus designs as NASA system concepts evolve. This was accomplished through component state-of-the-art evaluations and projections for use in system analysis. The systems analysis provides a 1553 baseline for next generation aircraft, which also served to identify functional requirements. The approach used is summarized in Figure VI-1. Subsequent generation platforms are not definitized; thus the analysis was treated generally by decomposition of complex networks into dedicated structures, star buses, and serial buses. Wavelength multiplexing and switched bus were considered. Example buses with top level tradeoffs were presented.

Figure VI-2 summarizes some of the problem areas identified that require additional development. Source reliability presents a major problem for achieving 10^9 hours/failure. Other component development in the areas of connectors for avionic use (especially for bulkhead penetration), optical access couplers, wavelength demultiplexers, optical switches, and loss reduction on all fronts should proceed to maturity with no severe problems. Additional efforts to establish procedures for fiber system operation and maintenance (O&M) are required.

The system analysis resulted in detailed comparisons of dedicated links, star buses, and serial buses with and without full duplex operation and with considerations for terminal-to-terminal communication requirements. This baseline was then used to consider potential extensions of busing methods to include wavelength multiplexing and optical switches. Figure VI-3 summarizes some of the advantages of these techniques.

Example buses were illustrated for various areas of the aircraft as potential starting point for more detail analysis as the platform becomes definitized. As this occurs, future studies can modify the baselines presented here and perform detailed tradeoffs not only in terms of

BUS STUDY - SYSTEMS ANALYSIS APPROACH

Figure VI-1

- PARTITIONED vs INTEGRATED SYSTEMS
  - 1553 BASELINE IDENTIFIED FUNCTIONAL REQUIREMENTS (FUNCTIONS LOOSELY TIED TOGETHER BY HIGHER LEVEL SYSTEM)
  - INTEGRATE FUNCTIONS AND DISTRIBUTE AMONG SEVERAL (FAULT TOLERANT) COMPUTER BAYS
- COMPLEX NETWORKS RESULT FOR EITHER APPROACH

  DECOMPOSE THESE INTO: DEDICATED (POINT-TO-POINT) LINKS
  STAR BUSES
  SERIAL BUSES
- ANALYZE AND COMPARE THESE SIMPLER BUILDING BLOCKS

BUS STUDY - COMPONENTS

Figure VI-2

HUGHES

- SOURCE LIFETIME PRESENTS POTENTIAL RELIABILITY PROBLEMS
- CONNECTORS FOR AVIONIC USE MUST BE DEVELOPED (BULKHEADS)
- WAVELENGTH DEMULTIPLEXER, OPTICAL SWITCHES LOSSES MUST BE REDUCED
  WDM SHOULD ACCOMMODATE UP TO 25 COLORS
- IN LINE LOSSES (CONNECTORS, TAPS) MUST BE REDUCED FOR SERIAL NETWORKS
- FIBER O & M PROBLEMS MUST BE OVERCOME

- WAVELENGTH MULTIPLEXING
  - Overlay Parallel Channels on Same Network To:
    - Increase Data Rate/Simplify Electronics
    - Separate Functions - Support Multiple Protocols
    - Allow Control Functions (Such as Interrupt Lines, Clocks, Disable "Babbling Terminal", etc.
    - Provide Multiple (Electronic) Redundancy on Some Physical Channel for Increased Reliability.

- OPTICAL SWITCHES
  - Higher Reliability by Reconfiguration if Fault Detected
  - Dynamic Reconfiguration for Message Routing

communication performance, but other important parameters as well, such as weight, reliability, operation and maintenance, and life cycle cost.

In general, fiber optics appears to offer a number of advantages for future avionic system designs, especially in the area of computer-to-computer interconnects and transfer of other high-speed signals. These advantages are partially offset, at present, by some technical problems and cost, both of which are rapidly improving through ongoing intensive development on all fronts.

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