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NAVAL POSTGRADUATE SCHOOL Monterey, California



THESIS

APPLICATIONS
OF
HIGH SPEED NETWORKS

by

Olav Kvaslerud

September 1991

Thesis Advisors:

Dr. G. M Lundy

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This thesis discusses the utility and application of high speed networks in the evolving technological environment of communications. In the early sections of this work the primary thesis explicitly presents the properties of fiber optics, existing and developing high speed networks, and applications of these high speed networks. The analysis and validation of this thesis leads to two major postulations.

The first investigates the possibility of replacing the current communication network for the Aegis real-time combat system aboard Naval ships with a dual optical fiber ring. This network would consolidate all sensors, weapons, electronic equipment, and computers into a single communication network, possessing a simple topology, higher data transfer capability, and enhanced security. The network has also been designed to accommodate the projected requirements of the next generation of surface combatant. The future system is expected to build upon the current Aegis combat system architecture, becoming more complex but remaining a well integrated and easily operable combat system. A high speed network based on FDDI (Fiber Distributed Data Network) can satisfy the demand for more bandwidth, integrating both real-time and other communication services aboard a ship. This paper supports the view that FDDI can not only successfully replace the current communications in a ship's combat system, but also provide an enhanced level of operation. There are also several other advantages which are quite significant. These include a significant reduction in weight and volume, and reduced susceptibility to electromagnetic interference.

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The second major construction is the configuration of a hospital health care system utilizing a high speed network. The hospital network would connect the medical hardware, electronic equipment, and computers into a single network. It is projected the intern-hospital network will interface with an external network employing emerging telephone transmission capabilities. The speed networks based on Distributed Queue Dual Bus (DQDB) and SYNchronous Optic Network (SONET)/ Asynchronous Transfer (ATM) can satisfy the demand for more bandwidth, integrating services such as voice, video, image, and text.

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***APPLICATIONS
OF
HIGH SPEED NETWORKS***

by
Olav Kvaslerud
Major, Norwegian Air Force
Bachelor of Science, University of Oslo, 1982

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

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I. INTRODUCTION

A. INTRODUCTION AND MOTIVATION

This thesis discusses the characteristics of high speed networks in regard to their suitability and applicability as the primary medium of the communications systems of the future.

The exploration of this theme, and the research that supports it, has been motivated by a rapidly evolving set of conditions, which includes (1) prospects for local, metropolitan and wide area networks having a capacity of 100 megabits per second or more; (2) continuing refinement of fiber optic technology and emerging price structure that makes it increasingly competitive; (3) the continued pace of advancing semiconductor technology; (4) the development of a body of specific application technology; (5) the availability of inexpensive chips that possess enormous capacity for computation and storage; and (6) the overall inadequacies in existing software technology that in the short term prevents these technological advances from being productively exploited.

Transmission protocols that successfully bridge the incompatibilities between underlying topologies have been devised. Likewise, data translation mechanisms which permit data encoding between disparate systems have also been developed. These advances have created the opportunity for interconnecting multiple computers at a single site (e.g., corporate office, or research center) with other computers that are separated by great distance. The result is that computer networking is becoming an increasingly prevalent practice. And the extension of the concept of networking to include systemic contact between varied and separate locations is proceeding at an even accelerating pace, creating the imminent prospect of ever larger mega-networks.

Given the clear and present trend towards networking, this thesis represents the view that high speed networks would not only introduce an array of advantageous features, but are in fact indispensable to the operation of the emerging communications environment. Directly applicable to systems comprised of extended computer interconnections are the characteristic properties of high speed networks, low error rates, high bandwidth, low latency, full connectivity, reliability and simplified maintenance.

To appreciate the advantage and necessity of implementing high speed networks, consider that several existing computer communications require between 1 and 100 megabits per second, and future applications might increase it by at least one order of magnitude. It is sufficient to note that on a 100 megabits per second networks, the transmission time would be a small fraction of one millisecond for most applications, and from one to a few seconds for applications with very high information volume. Though the obvious attraction and demand for higher bandwidth is often cited as the motivating factor for adopting high speed networks, features such as guaranteed response time (real-time), potential for enabling numerous multimedia utilizations, and inherently greater reliability may be of equal importance.

This thesis examines and synthesizes a far reaching range of information in order to ultimately pursue the goal of proposing a hybrid architecture that is applicable, in a practical manner, to network based distributed systems. The integration of fiber optic technology, the characteristics and potential configurations of high speed networks, as well as ongoing trends in computer research have been assimilated into a symbiotic model of the future.

The architecture for two hypothetical systems, one for naval surface combat and the other for hospital information, are presented within this thesis. Both have been designed in the hopes of fulfilling the multiple objectives of highly efficient communication, site autonomy, reliability, simplified construction and maintenance and cost effectiveness.

B. METHODOLOGY

This research was performed in accordance with the experimental scientific method: a general thesis that the implementation of high speed networks would be feasible in numerous applications was first developed. Then a careful review of existing fiber optic technology, existing and developing high speed networks, and an analysis of the existing and emerging applications was undertaken to confirm this hypothesis. The validation of this thesis is the basis for the primary thesis presented in the following chapter.

C. OVERVIEW OF THESIS

Chapter II, entitled High Speed Networks, is the formal introduction to this subject. After a brief history of fiber optics, a detailed discussion of fiber optics and the most promising high

speed network are presented. Finally, Chapter II concludes by analyzing the commercial advantages of installing high speed networks.

The focal point of this thesis is contained in Chapters III and IV. These chapters present a configuration of a new communication model for a naval combat system and a hospital information system. In Chapter III a communication architecture for a naval combat system is suggested. A careful analysis of the communications requirements is performed and evaluated against expected capacity of high speed networks. In Chapter IV a communication architecture for a hospital information system is suggested. As in the previous chapter, the estimated requirements were compared with the capability of several high speed networks, including FDDI, DQDB, and SONET/ATM.

D. CONVENTIONS

Each chapter in this thesis is comprised of lettered sections. A chapter number and a section letter must be combined to identify a specific section in the context of the entire thesis.

Italics are used when new terms are introduced, for lower case variables, and for emphasis. Quotation marks are only used for unusual terms. The appendix contains a detailed list of all acronyms with the full text.

Over 30 tables and figures are included; they are an integral part of this document and should be carefully considered along with the text.

II. FIBER OPTICS AND HIGH SPEED NETWORKS

This chapter provides the reader with the necessary theoretical background concerning fiber optics and high speed network communication. More generally, it provides the perspective for the emphasis that this document places on applications of high speed networks.

This chapter proceeds according to the following plan: Section A first introduces basic theoretical information about fiber optics that is useful in understanding the possible advantages of its use in communication. Section B and C provide basic theory in network topology and methods of network access. Section D surveys the current status of high speed networks. This survey enables us to classify the range of applications into categories according to users requirements. Finally, section E demonstrates the need for high speed networks. Before debating the implementation and design of high speed networks, the need for gigabit per second services for an end user will be justified.

A. FIBER OPTICS

1. Brief history

Communication by means of signal fires, lamps, sunlight-mirror and Morse code has been carried out for centuries. All of these methods of communication have shown the utility of light transmission, and are precursors of fiber optic transmission.

Advances in technologies surrounding the telephone and telegraph in the past one-hundred years have formed the basis of a vast growth in information exchange. As early as 1890 the first mechanism of voice transmission via light was carried out by Alexander Graham Bell [Ref. 64] The *photophone*, as it was called, used sunlight reflected off a voice-operated mirror to send signals through the air to a selenium receiver. The transmissions were limited by weather conditions, line of sight and were very low in bandwidth. In 1966 Standard Telecommunications Laboratories in England proposed that a glass optical waveguide might make communication by light practical. Corning Glass Works announced in 1970 the development of an optical fiber having a loss of only 16 decibels per kilometer (dB/km). In 1976 NASAs Kennedy Space Center together with Corning developed and installed the first optical fiber system to replace underground copper cable [Ref. 20]. The system remains in use today.

In the same year AT&T installed the first experimental optical fiber telephone link in Atlanta, and a year later the first operational link was installed by GTE in Southern California.

The focal points of transmission technologies are electricity, electro-magnetics and light transmission. Primarily, electrical signals were sent via copper wires to interpreting devices (telephones, sensors etc.). Electro-optics is a field of transmission physics that is a progression of the earlier efforts. This area is especially concerned with conversion of electrical power into optical power. The reverse procedure, converting optical power into electrical power is the field of optoelectronics. In the field of communication, optical waveguides are increasingly utilized as an alternative to copper wires.

2. Principles of fiber optics

a. Fiber Construction

An optical fiber is designed to direct and guide light over a distance or path that may be curved. The source or transmitter places light of infrared wavelength into the fiber that reflects the *lightwave* inward from the boundary wall and thereby through the medium. At the receiver, the lightwave is recovered and usually converted back into an electrical signal.

Modern optical fibers are constructed of either germanium-doped silica (sand) glasses or polymethylmethacrylate plastic (plexiglass). The high purity glasses or plastics are normally drawn into geometric cylinders. A tube filled with an appropriate fluid may also serve as an optical waveguide. Optical fiber does not have to be circular in construction; flat or planar construction may be easier to splice or couple. Optical fiber sizes range from 5 micrometers (μm) in diameter (about the size of human hair) to 140 μm . The size of the optical fiber with protective plastic coating is approximately 1 millimeter (mm).

b. Physics of Optical Fiber

Light, in theory is said to have a dual nature. It can be viewed as a discrete particle or a series of continuous waves. As a practical matter, wave theory provides a working explanation for the process of light propagation within fibers. *Reflection* is the bending or return of a ray that hits a medium boundary. The angle of incidence is equal to the angle of reflection. *Refraction* is the bending of light rays as they pass through the boundary of one transmission medium to another medium.

Optical fiber consists of an inner core of glass with a high index of refraction (n_1) surrounded by a cylindrical outer coating of glass with a lower index of refraction (n_2). Light is trapped in the core by total internal reflection at the core/cladding boundary. According to Snell's Law, when a light ray traveling in a more dense medium n_1 strikes a boundary with a less dense medium n_2 , a portion of the light passes into the less dense medium and the remainder is reflected back into n_1 . When the light strikes at a more shallow angle more light is reflected until the *critical angle* is reached. At angles smaller or equal to the critical angle no light passes through the boundary, resulting in total internal reflection. Figure 2-1 depicts the cross-section of an optical fiber.

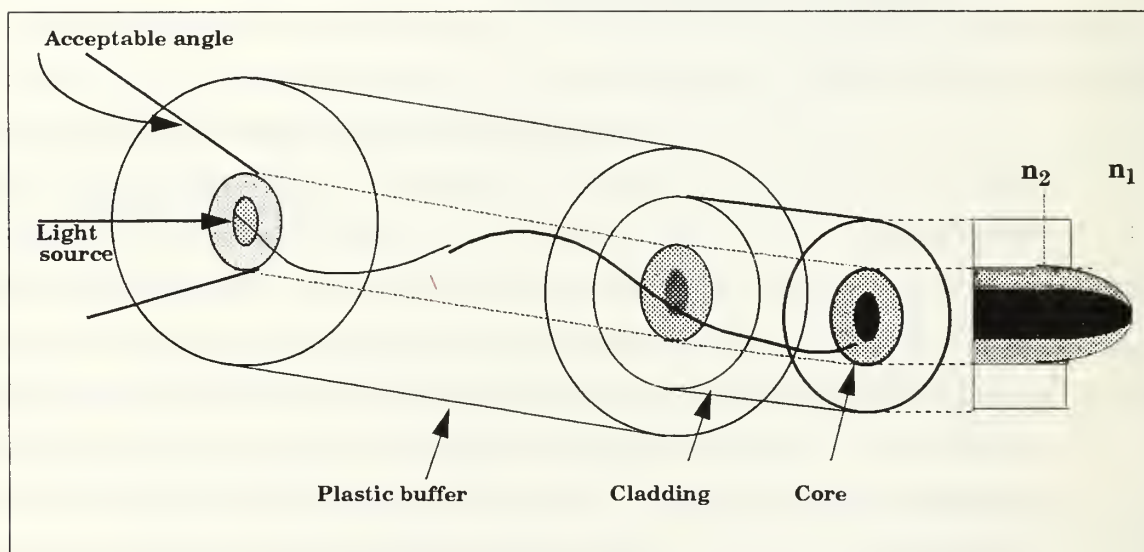


Figure 2 - 1. Cross-section of an optical fiber

Light sources transmit the light waves through the air to the face of the fiber. The incident face of the optical fiber must be polished to ensure the best transmission of light. The angle at which the light is inserted into the fiber must be within the *acceptance angle*.

$$\begin{aligned} \text{Cosine (critical angle)} &= \text{Cladding Refractive Index/Core Refractive Index} \\ &= \text{Cos}(\theta) = n_2/n_1 \end{aligned}$$

The optical fiber numerical aperture (NA) is the sine of the acceptable angle. This defines an acceptance cone within which all rays will enter the fiber [Ref. 34].

c. Optical Source

The optical source converts electrical signals to light. Long-haul telecommunications demand very expensive components called *laser diodes* (LD), while *local area networks* (LAN) normally use *light emitting diodes* (LED). Commercial manufacturers categorize LEDs by the wavelength of the light produced as well as the maximum optical power available. They can launch about 20 microwatt (μW) into a multi-mode fiber, and operate reliably at bandwidths of 100 MHz. LEDs operate by discharging radiated energy as a function of the current flowing through the device. LDs are semiconductor devices that operate on the same principles as LEDs but offer increased optical power and higher modulation rates. A laser diode couples about 1 milliwatt (mW) of light into a single-mode fiber, and operate at bandwidths of 50 MHz to 10 GHz. Because of more complex drive circuitry the LD cost about twice that of LED. In most cases, the source transmits at near infrared (see Table 2-1) wavelengths to take advantage of the greater transparency of the medium in that region of the spectrum [Ref. 64]. The most commonly used wavelength windows are 850, 1310 and 1510 nanometers (nm).

Table 2 - 1. ELECTROMAGNETIC FREQUENCY SPECTRUM

| Name \ Wave- | Frequency | Intl units | Length | | Use |
|-----------------|--------------|------------|----------------------|---------------|-------------|
| | | | Meters | Intl units | |
| Gamma rays | 10^{21} Hz | | $3 \cdot 10^{-13}$ m | < .1 nm | |
| X - Rays | 10^{18} Hz | | $3 \cdot 10^{-10}$ m | .1-10 nm | |
| Ultraviolet | 10^{15} Hz | | $3 \cdot 10^{-7}$ m | 10-400 nm | |
| Visible light | | | | 400-700 nm | |
| Infrared light | 10^{12} Hz | 1 THz | $3 \cdot 10^{-4}$ m | 700nm-1000 nm | Fiber optic |
| Microwave | 10^9 Hz | 1 GHz | .3 m | 1-100 mm | Micro wave |
| Radio | 10^6 Hz | 1 MHz | 300 m | 1mm-100 km | Short wave |
| Voice frequency | $< 10^3$ Hz | < 1kHz | $> 3 \cdot 10^5$ m | | Audio |

d. Optical Fiber

Fiber optic cables are classified into two categories, *single-mode* and *multi-mode*. The single mode fiber, by definition, is one that carries light in only a single waveguide mode.

Single-mode fiber systems are most commonly found in long-haul applications or when high transmission capacity is necessary. Due to their inherently higher capacity for transmission, the use of single mode fibers has become dominant in the industry during the last five years. Though single-mode fibers demand relatively expensive components, such as laser diodes and *avalanche photodiodes* (APD), the cost of components has been justified by the very high data rates produced and the ability to reduce the number of repeaters. In LANs, multi-mode fiber is normally a better choice. In multi-mode optical fiber, simpler and cheaper components such as LEDs and *positive-intrinsic-negative* (PIN) photodiodes are used. Multimode fibers are also easier to splice and connect.

Four different types of multi-mode fiber are presently available on the market. The fiber types are normally separated by giving the geometric dimension on the core/clad: 50/125, 62.5/125, 85/125 and 100/140 μm . The availability of several multi-mode optical fibers complicates deciding on the right choice, but also allows the network-designer flexibility in choosing the fiber best suited for the specific application. The parameters that impact physical feasibilities are: the core/clad geometry, the numerical aperture, the index of refraction, and sensitivity to bending. The most commonly used type of multi-mode fiber is the 50/125 and the 62.5/125 fiber [Ref. 45].

Step-index characterizes a fiber that has an abrupt or step changes in the refractive index between core and cladding. In order to reduce the effect of dispersion and increase the bandwidth-distance graded index fiber are replacing step index fiber. In the graded index fiber, the light rays are repeatedly bent towards the fiber axis rather than reflected at the core/cladding boundary. That is, the fiber may have layers which are designed to smoothly bend the rays towards the axis. Theoretically, all ray paths will reach the detector at the same time. But in any given fiber, only a limited number of angles in accordance to the laws of electromagnetism are permitted within the pathways, and they correspond to a specific number of modes, similar to the modes in metal waveguide carrying microwaves. When a fiber core radius is many times the propagating wavelength, numerous optical modes may be placed inside it. As the size of the core is reduced, fewer modes are accommodated. A single-mode guide results when the core dimensions are on the order of the wavelength. Single mode fiber

has a core diameter of two to twelve μs . Figure 2-2 depicts single and graded multi-mode fibers [Ref. 20].

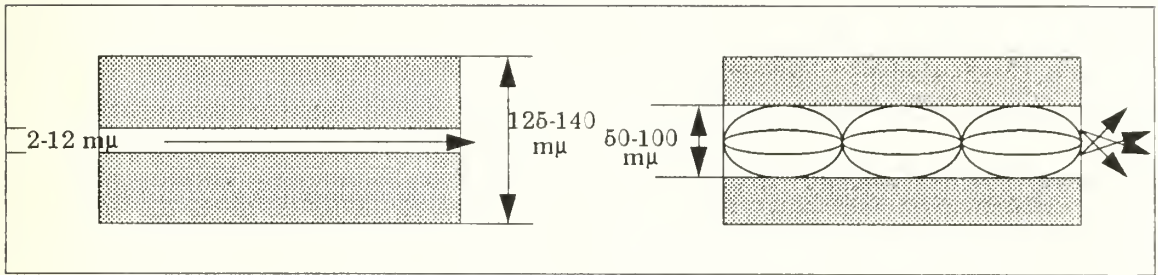


Figure 2 - 2. Single-Mode Fiber (left). Multi-Mode, Graded Index Fiber (right)

The pulse of light in a multi-mode will tend to spread as it travels through the fiber; if the train of pulses are spaced close enough, they will overlap and appear as one long pulse at the fiber output. This phenomena is called modal dispersion, and sets definite limits upon the length of the fiber (L) and number of pulses that can be transmitted per second (bandwidth, BW). The bandwidth-distance ($L \cdot BW$) product is an important figure in the merit of the fiber. To put the different optical fiber bandwidths into perspective, a telephone call requires a 4 KHz bandwidth, while a television channel requires about 6 MHz. Thus, a single mode with 200 GHz bandwidth-distance product can theoretically carry $5.0 \cdot 10^6$ phone calls and $3.3 \cdot 10^4$ television channels, a distance of 1 km. Table 2-2 depicts the impact wavelength, fiber-type and distance have on the bandwidth [Ref. 45, 64].

The type of fiber determines the cost and precision of cable connectors. A connector is required to align the end of the fiber with the source/detector to minimize loss of optical power. To attach an end connector to a fiber cable, the protective coat and cladding must be cut away. The exposed fiber must then be cleaned and placed into the connector with a portion of the end of the fiber extended. An optical sealant is used to hold the fiber in the proper position, and the exposed portion carefully cleaved at the connector face. Typical connector attenuation is less than .3 dB. Splices are performed in a similar fashion and induce about 1 dB loss for each splice. Optical fiber connectors are much more difficult to attach and more critical to performance than metallic connectors.

Table 2 - 2. OPTICAL FIBER PARAMETERS AND BANDWIDTH LIMITS

| Diameter core/clad | Fiber type wavelength (nm) | Bandwidth-distance product GHz-km | 100 m fiber | | 10 km fiber | | Relative Macro-bend loss(dB) |
|--|----------------------------|-----------------------------------|---------------|---------------------|---------------|---------------------|------------------------------|
| | | | Bandwidth MHz | Digital-TV channels | Bandwidth MHz | Digital-TV channels | |
| 60/125 μm multi-mode graded | 850 | 175 | 1750 | 8 | 50 | 0 | < 1.0 |
| | 1310 | 500 | 5000 | 25 | 150 | 0 | |
| 50/125 μm multi-mode graded | 850 | 300 | 3000 | 15 | 90 | 0 | 1.0-2.0 |
| | 1310 | 1000 | 10,000 | 50 | 300 | 1 | |
| 10 μm single-mode | 1310 | 200.000 | 2,000.000 | 10,000 | 60,000 | 300 | |

NOTE: Figure for Television channels are based on FM-digitized Television with a bit rate of 100 Mb/s and a subcarrier channel spacing of 200 MHz.

e. Optical Detector

The optical detector (receiver) converts the optical signal back into an electrical signal. The receiver can be seen as the most critical element to system performance. The receiver must correctly detect optical modulation and transfer the extracted information. The detector consists of a light sensitive, reverse-biased diode: either a PIN photodiode for multi-mode fiber or an ADP for single-mode fiber. In either case the detector is chosen for maximum sensitivity at the wavelength produced by the source. As with the optical source, detectors are determined by the wavelength used. Gallium-aluminium-arsenide detectors are used for the first wavelength window and indium-gallium-arsenide detectors are used for the two higher wavelength windows.

B. TOPOLOGY

Network topologies determine the physical and logical arrangements of the stations on the network. The logical topologies are identical to those found in copper wire networks. To date, the fiber optical topologies proposed for implementation are linear (bus), ring, star and mesh topologies, or hybrids of these. A network topology can be evaluated by determining the maximum number of stations that can be supported in relationship to the power requirements of the receiving stations.

1. Linear topology

The linear topology uses the passive “T” coupler or taps to couple optical power from a linear succession of stations. A coupler is a passive optical device that connects a given numbers of fibers (1 or more) to a common node. Here the optical power from the input fiber is divided, usually, but not necessarily, on an equal basis, into all of the output fibers. The number of stations is limited by the optical power that can be launched into the fiber as well as the fiber size and total attenuation, which includes connector, splice and T-coupler losses. When any stations on the bus generates a signal, all other stations receive the signal. Whether they perform some action in response to the signal is a function of the protocol of the network.

One example of linear topology is the Distributed Queue Dual Bus (DQDB) network. The DQDB network is based on dual bus topology. Figure 2-3 depicts this topology.

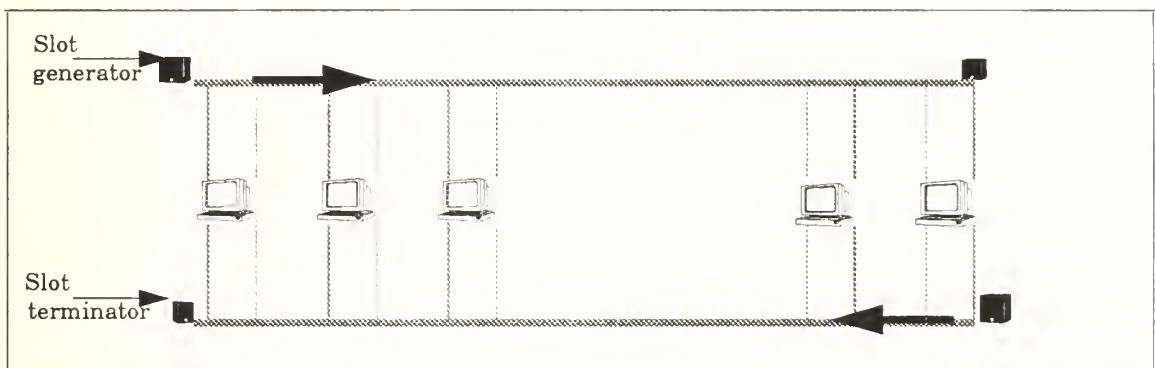


Figure 2 - 3. Dual linear (dual bus) topology

2. Ring topology

Rings are one of the more popular LAN topologies frequently used for fiber optic networks. It is important to note that a ring consists of a sequence of point-to-point connections, where each station, acting as a repeater in the transmission loop, forms a cycle. The various stations are only connected to their adjacent neighbor on the ring. The point-to-point connections take advantage of the high speed and low attenuation properties of the optical fiber. The ring can be either a single or dual ring. One example of the dual ring is the ANSI standardized Fiber Distributed Data Interface (FDDI) network [Ref. 56]. The FDDI network is based on a dual counter-rotating optical ring. This topology allows the network to continue operating in the event that one of the stations fails, or even if one of the point-to-point

optical fiber segments are defective. Figure 2-4 depicts the FDDI dual ring. Ring topologies are also very popular for networks of proprietary design. These networks are typically quite high in performance.

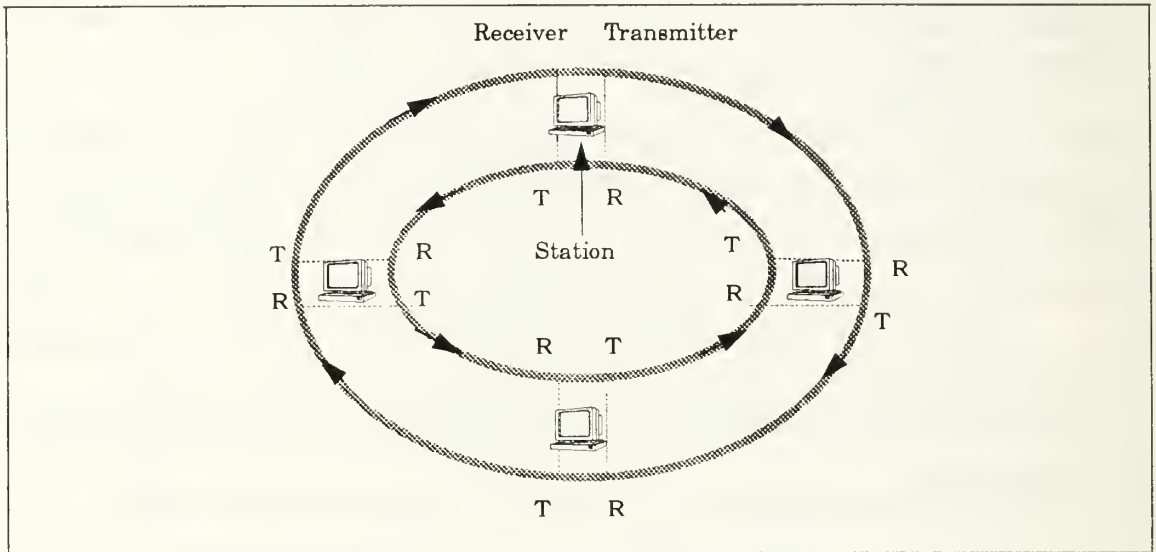


Figure 2 - 4. Dual counter-rotating topology

3. Star topology

With respect to star topology, it is interesting to note the passive fiber optical star topology is very similar to linear topology. In both cases a passive coupler is used for signal distribution. The electronic star center may be more than a repeater, providing complex functions such as message routing, error checking and network configuration. The normal star topology requires all of the fibers to be brought to a central distribution station. An expansion of the star configuration can be accomplished through the utilization of a number of star couplers, each serving a small cluster of stations (distributed configuration). Figure 2-5 depicts the distributed star topology. In any event, the fiber optic links connected to the center are similar to the point-to-point links previously seen in ring networks.

Star topology displays the attraction of avoiding the losses that results from using numerous concentrators. Reasonably large networks (several hundred nodes) are practical when using active star optical networks. In addition, an active star can include a source of intelligence at its hub, thereby simplifying network access protocol [Ref. 56].

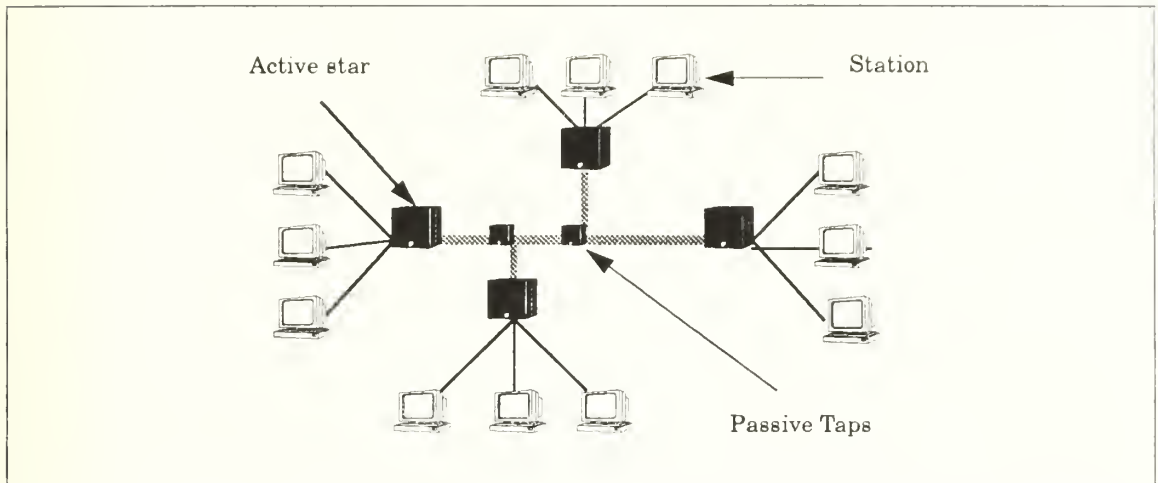


Figure 2 - 5. Distributed star coupler topology (Active, passive star)

4. Mesh topology

In networks where very high reliability is required the mesh topology can be used. This topology uses totally redundant links to interconnect all the nodes of the network. The disadvantages entail considerably more cabling, hard and software complexity, and additional costs.

C. ACCESS METHODS

Access methods, or protocols, determine how the network resources are made available to the stations attached to the LAN. High speed media access schemes can be divided into three main classes: demand assignment, fixed assignment and adaptive assignment access protocols.

1. Demand assignment

The demand assignment access method orders message transmission on the media by serving the stations in acyclic or non-cyclic order. The access protocol is normally based on ring or linear topologies.

Typically the ring systems are token rings or slotted rings. In a token ring network an enabling digital packet is continuously passed from station to station. A station can claim the token and thus control information transfer on the network, releasing the token upon completion. The token is passed around the ring sequentially, from station to station. This protocol permits true distributed processing. A representative of token ring protocol is FDDI.

In the slotted ring, a constant number of fixed length slots continuously circulate around the ring. An indicator in the slot header signals the status of the slot. Any station ready to transmit can occupy the first empty slot by setting the indicator to "full" and place its data into the slot. The release of the slot can be initiated by either source or receiver. The Cambridge Backbone Network (CBN) is a representative fiber optic 600 Mb/s network that incorporates source release.

Like some of the slotted rings, the unidirectional buses (linear topology) integrate traffic of varying priorities by means of rounds. The rounds are generated by a central master station or distributed among the stations. Access to the media follows three basic schemes: random access, polled access and reserved access. Random access schemes employ contention protocols that allow stations to compete for network resources in such a way that collisions may occasionally occur. Means are provided, however, to detect collision and avoid deadlock. An example of this type of safeguard is Carrier Sense Medium Access/Collision Detection (CSMA/CD) protocol [Ref. 50]. Following this protocol, when a station is ready to transmit, it first senses the media and only transmits if the media is idle. The polled access method is employed in unidirectional bus networks, where a central master station polls each station for transmission requests. The stations are numbered according to their upstream positions, which, in turn, governs the right to transmit. An example on this protocol is *Logical Integrated Optical Network* (LION). In the reserved access scheme, stations alternate reservations and transmissions. Station agree upon the next station to transmit, prior to transmission. An example of a network employing a reservation access scheme is Distributed Queued Dual Bus (DQDB), which was originally known as Queued Packet and Synchronous Exchange (QPSX).

2. Fixed assignment

Fixed assignment protocols represent another class of medium access protocols. The total network bandwidth is divided among the attached stations in terms of time, frequency or wavelength domain fixed design. Each station is then assured access to the media's capacity. The protocols are referred to as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) or Wavelength Division Multiple Access (WDMA) [Ref. 50]. These access schemes are potentially well suited for future applications in ultra-fast fiber optic

networks (10 - 500 GBPS). The topologies commonly used in these access methods are star or ring configurations.

TDMA may be performed either synchronously or asynchronously. Synchronous TDMA implies that only one user transmits at a time. The scheme requires each station to have a fixed time slot, whether communicating over the network or not. Asynchronous TDMA permits time slots to be created only when needed for communication between stations of the network. FDMA and WDMA respectively are electronic and optical methods. For combining a number of information channels onto a single optical fiber, thereby allocating the fiber bandwidth among the stations. Although these techniques have been used effectively, they restrict the number of network stations due to limitations imposed by the optoelectrical component. A representative TDMA network is SONET/Synchronous Transfer Mode (STM).

3. Adaptive assignment

The last media access protocols widely used is adaptive assignment. These protocols are hybrids that combine random and controlled assignment access. Under conditions of low transmission rates, a station senses the medium and transmits when the medium is idle. When the data load increases, creating possibilities for collisions, the protocol switches over to more restrictive collision-free methods, such as token passing or TDMA [Ref. 50]. A protocol may also change access methods according to the type of service (message) that is transmitted.

When ATM is used to carry Broadband Integrated Services Digital Network (BISDN) signals it may be imbedded in the SONET frame. It should not come as a surprise then that the near term solutions to commercial applications will involve a hybrid SONET/ATM approach to support user services on both STM and ATM channels.

D. HIGH SPEED NETWORKS

During the last ten years more than sixty different media access protocols for networks operating in the region of 50 Mb/s to 1 Gb/s have been reported [Ref. 55]. Given the additional requirements in capacity to service high speed local, metropolitan and wide area networks, current design standards and planning are being developed that utilize a fiber optic transmission base. The design and implementation of a network often results in complex channel access schemes for optimizing the delay, throughput and fairness of the network. This

is particularly true in high-speed networks, because they often support multimedia transmission (e.g., voice, video and data). Typically, complicated access procedures and data buffering must be executed very quickly to match the data transmission rates of optical fiber. In this section the most relevant of current and emerging standards for local, metropolitan and wide area networks are described. Table 2-3 depicts the data transmission rates for these networks.

Table 2 - 3. HIGH SPEED NETWORKS PERFORMANCE

| Data rate Mb/s Networks | 100 | 155 | 200 | 300 | 600+ | 800 + | 900 + | 1200 + | 1800 + | 2400 + |
|--|------------|------------|------------|------------|-------------|--------------|--------------|---------------|---------------|---------------|
| FDDI | • | | | • | | • | | | | |
| DQDB | | • | | | | | | | | |
| LION | | | | | • | | | | | |
| CBN | | | • | | | • | | | | |
| SONET/ATM | | • | | | • | | • | • | • | • |

1. FDDI AND FDDI-II

a. FDDI

The American National Standard Institute (ANSI) Committee X3T9.5, which is responsible for defining FDDI (Fiber Distributed Data Interface), has been working to develop a standard for several years [Ref. 30]. Now after several recent public interoperability tests and demonstrations, user confidence in FDDI points to the possibility that it may become the new standard LAN technology of choice in 1990s [Ref. 23]. The committee used the existing IEEE 802.5 token ring standard as the basis for FDDI. Consequently, FDDI bears some similarity to the IEEE 802.5. Though their functions are similar, FDDI offers a much greater bandwidth. The X3T9.5 committee adopted the 802.5, making necessary changes in order to exploit the higher speed of the fiber ring. The data packets (frames) employ the same 48-bit address structure defined in IEEE P802 LAN protocols.

FDDI provides a 100 megabits per second (Mb/s) high bandwidth general purpose interconnection among computers and peripheral equipment. FDDI uses two counter-

rotating rings, called the *primary* ring and the *secondary* ring. Data traffic usually travels on the primary ring. The secondary ring operates in the opposite direction and is available for fault tolerance. The two fiber-optic counter-rotating token rings control the access to the medium. The fiber path accommodates up to 1000 physical connections on a maximum of 200 kilometers (km). These values permit a configuration of 500 stations (nodes) on a dual ring, with a maximum perimeter of 100 km. After receiving the token a station can send packets comprised of up to 4500 bytes of information. The Target Token Rotation Time (TTRT) controls each stations right to transmit. Priorities can be assigned to the stations by manipulating their TTRT. FDDI token-passing network accommodates synchronous and asynchronous data transmission. Synchronous service is for applications with very stringent requirements on delay time to channel access. Examples are packetized voice, video and real-time control messages. Asynchronous service supports applications which do not have such stringent channel-access requirements.

FDDI defines the types of stations based on the attachment to the dual counter-rotating trunk ring. One type is the dual attachment station (DAS), which has two ports and attaches directly into the trunk rings. One or more medium access control (MAC) entities configure the DAS. A second type of station uses a concentrator, single or dual attached (DAC), as a device to provide the attachment. A concentrator also has ports in addition to those required for its attachment to the FDDI ring. A DAC can attach directly to the trunk ring, and provide the capability to connect slave stations into either, or both, of the logical rings provided by the trunk ring. Single attached stations (SAS) connect only to concentrators, either Single or Dual Attached (DAC). A concentrator is a simple device with the advantage of a star topology, accomplished through connecting a series of stations (such as SAS, Figure 2-6) to the main dual ring.

For a number of reasons, the topology of FDDI has been defined as a dual ring. A ring offers, among other advantages, superior reliability, availability and serviceability. For example, the dual counter-rotating ring alleviates the problem associated with multiple points of failure within the network. If a station or link fails, the two counter-rotating paths wrap together around the fault, allowing communication to continue. A second consideration is that optical fiber can be easily accommodated to a ring configuration. Optical fiber offers high

bandwidth, best suited to bit serial transmission, thereby reducing size, cost and hardware complexity.

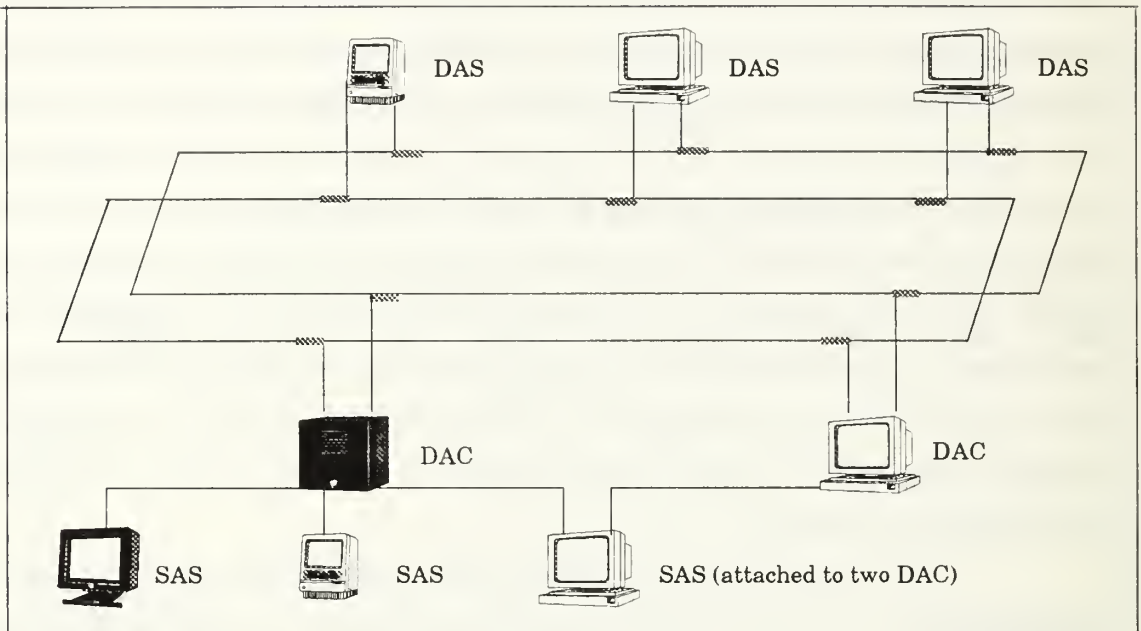


Figure 2 - 6. Dual ring with Dual and Single Attachment

The FDDI specifications relate to layer 1 and layer 2 in the OSI reference model. FDDI assumes the use of IEEE 802.5 standard, Logical Link Control (LLC). The basic FDDI standard is organized in four parts:

- Medium Access Control standard (MAC)
- Physical Layer Protocol standard (PHY)
- Physical Layer Medium Dependent standard (PMD)
- Station management standard (SMT)

The MAC is specified in terms of the MAC services and MAC protocol. The FDDI MAC provides a superset of services required by LLC (IEEE 802.2 LLC) or any higher level user. The interface includes facilities for transmitting and receiving protocol data units (PDUs), and provides operation status information for use in, higher-layer, error recovery procedures. The specifications define the frame structure and interactions that take place between MAC entities. In general, MAC specifies access to the medium, addressing, data

checking, frame format, and frame content interpretation.

The PHY defines the physical layer services and addresses the data encoding/decoding, clocking, and data framing. The physical layer services are defined in terms of primitives and parameters. These primitives support the transfer of data from a single MAC entity to all MAC entities contained within the same local network defined by the medium. The data encoding scheme is specified by using a code referred to as 4B/5B. In this scheme, encoding is done four bits at a time; each four bits of data are encoded into a symbol with five cells so that each cell contains a single element (presence or absence of light). In effect, each set of four bits are encoded as five bits. 100 Mb/s is achieved with 125 Mbaud. The 4B/5B is further encoded using Non Return to Zero Inverted (NRZI) [Ref. 23]. Employing differential encoding, NRZI has proven itself to be a reliable means of detecting transition in the presence of noise and distortion. This reliability consideration is due to the signal being decoded by comparative changes of polarity in the adjacent signal elements rather than the absolute value of a signal element.

The PMD defines the physical medium and specifies its related components, and medium characteristics. This standard specifies an optical fiber ring with a data rate of 100 Mb/s, using NRZI-4B/5B encoding scheme. The wavelength specified for data transmission is 1310 nanometers (nm). The specification indicates the use of multimode fiber transmission. The maximum distance between adjacent stations is two km.

The SMT defines the FDDI station and ring configurations, and specifies the controls required for proper operation and interoperability of stations in an FDDI ring. SMT is divided into three broad categories [Ref. 49]: Connection Management, Ring Management, and Operation management. These are multiple stations services for the purpose of achieving proper operation and interoperability.

The effective sustained data rate at the data link layer can be well over 90 percent of the peak rate [Ref. 30, 31]. Recent work on improving the performance of FDDI indicates that a throughput of 300 Mb/s or more may be possible [Ref. 42, 43]. The improvements entail making use of the second ring, and introducing a subtoken into the system. Throughput is increased without altering the basic timing and token passing protocol. There are also FDDI networks under development with even higher data rates. An increase in transmission speed will lead to the incorporation of single-mode fiber and Laser Diode (LD)

transmitters, which is what the ANSI X3T9.3 has suggested for the 800 Mb/s FDDI. The X3T9.3 Fiber Channel Committee chose in 1989 the IBM 8B/10B block code, which introduces more symbol possibilities than with 4B/5B encoding [Ref. 23].

b. FDDI-II

Networks that support multimedia communication must be able to handle voice, video and high-speed data communications in an integrated network. Networks that are more capable of handling multimedia communication are currently emerging, such as FDDI-II. FDDI and FDDI-II stations can interoperate directly using the standard FDDI protocol [Ref. 57]. FDDI-II integrates isochronous and packet data on the same FDDI medium by use of the *Hybrid Ring Control* (HRC). Hybrid Mode operation requires the presence of a HRC entity between the FDDI MAC and the FDDI Physical layer (PHY). This differs from Basic Mode (FDDI standard) in that both the FDDI token operation and isochronous data transfer are multiplexed onto the same medium. The transfer is accomplished by a dynamic allocation of bandwidth between packet and isochronous traffic in units of 6.144 Mb/s (16 bandwidth channels for connection-oriented service) [Ref. 54]. Every 125 μ s a new frame is inserted by a master station. After initialization FDDI-II remains in the Basic Mode until a user application needs to transmit isochronous data, such as voice. One possible interoperation strategy is to make use of the second ring to carry FDDI-II data, while the primary ring carries standard FDDI data. In time critical systems this facilitates the real-time requirements.

2. DQDB

The Distributed Queue Dual Bus (DQDB) *metropolitan area network* (MAN), has recently been standardized in IEEE working group 802.6. This group has defined these operational requirements for MANs; they should be capable of operating over areas of at least 50 km and should provide services with guaranteed bandwidth and access delay.

DQDB is based on two contrary-flowing unidirectional fiber optic 155 Mb/s buses. The activity on the media is controlled by a master station (slot-generator), one on each bus. This generates a continual sequence of 53 byte slots, that passes all down-stream stations. Each bus operates in an independent manner. Any station with data for downstream transmission can write into an empty slot. Each slot has a busy bit and request bit. The busy

bit is set whenever a station writes into a slot, so the other stations know it is in use. The request bit is used when a station wants to transmit; it signals the upstream stations (on the opposite bus) that it has entered the distributed queue. That is, all stations on a bus with data to send are seen as a queue, waiting its turn to get the next available slot.

The Distributed Queue is implemented through three counters; the CountDown Counter (CDC), the REQuest Counter (REQC) and the Bandwidth Balancing Counter (BBC) (see Figure 2-7). The request counter is incremented each time a slot passes on the opposite bus, with the request bit set. It is decremented when an empty slot passes, if the station does not have data to transmit (segment queued). The count down counter is used when the station has a segment queued for transmission. The current value of the REQC is copied into the CDC, and the REQC is reset to zero. The CDC keeps track of the number of downstream stations that are ahead in the queue. It is decremented each time an empty slot passes. When its value reaches zero, the next empty slot is grabbed, and the segment transmitted. Each station may only have one segment queued for transmission at a time [Ref. 46].

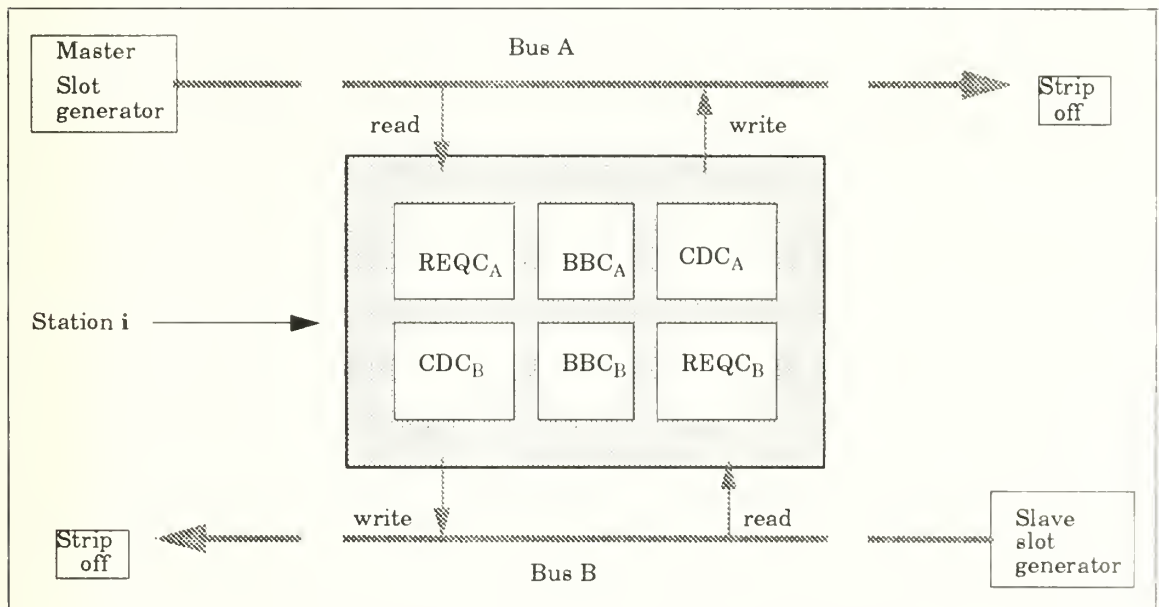


Figure 2 - 7. A station with its counters in a DQDB network

The protocol can support three level of priorities. For each there is a distributed queue. That is, in each station there are a total of three request counters and three countdown counters for each bus. The bandwidth balancing counter is used to keep the use of slots evenly

balanced between all stations. The station measures the idle capacity on the bus (request bits from downstream and busy bits from upstream), and computes the fraction α of the bus' bandwidth that the station may use. If the station's load is greater than this, the station allows an empty slot to "occasionally" pass. This is determined by setting a BBC value. It is decremented when an empty slot passes by. When its value reaches zero, the next idle slot is allowed to pass by unused (CDC is also zero) [Ref. 21].

The issue of fairness is a difficulty within this protocol. Inequities result from small slot size and a large network. That is, the propagation delay is much longer than the transmission time of a segment. This allows numerous slots to be in transit between widely separated stations. Therefore, stations geographically closer to the slot-generators have an advantage over downstream stations.

3. BISDN

The internationally agreed upon definition of *Integrated Services Digital Network* (ISDN) is a network evolved from the telephony integrated digital network (IDN) that provide end-to-end digital connections supporting a wide ranges of services, including voice and non-voice services, to which the users have access by a limited set of standard multi-purpose interfaces". The new ISDN interface enables the integration of telecommunication services by breaking them down into smaller components, called "bearers". A bearer service is a simple information carrier service, like a 64 kbit/s data service. These 64 kbit/s bearers are inadequate however for many applications in rapid inter-computer communication or video image transfer. In order to integrate of voice, video and data applications on the same network, a *Broadband Integrated Services Digital Network* (BISDN) is being developed. One of the most important reasons to implement BISDN is the existence of an international standard. The standardization work on BISDN was initiated in 1985. The discussion began by the definition of BISDN User Network Interface (UNI) and Network Node Interface (NNI) structure and channel rate. To resolve the different digital transmission hierarchies in the U.S., Europe and Japan it was decided to standardize the NNI by a unique worldwide Synchronous Digital Hierarchy (SDH). Figure 2-8 illustrates the worldwide unique SDH [Ref. 33]. The SDH specifies 155.52 Mb/s as the world wide unique interface bit rate. Two transmission rates have been identified for UNI: 155.52 and 622.08 Mb/s.

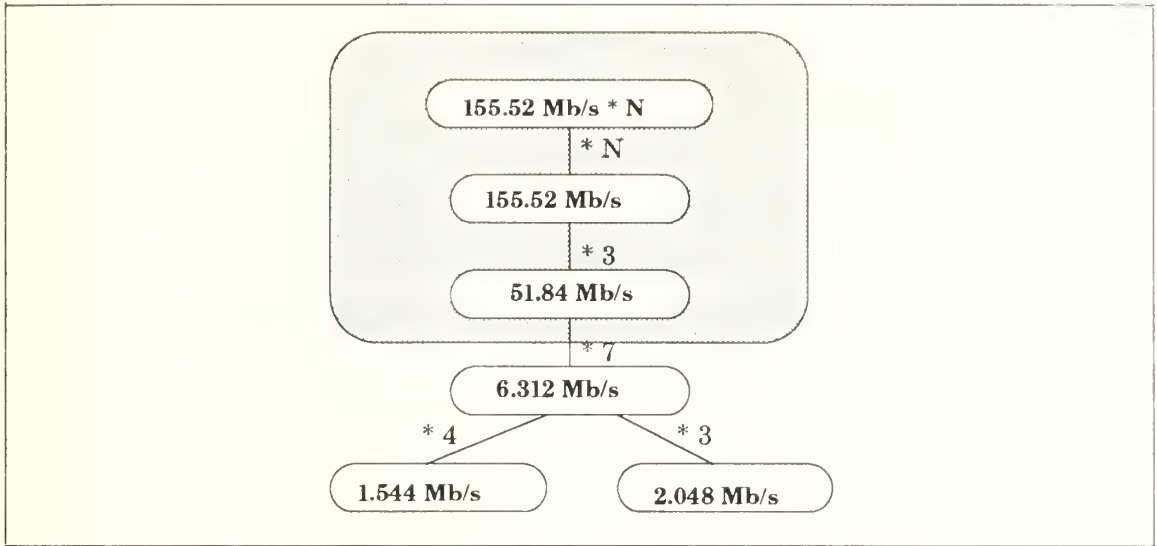


Figure 2 - 8. New Synchronous Digital Hierarchy (SDH)

Figure 2-9 depicts the hierarchical relationship of some of the functional layers required for information transfer across BISDN. The international standard on BISDN generically calls the switching and multiplexing aspects the “transfer modes.” Connection-less services, multimedia, and digital signal processing capabilities can all be included in BISDN as service modules.

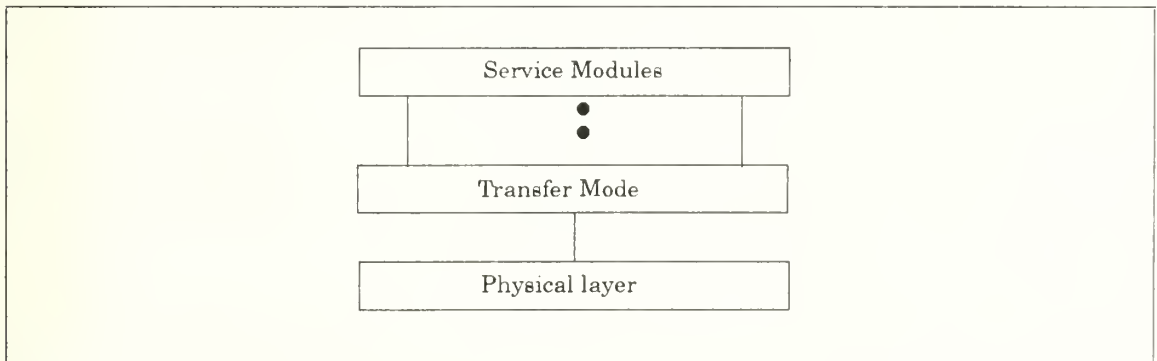


Figure 2 - 9. BISDN functional layers

To support the wide variety of services, two new standards have been proposed and are currently under intensive worldwide study. These are:

- Synchronous Optic NETWORK (SONET)/Synchronous Transfer Mode (STM)
- Asynchronous Transfer Mode (ATM) protocol

a. SONET

SONET (Synchronous Optical NETWORK) is the name of a newly adopted standard, originally proposed by Bellcore (Bell Communications Research) in Morristown, N.J. It specifies a transmission system for a broadband interface at the physical layer using framing techniques to transport information. SONET defines standard optical signals, a synchronous frame structure for multiplexed digital traffic, and operational procedures. SONET standardization began during 1985 in the T1XI subcommittee of the American National Standards Institute (ANSI) accredited Exchange Carrier Standards Association committee. As standardization progressed, two key challenges emerged. The first was to make SONET work in a plesiochronous environment and still retain its synchronous nature. The solution was obtained through the use of pointers indicating the phase of data payload within the overall frame structure. The second challenge was to break down incompatibilities between U.S. (based on 1.544 Mb/s) and European (based 2.048 Mb/s) signal hierarchies. The SONET concept was adopted by the CCITT in 1989 under the name Synchronous Digital Hierarchy (SDH). The features of the standard include [Ref. 5]:

- the virtual limitless bandwidth available with optical fiber technology. SONET's current maximum data rate of 2.5 Gb/s is the equivalent of 48 T3¹ lines, though this does not necessarily represent the limit;
- an optical interface allowing optical midspan meets between different supplier's equipment. A base rate of 51.84 Mb/s, the Synchronous Transport Signal - Level-1 (STS-1), was chosen to carry all signals in the North America hierarchy up to DS3²;
- the use of synchronous multiplexing and demultiplexing for simple combining of the channels to obtain easy access to SONET payloads and exploit the increasing synchronization of the network;

1. T3 and T1 -Transmission 3 and Transmission 1 - higher order digital bit speed, 45.736 Mb/s (T3) and 1.544 Mb/s= 24 channels * 64 kb/s plus 8 kb/s (T1)
 2. DS3 and DS1 - Digital Line system 3 and Digital Line system 1 - the digital signal that results from a conversion of an T3 or T1 signal

- an extensive network management, accomplished through the specification of a sufficient number of overhead channels and their functions to fully support facility maintenance;
- the asynchronous transfer mode (ATM) included in the SONET Phase II supplements. This feature will enable the protocol to accommodate both circuit and packet switching.

The *Optical Carrier* (OC) signals are the actual signals that travel across SONET optical connections. Until optics replace electronics as the basis for data processing equipment, it will be necessary to translate the electrical signals produced by the computers into optical signals. This is usually done inside the transmission device, multiplexer, switch, LD or other device physically connected to SONET optical fiber. An incoming signal to a SONET device is in a standard electrical format. The device adds overhead data to the signal to create a basic SONET electrical signal, called STS-1¹. Multiple STS-1 signals are multiplexed to create a higher speed ST Signal (corresponding to the OC signal rates). These ST Signals are then converted to the optical carrier signal. OC rates range from OC-1², which at 51.84 Mb/s is the equivalent of one DS-3 channel, to OC-48, which at 2.5 Gb/s is the equivalent of 48 DS-3s [Ref. 51].

The basic building block and the first level of the SONET signal hierarchy is called Synchronous Transport Signal - Level 1 (STS-1) transmitted at 51.84 Mb/s. The STS-1 is assumed to be synchronous with an appropriate network synchronization source. The STS-1 frame structure can be modeled as a 90-column by 9-row structure of bytes (8 bits) (see Figure 2-10) [Ref. 5]. The transmission order of bytes is row by row, from left to right, with one entire frame being transmitted every 125 μ s (which ties into the 64 kb/s sampling rate for voice signals which produces one byte every 125 μ s). The first three columns of the STS-1 contain section and line overhead. The remaining 87 columns contain the *Synchronous Payload Envelope* (SPE) which carries the data plus nine bytes Path overhead. Since overhead takes about 1.7 Mb/s, a 44.736 Mb/s DS-3 signal can be asynchronously multiplexed into the

-
1. STS-1: Synchronous Transport Signal level 1 - the basic logical building block signal with a rate of 51.840 Mb/s
 2. OC-1: Optical Carrier level 1 - the optical signal that results from an optical conversion of an STS-1 signal

available bandwidth of STS-1. It is also possible to synchronously multiplex a DS-1 signal (at 1.544 Mb/s) into an STS-1 signal. The difference between an STS-1 signal into which 28 DS-1s can be synchronously multiplexed and one that contains a single asynchronously multiplexed DS-3 signal is the individual access of the synchronously multiplexed DS-1s. This represents a distinct advancement advantage over previous protocols.

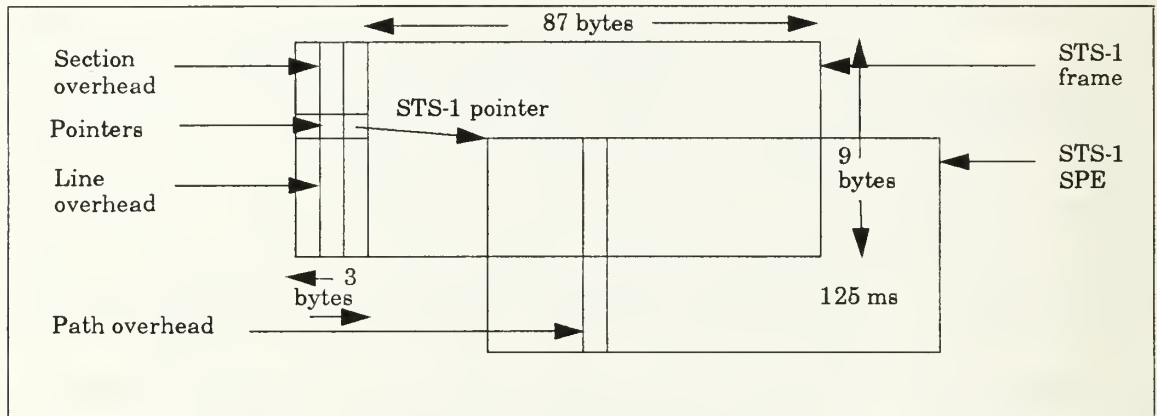


Figure 2 - 10. STS-1 frame and payload access

Another advantage of SONET is that it is capable of upward mobility in handling higher data rate signals than today's standard DS-3 signals. (For European standard transmission of 139.264 Mb/s the STS-1 is not particularly useful). Higher data rate SONET signals are obtained by first byte interleave N copies of STS-1 frames into so-called STS-N frame. The frame is now $N \times 90$ column (bytes) wide 9 rows high. The time duration of the frame is $125N \mu\text{s}$. For example three STS-1 frames can be multiplexed to reach the 155.74 Mb/s rate preferred by the European network (see Figure 2-7). The payload pointers are used to multiplex N STS-1 frames into STS-N levels. When multiplexed, the section and line overhead bytes of the first STS-1 frame are used for overhead information, and the overhead bytes in the rest of the multiplexed frames are not used. The STS-N frames are then scrambled (to avoid the possibilities of long strings of zeros and ones) and converted to an OC-N signal. The line rate of the OC-N signal is exactly N times the rate of the OC-1 signal rate.

The STS-1 payload pointer is a key innovation of SONET, and is used for multiplexing synchronization in a plesiochronous environment and also frame align STS-N signals. The novel technique allows easy access to synchronous payload while avoiding the

need for 125 μ s buffers [Ref. 5]. The payload pointer is a number carried in each STS-1 line overhead that indicates the starting byte location of the STS-1 SPE payload within the SPS-1 frame. Thus, the payload is not locked to the STS-1 frame structure (floating payload). A late starting-payload is allowed to overlap into the following STS-1 frame (see Figure 2-11). The other method of aligning signals within the STS-1 frame is to rigidly fix the location of the payload. The floating payload, an innovation of SONET and exhibits an advantage when dealing with signals that are not set up by a master-clock. In SONET a DS-3 (at 44.736 Mb/s) signal is mapped into STS-1 directly. No buffer or master synchronization of the signal is required.

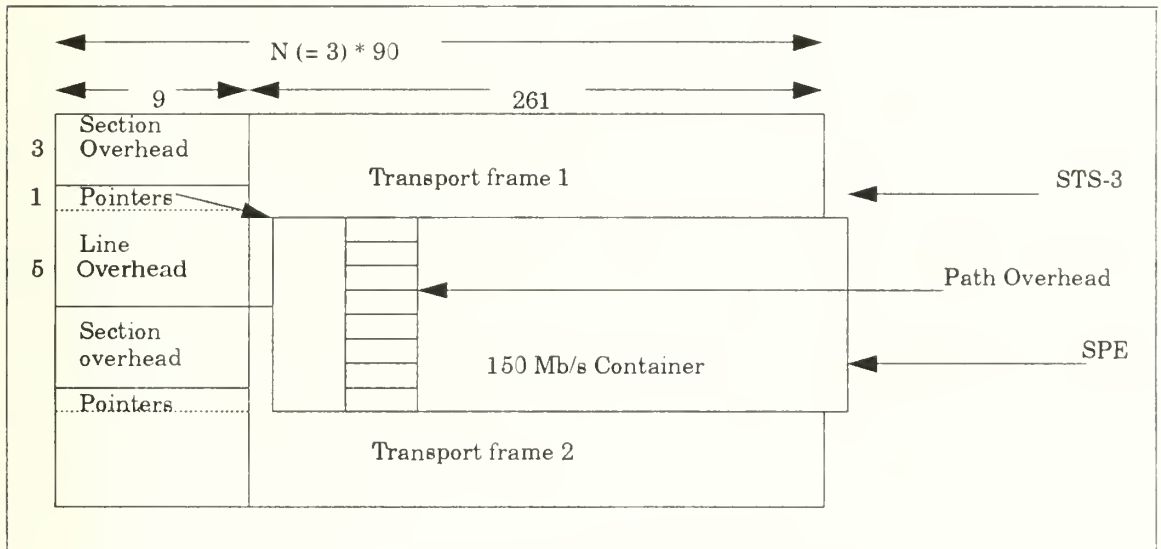


Figure 2 - 11. SONET frames and access payload

To transport payloads requiring less than an STS-1 payload capacity, the STS-1 SPE is divided into a payload structure called *Virtual Tributaries* (VTs). There are sizes of VTs to carrying capacities equal those of present standards, both U.S. and European. Each VT occupies several 9-row columns within the SPE. A VT group is a 12 column by 9 row payload structure that can carry several VTs (four DS1, three CEPT-1 etc.). Seven VT groups, one path overhead and two unused columns are byte interleaved to form one STS-1 payload. The VT can also operate in “floating” mode, similar to the STS-1 floating payload.

From the viewpoint of network management SONET contains several innovative features. One of the basic concepts of the synchronous signal format is its layered

structure and the overhead supporting the signal processing. The four basic layers of the signal format (see Figure 2-12) and their relationship to network management are as follows [Ref. 24]:

- Photonic layer - defines the optical pulse shape, power level and wavelength.
- Section overhead layer - provides basic transport function of framing on STS-1 signal. In addition, section overhead provides basic level performance monitoring of the payload. The list of performance primitives are divided into anomalies, defects and failure, which are described in detail in the draft ANSI T1M1 standard [Ref.27]. Section overhead contains a local orderwire channel (interoffice voice communication), a user channel (64 kb/s channel for use by network providers), and a 192 kb/s Data Communication Channel (DCC) (for use by SONET network element to transmit alarm, status, control and performance information);
- Line overhead layer - provides STS-1 payload pointer storage and automatic protection switching commands. The payload pointer provides performance monitoring of the payload in addition to multiplexing and frame alignment. Line overhead contains an express orderwire, and a 576 kb/s DCC;
- Path overhead layer - provides an end-to-end management of payload. It also supplies performance monitoring, signal labeling, status feedback, and an STS tracing function. Path overhead contains a user channel. VT path overhead provides management functions for the floating VTs.

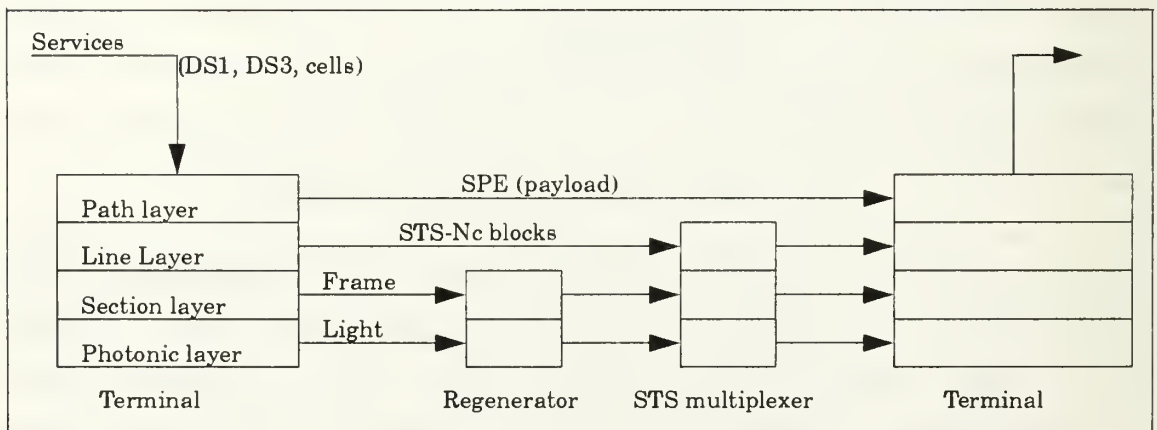


Figure 2 - 12. SONET hierarchical structure

b. ATM

The Consultative Committee International du Telephone et Thelegraph (CCITT) has embraced Asynchronous Transfer Mode (ATM) as the target switching and multiplexing

method for carrying all signals in the BISDN [Ref. 53]. In ATM, all information to be transferred is packed into fixed-size slots called “cells,” which are identified and switched by means of a label in the header. The term “asynchronous” refers to the fact that cells allocated to the same connection may exhibit an irregular pattern since cells are filled according to the actual demand (this aspect is well-known from existing packet transfer mode). All communication in an ATM network is connection-oriented, e.g., a connection needs to be established before data transmission can begin.

ATM is a multiplexing and switching technique that is confined to Layer 1 and basic functions of Layer 2. Traditional time division multiplexing divides bandwidth into a number of fixed capacity channels. It is a fixed mapping of bits from each sub-channel into the fixed-length repetitive time frame, typically on a byte interleave basis. The time frame is 125 μ s, where the frame consists of a number slots with slot corresponding to one of the constituent channels. A slot or channel is efficiently identified by its position in the time frame. Another means of identifying the channel or slot is to add a label to each slot (labelled multiplexing). Slots for a given channel no longer need to be in the same position in each time-frame, or even in every frame after they are labelled. The asynchronous scheme divides the time among the competing channels according to demand, and is capable of multiplexing both continuous-bit-rate and bursty traffic. ATM operates in a deterministic mode, and can support real-time traffic by circuit-mode emulation. It also employs a statistical mode to concentrate bursty data. Figure 2-13 depicts STM and ATM multiplexing respectively [Ref. 28.]

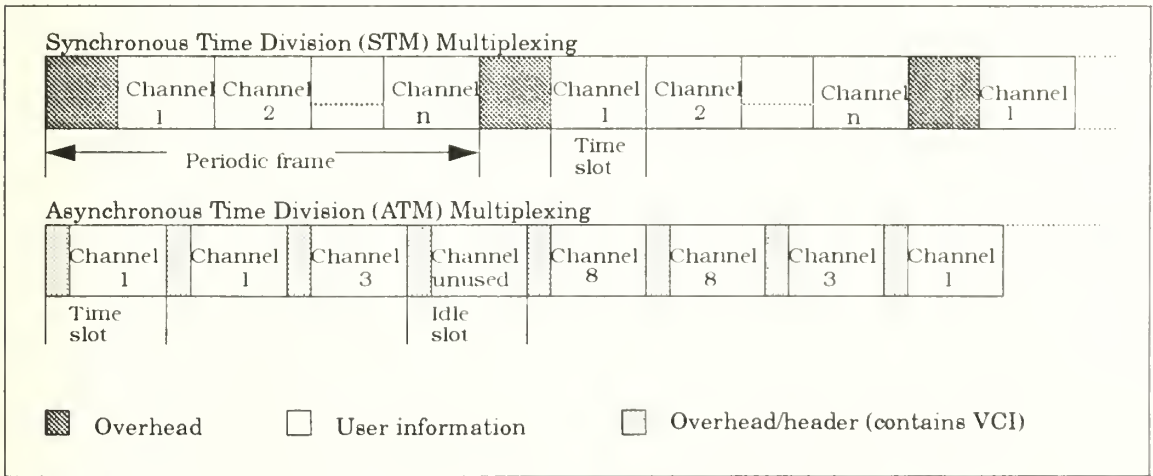


Figure 2 - 13. STM and ATM principles

Fast packet switching operates on packets having a header with some addressing scheme amenable to rapid decoding by switch routing to the destination output port. To build a large fast switching system necessitate exploiting the routing independence of packets belonging to different virtual circuits. This must be accomplished in order to achieve a degree of parallelism by constructing a distributed switch. The type of switch, self-routing, processes the packet header to determine the next hop the packet will make on its route through the fabric.

The ATM layer in Figure 2-14 is common to all services [Ref.28]. Its functions are represented by the ATM cell header functions. Note that, the boundary between the cell header and the cell information field correspond to the boundary between the ATM layer and the higher layers. A cell is a fixed length packet consisting of a 5-byte header and a 48-byte information field. A message being transmitted must be segmented into these fixed length cells at the source station and reassembled at the destination. The specific 53-byte choice was a compromise between a delay of voice packets and maximum payload. From the standpoint of performance, it appears that there should be a possibility of utilizing for variable packet lengths to accommodate a more flexible "fit" [Ref. 1].

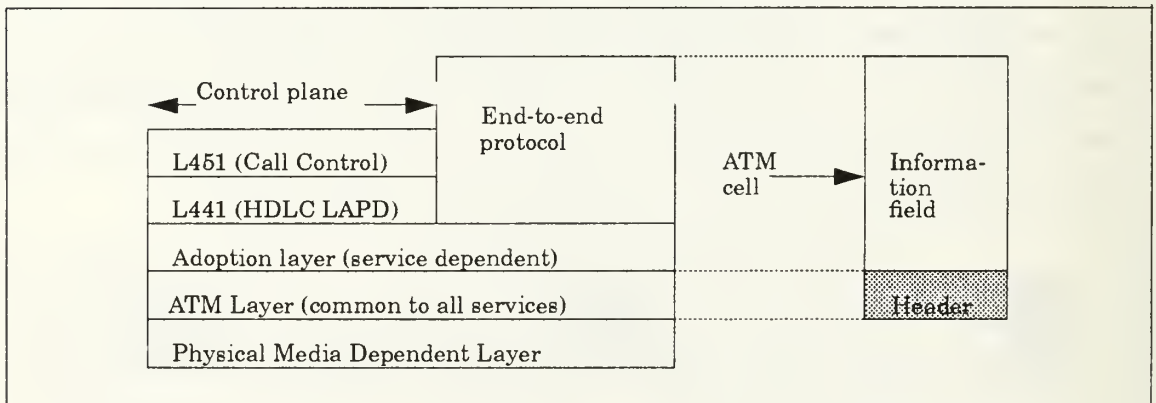


Figure 2 - 14. Protocol model for ATM

The ATM header contains the label called Virtual Channel Identifier (VCI), flow control, payload type, Virtual Path Identifier (VPI), and an error detection field (see Figure 2-15). Error detection and correction on the ATM level is confined to the header. A special VCI may be used to indicate unassigned cells.

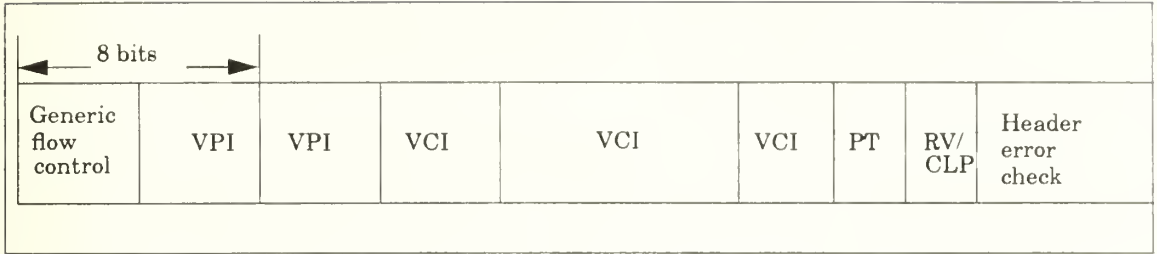


Figure 2 - 15. ATM Cell header at User Network Interface (UNI)

For the physical layer interface structure, two options exist: namely the SONET/SDH- based option and the cell-based option. Figure 2-16 a and b show the two options for the 155.52 Mb/s interface [Ref. 28].

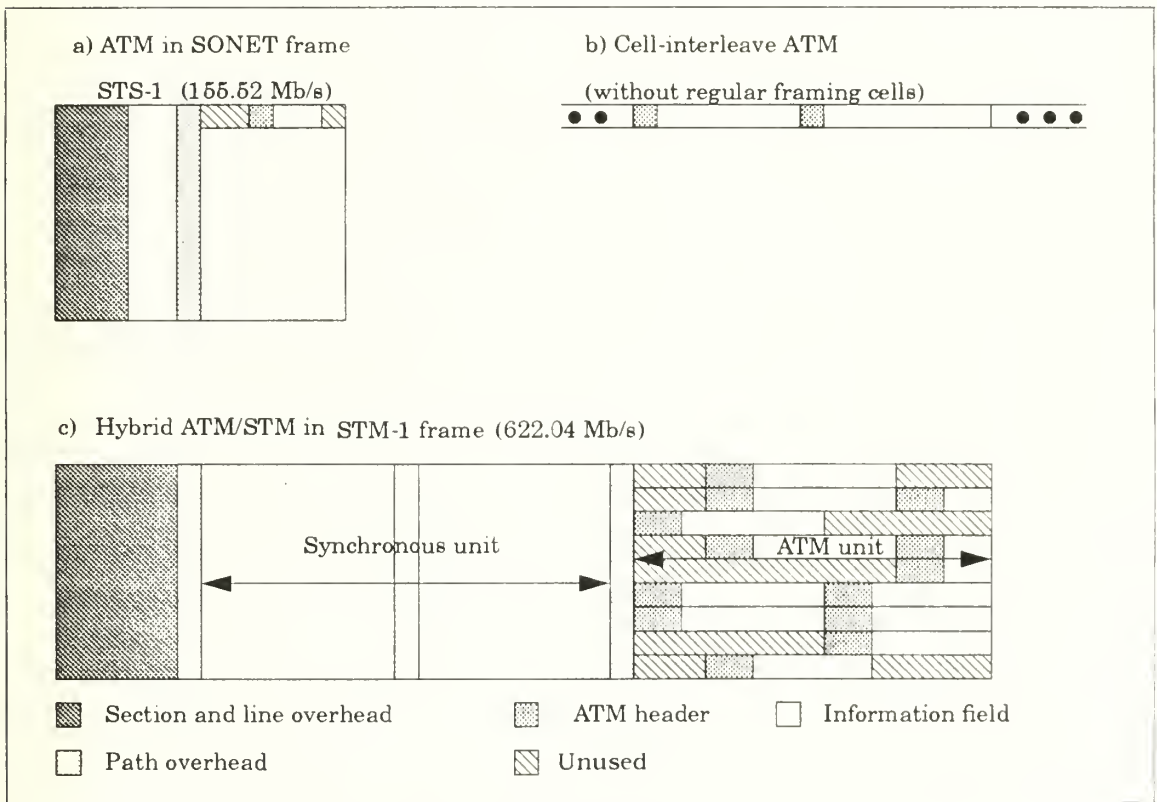


Figure 2 - 16. Transfer modes of ATM cells

In the purely cell-interleave ATM solution all overhead is inserted into cells. In the case of pure cell multiplexing, regular insertion of framing cells is recommended but not mandatory. The SONET based option maps an ATM cell stream to the STS-1 payload only,

leaving the overhead bytes intact. The feasibility of the 622.04 Mb/s interface (STM-1) is somewhat unclear. A hybrid solution (ATM/STM usage) or subdivision of the 622.04 Mb/s interface into smaller ATM modules (e.g., 155.52 Mb/s) are being considered. Figure 2-16 c depicts the hybrid solution [Ref. 28].

Due to its inherent flexibility in terms of actual bandwidth consumption (according to individual needs of different services), a role for ATM in broadband applications has been almost universally recognized. However, the ATM approach requires the solution of many new problems. For example, the possible impact of cell loss, cell delay, collision, and cell jitter on the quality of all broadband and other services need to be determined.

4. Other high speed networks

a. CBR

The Cambridge Backbone Ring (CBR) is an experimental ring network for multimedia data designed by Olivetti Research Limited and the University of Cambridge. The current aim of the network is to serve as a backbone for an area of 50 km in diameter. Initially designed for line rates between 500 and 1000 Mb/s. The basic stations can achieve up to 200 Mb/s on a point-to-point basis, but higher bandwidth stations are possible.

CBR is a slotted ring. When the transmission rate approaches 1 Gb/s, one slot per revolution would not be sufficient to handle the traffic. To overcome this, enabling stations transmit multiple mini-packets in each revolution [Ref. 19]. One problem that has not been fully resolved is the out-of-order reception by a re-transmission. Four CBR slots are aggregated into groups to form a frame. A 50 km diameter ring would have about 500 frames separated by synchronization characters. Each frame consist of a 5 byte overhead and a 144 byte datafield (four mini-packets).

In the CBR architecture the bandwidth of the single mode fiber can be partitioned into a number of TDM channels. The ring has been designed to simultaneously carry traffic from 10 to 50 stations. This enables stations of varying cost and bandwidth to be attached to one network. The parameters are set by the number of channels a station can use concurrently. CBR forms a switch for short mini-packets, very similar to the "cells" found in the ATM. A network of the CBR type can also serve as a local distribution loop for ATM traffic.

b. LION

Logical integrated optical network (LION) is a polled access protocol network of 636 Mb/s [Ref. 55]. LION uses folded unidirectional bus topology with one master station. This master station polls the attached stations during two different rounds, corresponding to two different priorities. During the high priority round, only some of the stations, selected by the master station, are allowed to access the media. This scheme can support real-time traffic.

E. APPLICATIONS OF HIGH SPEED NETWORKS

Networks have become an integral part of computing. Computing applications in all sectors are now dependent upon networks to routinely, accurately and rapidly convey massive amounts of data between computing devices. In the last five to ten years there has been a great deal of work done towards improving network performance. Kilobyte rates are passe, 10 Mb/s CSMA/CD are commonplace, massive use of 100 Mb/s FDDI is expected, and networks supporting gigabits are beginning to emerge. The high speeds possible in the fiber optic transmission have spurred development of networks that will exploit this capacity. Since a commercial undertaking needs to be grounded on efficient use of its capital outlay, the real issue has become a question of whether long term dividends will justify the initial investments. And whether the applications can truly utilize the bandwidth. Of course, there are several sound motivations for adopting high speed networks, such as (see also Table 2-4):

- Interconnection of future super-computers
- Scientific visualization - Graphics/Image
- Distributed computing - Computer integration
- Multimedia
- Full motion video - HDTV
- Military technology

1. Interconnection of future “super”computer environment

The workstation of tomorrow - might be called “digital video teleputer.” It has been predicted that in five years the computer will have digital video of varying resolutions, audio of the highest quality, and allow integration of text, digital sound, digital video, numeric data, and interactive 3D image generation. And all of this will be integrated in a nice interactive interface. Today a typical workstation operates at 2-8 MIPS (mega instructions per second), contains a few megabytes of memory and offers “effective” backplane bus and I/O rates of a few megabytes per second. Super-computers can perform 500 MFLOPS (mega floating point operations per second) to 2 gigaFLOPS, have up to 2 gigabytes of memory, and channels in 100 Mb/s range [Ref. 7]. The digital video teleputer of tomorrow will have a big, 16*9 aspect ratio, flat color display and a host of peripherals built in. The metrics? At least a gigabyte memory, a gigaFLOP of computation, a gigabit of bandwidth-gigas everywhere [Ref. 26]. For super-computers the pre terra may be more appropriate. And with the emerging of this type of capacity, we will see the actualization of realistic graphics in real-time. The digital video teleputer will, of course, be networked, for data, for telephone, for video; all digital, all fiber optic.

2. Scientific visualization - graphic/image

Graphics, especially high quality color graphics, will continue to make inroads; it has been graphics coupled with windowing systems that have lead to user friendly systems. Workstation and computer software facilitate integrated systems because of their ability to conduct communication by remote operation over the networks. Graphic (image) applications tend to change the basic unit of information from a character to a screen image. The trend has been encouraged by “visualization” driven applications wherein bits are turned to pictures on a grand scale. As visualization techniques now stand, image and color resolution can be displayed at sufficient frequencies to create a rudimentary level of animation.

Spatial and contrast resolution are two important parameters that characterize an image. Spatial resolution corresponds to the product of the number of horizontal and vertical pixels. At 512 pixels/line the scan lines can normally be seen on the monitor. The move up to 1024 pixels/line achieves a major step in clarity. In the future applications with a true resolution of 2048 pixels/line or 4096 pixels/line may be required by many users [Ref. 38]. The

contrast resolution represents the number of shades of gray or number of colors that can be displayed. The range varies from 256 colors for 8 bits/pixels to 2^{32} colors for 32 bits/color. Numerous applications require a color resolution greater than 8 bits/pixel. In computers, the display of the image is achieved through *progressive scanning*. That is, lines are displayed sequentially.

Applications based on still images are of considerable importance to the cartographic, medical and engineering professions. Medical imaging is a particularly interesting field, in which applications of new technology can have a very significant benefit. Besides radiology, there is growing interest in newer imaging modalities such as ultrasound (USI), nuclear medicine (NMI), computer tomography (CT), positron emission tomography (PET), and magnetic resonance (MRI). These modalities are inherently digital, requiring processing data obtained from a variety of sensors to create the image. In the future, ophthalmology, ortopedic surgery, cardiology, and cytogenetics will join radiology and pathology as areas that employ imaging techniques and broadband communication technologies. There are also benefits in distributing medical images to locations throughout the hospital as well as to remote locations.

Another dimension of image processing is that it allows different workstations to communicate by providing image format conversion. Image processors and 3D algorithms can process a large amount of data and thereby create 3D images. Two dimensional image slices are converted into a 3D display that can be rotated for viewing from any angle. 3D display is generated using volume-image techniques, in which the form or figures are assigned different levels of transparency.

3. Distributed computing - Computer integration

Advances in technology have generated increasing use of microprocessors in distributed real time systems. Distributed processing is essential for the control and operation of complex dynamic processes such as development and research of robotics, autonomous manufacturing, advanced aircraft and spacecraft, and air traffic control. Computer Integrated Manufacturing (CIM), areas of engineering (CAE), design (CAD), production process, etc. function more efficiently when they are integrated in a closed loop control system. Essential to this distributed system is the integrated communication network. Such a network must be capable of handling real-time data (e.g., robot controlled assembly-line) and non real-time data

(e.g., CAD image and design specification). Voice and video information may also be integrated with data traffic. A robot control system must recognize defects and quality problems within milliseconds, whereas a scanned page in color generates 200 Mb [Ref. 41].

4. Multimedia

In the future we expect PCs and workstations to be equipped not only with high resolution graphics and window/mouse based user interfaces, but also with options for audio and video input and output. There are many potential multimedia applications. One is the electronic catalog where a user can browse a set of catalog items, listen to audio descriptions, and view a video demonstrations of the products. Such a service requires data of three types: audio, video and numerical. The objects displayed can be of a continuous type (video or audio), discrete type (images or text), or a combination of both. Other multimedia applications exist in the areas of medicine, geography, business, information, command and control, and education.

In the future, an increasing amount of information will be provided by private or public database organizations that are geographically dispersed. The data must be combined in a manner commonly known as composition. Spatial composition involves assembling data based on overlaying or linking multiple objects into a single entity (e.g., composition of an image with additional textual information). For temporal composition there is a time ordering assignment (synchronization) to the presentation of the multimedia. The presentation of the audio is sequential, as it is for the image. Voice and video require real time delivery, whereas text and images merely require timely delivery. Transmission of voice requires lines of about 64 kb/s, whereas stereo Compact Disc (CD) quality audio requires 1.4 Mb/s.

Video conferencing is also an important application. This can be successfully implemented with workstations that have the ability of presenting one or more incoming full-rate video signals with high quality audio. A subject may then be presented to an audience at one or more remote locations or a more interactive approach to conferencing will also be possible. HDTV quality, which adds additional picture detail, better color and larger screens, will make video conferencing much more useful.

5. Full motion video - HDTV

The distribution of entertainment and news, based on broadcast signals, has been an activity almost entirely separated from the local, metropolitan or wide area networks. The

information and entertainment available have been broadcasted as analog radio and television signals on dedicated channels, or on coaxial-cable network (CATV) used for cable television. This network is limited by a maximum 10 Mb/s and one way communication. In contrast optical fiber has a gigabits bandwidth, and as part of switched, digital network carries voice, data or video services. The trend of replacing twisted pair with optical fiber has come all the way to the subscribers' home. The result is that cable television signals are beginning to be transported over fiber. The signal quality is excellent, since digital encoding ensures that images do not degrade during transmission to the home.

High definition television (HDTV) may be the primary format in the future. Televisions will be capable of showing high resolution pictures on large, extra wide screens, and producing sound as clearly as compact disc. HDTV improves on NTSC, PAL and other television system in some substantial ways. Instead of the current 525 line limit, it can utilize as many as 1125 lines. And although some proposed systems intended to display pictures in the same way as NTSC, by *interlacing* (transmitting first the odd-numbered lines, then the even-numbered lines), a number still plan to progressive scanning. HDTV also clears up some annoying defects of broadcast television. For example, information for light and color in NTSC is interleaved on the same signal. Because the two types of information overlap slightly, today's receivers can mix up color and light, especially in detailed patterns. With twice or four times the resolution, HDTV greatly reduces the impact of this effect to the viewer. The improved picture will permit the use of larger and wider screens. The *aspect ratio*, or ratio of width to height, of a conventional screen is 4:3. Many HDTV developers plan to use an aspect ratio of 16:9, which will allow movies to be transmitted much closer in form to their original composition. The SMPTE 240 M standard (1125/60 Hz) has 1035 visible lines (of 1125) and horizontal resolution of 1920 pixels [Ref. 11]. There are however several problems associated with the 1125/60Hz standard. One of which is, the Europeans use frame rate 25 (equivalent to their 50 Hz power-lines) and neither is a computer friendly number. One proposal is to increase visible lines to 1080 and horizontal resolution to 2048 pixels. Future development may give rise to HDTV with 5000 * 3000 format resolution [Ref. 26]. Computer vendors are also about to increase the frequency to 66Hz and even 72Hz (which is compatible to film-speed). The intention of HDTV is to bring film, video disc, tape, computer graphic, fiber optic and

microcomputer all together, and penetrate the communication and imaging industries, thereby recasting the role of visual information in society.

Table 2 - 4. ACCESS TIME AMONG DIFFERENT LOCAL AND METROPOLITAN NETWORKS

| Approximate Access Time in seconds/Sufficient bandwidth | | | | | | |
|---|--------------------|------------------|---------------|----------|----------|----------|
| Application | Image/Volume size) | Ethernet 10 Mb/s | DQDB 155 Mb/s | FDDI | | |
| | | | | 100 Mb/s | 300 Mb/s | 800 Mb/s |
| 2-D Images | 1,024*1024 | .08 | .01 | .01 | 0 | 0 |
| | | .17 | .01 | .02 | .01 | 0 |
| | | .34 | .02 | .03 | .01 | 0 |
| | 2,048*2,048 | .34 | .02 | .03 | .01 | 0 |
| | | .68 | .05 | .07 | .02 | 0 |
| | | 1.35 | .09 | .14 | .05 | .02 |
| | 4,096*4,096 | 1.35 | .09 | .14 | .05 | .02 |
| | | 2.69 | .18 | .27 | .09 | .04 |
| | | 5.37 | .35 | .54 | .18 | .07 |
| 3-D Images | 256*256*256 | 1.34 | .09 | .14 | .05 | .02 |
| | | 2.02 | .13 | .21 | .07 | .03 |
| | | 2.69 | .17 | .27 | .09 | .04 |
| | 512*512*512 | 10.74 | .70 | 1.08 | .36 | .13 |
| | | 16.11 | 1.04 | 1.62 | .54 | .20 |
| | | 21.48 | 1.39 | 2.15 | .72 | .27 |
| | 1,024*1,024*1,024 | 85.90 | 5.55 | 8.60 | 2.87 | 1.08 |
| | | 128.85 | 8.31 | 12.89 | 4.30 | 1.62 |
| | | 171.80 | 11.09 | 17.18 | 5.73 | 2.15 |
| Video-telephony | 30f/s*1,125*1,920 | No | Yes | Yes | Yes | Yes |
| | | No | Yes | No | Yes | Yes |
| | | No | No | No | Yes | Yes |

6. Military technology

Recent trends in the development of defense systems are indicative of a new mode in dealing with a hostile environment. Modern technology promises high speed, high performance integrated systems that are able to detect and process a broad spectrum of input signals and generate an immediate response to an enemy threat. Aegis is a combat system available to surface navy that posses these characteristics. The range of services in the current Aegis

combat system requires real time processing and high-speed communication on the order of 50 - 100 Mb/s. Expanding the system to facilitate integration of high-quality sound and full motion graphics will demand a further increase the transmission rate.

Appropriate areas for future developments include parallel processing infrared (IR) detection system, optical processing, visualization in 2D and 3D, virtual reality, and real time synthetic aperture radar (SAR). Recently, command guidance has been testing missiles equipped with terminal seekers that incorporate television, infrared, or millimeter wave technology capable of producing target imagery. The signals are transmitted to the launching platform through a two-way duplex data link then forming a dual payout system. Based on the visual presentation, commands are transmitted back to the missile for point-guidance.

Virtual reality is a new form of media. It is participatory, multi-sensory, 3D, and real time. It almost creates the sensation of stepping through the screen and into an imaginary world. A virtual environment may be derivative of either a real or purely imagined environment. In the first instance, the system attempts to construct an environment that may commonly occur. However, certain elements within the environment, a figure for instance, posses the ability to act or behave in ways that are not normally possible. Generally these characteristics pertain to areas of perspective, dimension, elongation, compression, etc. Applications for this type of program can easily be targeted for use in aircraft flight simulation, vehicle simulation, war games simulations, etc.

F. DATA-COMPRESSSION

Table 2-5 indicates the requirements for processing speed, massive data storage and high bandwidth communication [Ref. 26, 41, 60]. If a suitable approach is used, however, data compression can reduce these quantities significantly. Image processing can reformat and compress high-density digital pixel data. Motion detection is a related compression technique that extracts movement from frame to frame and only sends the parts that change. Compression algorithm techniques have been implemented in hardware called CODEC (coder-decoder). The compressing algorithm enables accurate reconstruction of all the original pixels (lossless) or, if so desired, an approximate reconstruction of the original pixels (lossy). Images may be compressed by a factor of three to 15 times depending upon the type of image [Ref. 41].

Techniques currently under development for compressing video signals seek to attain signals compressed by a factor of 10, leading to bit rates below 150 Mb/s [Ref. 26].

Table 2 - 5. UNCOMPRESSED OBJECT SIZE IN BITS PER SECOND AND ACCEPTABLE DELAY

| | Voice CD quality | Aegis SPY - 1 radar | CAD/CAM non-real time | CIM robot real-time | Medical CT/MRI 2D image | Video Conference HDTV-quality | HDTV |
|--------------------------------|------------------|---------------------|-----------------------|---------------------|-------------------------|-------------------------------|--------------------------|
| Bit rate per s. (Mbits) | 1.4 | 5 | 10-100 | .001 | 10-536 | 3-360 | 1555 10800 |
| Acceptable delay (s) | .125 | .008 | 1.0 | .02 | 1.0 | 1.0 | .033 |

III. IMPROVING THE AEGIS COMBAT SYSTEM WITH HIGH SPEED NETWORKS

This chapter discusses the possibility of replacing the current communication network of the Aegis real-time combat system with a dual optical fiber ring. This network would connect all the sensors, weapons, electronic equipment and computers into a single network, possessing a simple topology, higher data transfer capability, and enhanced security.

Section A surveys the Aegis Combat System. The Aegis Combat System is the most powerful and complex combat system available to the surface fleet of the U.S. Navy. Designed for guided missile cruisers, the Aegis was engineered as an integrated system incorporating information exchange between sensors and weapons.

Interest in applying a LAN technology has been growing over the last several years. An example of this interest is the Aegis Data Bus Experiment [Ref. 14]. The experiment showed that it is possible to operate the Aegis weapon system, using fairly stressful scenarios, with a portion of its point-to-point links replaced by a data bus. During an experimental peak load the bandwidth used represented only two percent of the available bus bandwidth. Section B would determine if a LAN based on optical fiber can provide the interconnection to support system flexibility, reliability and higher throughput rates.

Section C presents the configuration of a Aegis Combat System using FDDI. The network used in this paper is a token ring technology using fiber optical media, specified by ANSI's X3T9.5 FDDI standard. The FDDI protocol has been chosen for its high bandwidth and because it also supports the functions needed in real-time communication.

A. THE COMBAT SYSTEM

Aegis, named after the shield of Zeus, was originally designed for the Ticonderoga (CG-47) class guided missile cruiser. The launch of the first, the USS Ticonderoga, was in 1981. A more compact Aegis system developed for the Arleigh Burke class guided missile destroyer is now at sea. Aegis is a combination of complex radars, computers, graphical displays, missiles and missile control systems. Aegis' major advantages are sensor speed and accuracy, reliability, integrated software, self diagnostic action capacity, "graceful degradation" (software driven), launcher capacity, and reaction time - as well as the system reaction time

allowed by interactive doctrine statements. The combat system performs well in hostile environments such as severe weather or in the presence of electronic countermeasures. As an area defense system, it can shield an entire task force by simultaneously tracking up to 250 airborne, surface or subsurface targets [Ref. 2]. Target ranges can exceed 300 miles, and are prioritized for engagement according to the threat each poses. Aegis is also designed to deal with a high speed cruise missile threat, with unique capabilities to defend against those launched from short range (fast reaction time). The fully integrated architecture allows operation in a variety of modes, including fully automated. While in the automatic mode the system can position and fire a weapon at a target that meets previously predetermined threat doctrine.

Aegis consists of three major system components. These are the powerful phased array multi-function radar, called AN/SPY-1, the Command and Decision system (C&D), and the Weapon Control System (WCS). The SPY-1's function is to detect targets. C&D performs command, control and communication functions. The WCS function is to evaluate the engagement, and provide and execute fire control solutions as well (see Figure 3-1).

The SPY-1 radar is a multifunction search, track and fire control radar that schedules its dwells based on an identification (ID) hierarchy while maintaining a hemisphere search within specified time limits. Dwell type power and energy are determined by the target and environment. It must also be able to support missiles in flight. The other radars: the SPS-49 (air search), the SPS-55 (surface search), the LN-66 and SPS-64 (navigation) contribute to the picture. The SPG-62 is solely for terminal guidance.

The second major component, the command and decision system, consists of computers and display consoles. It integrates all the sensors and weapons on an Aegis ship. The display system presents the battle area clearly and can produce the history of any target track. On the screen a particular track symbol indicates whether the threat is airborne, surface or subsurface. Each track symbol depicts direction of travel and target speed. Other symbols indicate whether the target is hostile, friendly or unknown. The arrangement provides the C&D center personnel with information on what the sensors see, enabling them to exploit the weapon system range and combat capability.

The third major component is the Weapon Control System. The Aegis combat system has an arsenal comprised of scores of weapons at its disposal. The vertical-launch system (VLS)

handles long range Tomahawk anti-ship or land-attack cruise missiles in addition to anti-submarine rockets and anti-aircraft missile (SM-2). The SM-2 missiles are command guided/semi-active and need guidance by ship radar. The SPY-1 radar can control more than a dozen missiles in flight, and the four Mark 99 target illuminators direct missiles in the terminal phase. The self-contained Phalanx system is an automatic point defense system directed against attacking cruise missiles. It contains two search and track radars, a firing control computer, and a 20 mm Gatling gun. The WCS activates, controls and directs weapon systems to their respective targets based on received positional data.

Aegis was originally developed as an Anti Air Warfare (AAW) system, with a centralized control in the command and decision (C&D) component [Ref. 63]. The evolution of the combat system now includes the Anti Subsurface Warfare (ASW) system, the Anti Surface Warfare (ASUW) system, the STRIKE Warfare system and the Electronic Warfare (EW) system. Figure 1 depicts the system architectural design. The separate components can operate somewhat autonomously. Concurrent, multiple flows of essentially separate data follow the detect-control-engage sequence.

Aegis will evolve towards an integrated system, providing support for command personnel that spans across the spectrum of warfare applications and therefore provide a coherent tactical picture within the ever-growing complexity of battle engagement. Combat system performance will depend heavily on the integrity, performance and communication in its computer system. Currently, Navy standard dedicated point-to-point connections provide communication between Aegis computer elements. Data paths are unidirectional; duplex communications need two cables. For reasons of reliability redundant cabling requires four cables between each pair of elements that must directly communicate in the combat system [Ref. 63].

Frink & Verven [Ref. 14] measured the effect of inserting a data bus into the combat system. Under wartime simulations it was possible to operate the Aegis combat system with a portion of its point-to-point links replaced with a data bus. The data rate measured on the bus indicated that the bandwidth was sufficient. Though message delays were introduced, these delays were insufficient to cause any problem to the combat system tested.

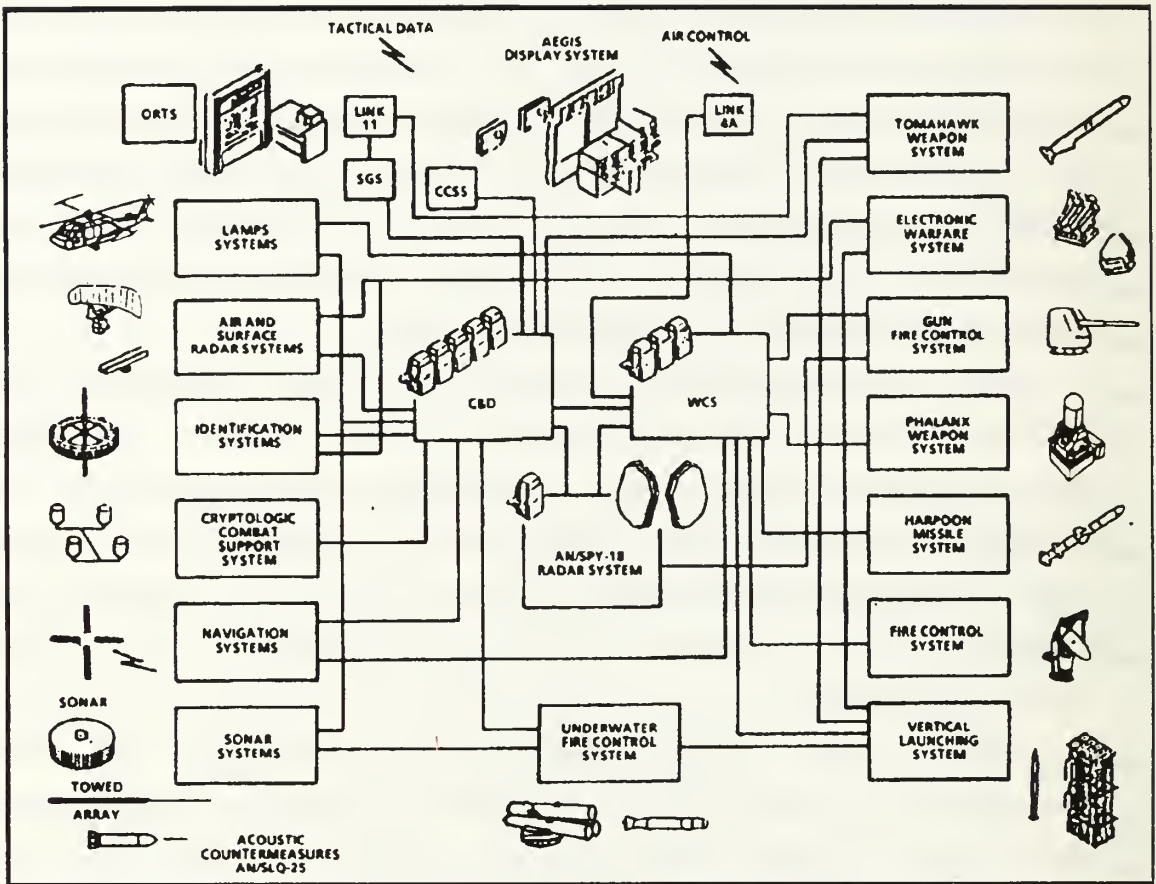


Figure 3 - 1. Aegis Combat System [Ref.14]

The “accuracy revolution” by precision-guided missiles (PGM) represents the greatest impact on warfare in recent years. Besides increasing firepower and range, these weapons introduce new levels of vulnerability to conventional naval units. PGMs in conjuncture with satellite surveillance pose a real and formidable threat. In the future, the environment of the naval surface combatant will be increasingly saturated with electronic countermeasures. Facing these threats, combat systems will see an exponential increase in the amount of shipboard information to be processed, disseminated and integrated. This information explosion will result from the need for cooperation between ships, and new or enhanced automated battle sensors and weapons, including space based sensors.

The next generation of combat system will likely be an upgrade of the current state-of-the-art Aegis command & control system. It will acquire, track and engage air targets in real time, most likely with criteria more refined than the present system. Improvement to the powerful phased array radar (SPY-1) for command-all-the-way will eliminate the need for separate illuminators and provide guidance for the missile all the way to the target. Work under way on monolithic microwave integrated circuits, aimed toward compacting a bulky radar transceiver down to several chips promises to drastically reduce both the cost and weight [Ref. 2]. The next century may witness combat systems equipped with High-Energy Laser Weapon Systems (HELWS) for close in air defense. The HELWS use a chemical laser and an optical tracking director to engage targets with directed energy. Since the time of flight for a laser weapon's directed energy is practically zero, the HELWS can shift target engagement rapidly. However detailed predictions about future combat system are beyond the scope of this paper.

The growth of information obtained and processed by the combat system of the future will create a need for increased computing and communication capability. The growth of processed information, along with enhanced threat and a more sophisticated tactical arena will necessitate an accelerate automation in order to decrease reaction time [Ref. 63]. The computer architecture for the future combat system may be an evolutionary growth of the current Aegis system or an entirely new design. In either case the future architecture will have to build upon cutting-edge technology. Using *ruggedized* off-the-shelf computer equipment is often more cost effective than having it specially constructed. It may be a fully distributed microprocessor-based concept, or a combination of distributed concept collocated with the equipment they support or embedded within the equipment itself. The combat system must be highly survivable, possessing the ability to fight "hurt." The architectural concept must have security at many levels within the computer system. Adaptability and the flexibility to accept new configurations and improvements are highly desirable.

An essential component of an advanced integrated combat system is the display system for accumulating operational, tactical and status information. The future system will use sophisticated color graphics to provide a real-time display that improves high-level decision making in a multi-warfare environment. Display elements will include both real-time and over-the-horizon track data, velocity leaders and history trails. The display will also include

color filled land areas, country boundaries, commercial airways, populated areas, military installations, weapon system response and expected missile performance against a threat. Projects are already underway transposing of coastline data into closed polygons to facilitate color filling of land areas.

The development of multimedia workstations and computers that can handle voice, video and high speed data in one machine will serve as fundamental support for a totally integrated combat system.

B. A SHIP COMBAT SYSTEM USING FDDI

1. Real-time Considerations

In this section we will examine the requirements of Aegis for real-time data transfer, and the capability of FDDI to meet these requirements. The figures used are the authors estimates; exact figures are either not available or classified. Our purpose is to show that FDDI can meet the Aegis needs with room to spare.

The combat system must be able to track and engage targets, control weapons, track contacts, and provide information about all of this to the C&D center. It is also clear that integration of the components of the system must meet hard real-time constraints [Ref. 18]. The correctness of the combat system does not only depend on the logic results of the computations, but also on the time in which the result is produced. For example, if the radar systems detect incoming hostile targets, the weapon systems must be capable of destroying the targets within a limited time. In all instances of the "smart" combat system, the systems maximum response time is the most critical aspect of its performance. In the real-time embedded combat system the obvious necessity for extremely accurate time predictions is paramount; the real-time communication subsystem must be able to predictably satisfy individual message timing requirements [Ref. 10].

FDDI's Medium Access Control (MAC) uses a *Timed Token Rotation* (TTR) protocol to control access to the medium. The initialization procedure establishes a *Target Token Rotation Time* (TTRT). The protocol then guarantees that each station gets the token within a time delay, which is determined by the TTRT. Sevcik and Johnson [Ref. 52] and Johnson [Ref. 31] have proven various timing properties of the protocol. FDDI defines two types of data, synchronous (time critical) and asynchronous (non-time critical), (FDDI-II also defines a third

type, isochronous for voice and video transmission [Ref. 54].) The use of the TTR protocol has beneficial effect on operations. It allows stations to request and establish guaranteed response time for synchronous data through Station Management (SMT). Each station can transmit synchronous data frames upon receiving the token. However the total time of transmission per opportunity allocated at ring initialization is somewhat short. Asynchronous data frames that carry any other data may be transmitted after the synchronous requirements are met.

The performance of any network depends upon the type and quantity workload as well as the network's structural and operational parameters. There are two kinds of parameters salient to our discussion, fixed and user determined. Examples of fixed parameters are cable length and number of stations. The user determined parameters, which a network manager can set, include various timer variables and synchronous bandwidth that may be offered to each station. The key factor that affects a performance are the TTRT and synchronous time allocation. The key parameter for workload are the number of active stations and load per station [Ref. 30]. For FDDI, throughput and the time expenditure to satisfy the real-time request measures the quality of service. Tables 3-1 and 3-2 list performance metrics for two configurations with 50 and 100 stations attached to the network. In a combat system aboard a ship the length of cabling will rarely exceed a few km. The tables list three values of TTRT that range from 4 ms to 16 ms. Higher values of TTRT may violate the real-time requirements for a combat system.

The 'responsiveness' metrics considered are:

TTRT: The target token rotation time is the value (T) agreed upon by all stations on the ring. The FDDI protocol guarantees that the maximum token rotation time will not exceed $2 \cdot T$, so stations with strict transmission delay requirements must request a TTRT equal to one half of the maximum acceptable delay. The long-term average token rotation time will not exceed the TTRT. For this example the TTRT is set to 8 milliseconds (ms). Tokens are special short fixed-length frames passed around in the ring and used to signify the right to transmit data. In a 100 Mbps network the token time (t), maximal time upon receiving a token, is 0.00088 ms [Ref. 30].

Ring latency: The time (L) required for a bit to travel from the source to the destination. In this combat system example the optical fiber length is 2 km. Lightwaves travel along the fiber at a speed of approximately $2/3$ the speed of light (200 meter per microsecond (μ s)). The station delay, the delay between receiving a bit

and repeating into the transmitter side, is of order .6 μ s per station [Ref. 12]. The ring latency computation for 100 stations is as follow: $L = (2 \text{ km}/0.2 \text{ km per } \mu\text{s}) + (100) * (.6 \mu\text{s}) = 70 \mu\text{s}$.

Access delay: The time between the end of the previous transmission and the beginning of a new transmission. Using the previous network parameter the average synchronous access delay = $T + L + t = (8 + .070 + .00088) \text{ ms} = 8.07088 \text{ ms}$. The maximum synchronous access delay = 16.07088 ms.

Table 3 - 1. TIMING PERFORMANCE OF FDDI TOKEN RING NETWORK

| Stations TTRT | Average access delay | | Maximum access delay | | Number of update per second under heavy load | |
|------------------|----------------------|------|----------------------|------|--|-----|
| | 50 | 100 | 50 | 100 | 50 | 100 |
| 4 ms | 4.05 | 4.1 | 8.05 | 8.1 | 246 | 246 |
| 8 ms | 8.05 | 8.1 | 16.05 | 16.1 | 123 | 123 |
| 16 ms | 16.05 | 16.1 | 32.05 | 32.1 | 62 | 62 |

Table 3 - 2. THROUGHPUT PERFORMANCE OF FDDI TOKEN RING NETWORK

| Stations TTRT | Performance efficiency [14] | | Transfer of bits per TTRT rotation per station | | Transfer of bits per station per second | |
|------------------|-----------------------------|-------|--|--------|---|---------|
| | 50 | 100 | 50 | 100 | 50 | 100 |
| 4 ms | .8691 | .7187 | 6,952 | 2,874 | 1,738,000 | 718,000 |
| 8 ms | .9347 | .8592 | 14,955 | 6,873 | 1,869,000 | 859,000 |
| 16 ms | .9463 | .9295 | 30,281 | 14,872 | 1,892,000 | 929,000 |

The network in this combat system will transport traffic between 50 to 100 active transmitting stations. Accordingly, the throughput at many of these stations will tend to be between 1/50 to 1/100 of effective ring bandwidth. Other stations, such as SPY-1 radar, graphic terminals, and voice terminals etc. may require access to a greater portion of the ring's bandwidth. Relatively expensive, high bandwidth stations need to be provided with adequate throughput. Most stations, however, can be of a simpler, lower throughput design. Table 3-3 depicts some of the estimated requirements for combat systems data transmission.

SPY-1 radar can track 250 targets simultaneously. The SPY-1 radar translates radar target tracks and communicates these target detections to the C&D center and WCS over the dual ring. FDDI facilitates both single and group addressing. For each track the data needed to transmit may contain range, longitude, latitude, height, velocity, and identification. The binary representation will comprise no more than 240 bits. In the worst case 60,000 bits needs to be transmitted over the network per update to represent data for a total of 250 tracks. The overhead created by the operation system, device driver and system to user for transmission from a station to another, with an optimized adaptor, is less than ten percent [Ref. 30]. The maximal byte representation of SPY-1 tracking capability will be approximately 66,000 bits.

A graphical map (chart) display provides the C&D center with information on the tactical environment. Map refreshment should be accomplished within two seconds. The National Television System Committee (NTSC) standard for television (550 x 760 pixels, and 8 bits color) can measure the bit-representation of the map display. The digital coding of NTSC is represented by 45 Mbps, and the screen is updated 30 times each second. Using two seconds delay on refreshment, the bit-representation is 760,000 bits per second (s). Including the overhead, this adds up to 836,000 bits per second.

Table 3-3. SOME ESTIMATED REQUIREMENTS FOR AEGIS COMBAT SYSTEMS DATA TRANSMISSION IN BITS PER TTRT ROTATION: SPY-1 RADAR, GRAPHIC- AND VOICE TERM.

| Time (TTRT) | SPY-1 radar bits per update | Graphic-terminal w/refreshment every 2 seconds | Voice-terminal synchronous T1 voice traffic |
|--------------------|------------------------------------|---|--|
| 4 ms | 66,000 | 3,360 | 288 |
| 8 ms | 66,000 | 6,720 | 576 |
| 16 ms | 66,000 | 13,440 | 1,152 |

An asynchronous high-speed optical network can simultaneously support packet data traffic with T1 voice traffic over a standard FDDI token ring. The T1 is a standard common carrier, capable of supporting 24 voice channels at a data rate of 1.544 Mbps. In a deterministic network this is made possible with a stream-to-packet interface inside the

workstation. The real-time stream-to-packet interface module is based on using double elastic buffers at both the network input and output ports [Ref. 22]. The requirement per voice station is 64,400 bits per second. Including the overhead, this adds up to 70,800 bits per second.

2. Reliability

A dual ring topology can offer superior reliability, availability and survivability, even in the event of physical damage occurring to the network. Should the primary ring be severed, the network continues sending all the information on the secondary ring. However, if both rings are broken at one or more places, the stations (nodes) cannot continue operating normally. In this event a "ring wrap" is necessary. In a ring wrap procedure, the faulty sections of both rings are isolated. A new ring or rings, are then reconfigured out of the remaining consecutive parts of the primary and secondary ring [Ref. 37, 40]. The two rings should optimally be routed through two physically separate paths, joined only at the dual stations. This greatly decreases the likelihood of a common-mode fault affecting both rings.

A dual station failure severs both rings. Two non-adjacent station failures break the network into two mutually isolated subrings. Any two operative stations in different subrings cannot communicate.

Concentrators provide another level of reliability to the network. If the stations connected to a concentrator fail, they will be isolated from the network. And the only condition under which a ring will go into "loopback" (wrap) is if the concentrator fails. Connecting a station to two different dual attached concentrators also takes the factor of reliability a step further. In a ring wrap the station can communicate through the operative concentrator, or to the most important subring [Ref. 58].

3. Weight and Volume

Keeping a ship's weight to a minimum is a primary concern of ship designers and builders. Reducing the weight in the superstructure (above the main deck) lowers the ships' center of gravity, an important factor in stability. Changes in superstructure through use of new light weight materials have contributed substantially to reductions in above waterline weight in high-technology ship. Yet, at the same time, emplacement of the evolving combat system has been concentrated in the superstructure. This system requires tons of coaxial and wire cables for interconnecting radars, computers, displays and weapons. In the worst of cases

there are as many as four cables between stations with needs to communicate with each other. Cable clutter, or wire pollution, has become a major concern and also constitutes a considerable maintenance problem aboard the ship [Ref. 17].

Up to now cable reduction, by using multiplexing techniques have been limited in scope and usually require additional equipment. Fiber optic with inherent high bandwidth introduces a new method. A ruggedized fiber optical cable weighs roughly 70 lbs (35 kg) per km, while a comparable 26 pair copper cable weighs roughly ten times that amount [Ref. 44]. The copper cable has a much smaller bandwidth and therefore requires repeaters to maintain signal quality. The combined effect of all these factors will elevate optical fiber to be the medium of choice for the 90's. Replacement of the point-to-point connections will result in a significant weight reduction. Other advantages of the fiber are the improvement in cable pollution and the systems life cycle. And it is easy to connect microprocessors to the ring, without additional wiring.

4. Security

From a security standpoint, optical fibers are vastly superior to both copper and Radio Frequency (RF) based communication links in Combat Systems. Optical fiber is reliable in rugged and hostile environments. They are resistant to corrosion because the medium is glass or plastic. Non-conductive optical fiber cables are immune to ground loops and the effects of lightning surges. In addition, spark hazards sometimes produced by electrical wires can be avoided by using fiber cable. Another factor of tremendous importance to military planners is their resistance to electromagnetic pulse (EMP) from nuclear blasts. Optical fiber components can recover after EMP [Ref. 8, 36].

Optical fibers are not susceptible to electromagnetic interference (EMI), which provides a measure of inherent data security since they resist hostile jamming. Optical fibers are also ideally suited for use in electronically noisy environments. Electromagnetic interference is a constant problem in shipboard environments, particularly around machinery and other high-powered electrical systems, such as radar. Adjacent parallel channels can be packed more densely because of the absence of crosstalk. Since there is neither radiated electrical or magnetic energy associated with optical fiber, hostile radar can not home in on the cable [Ref. 13]. Tapping or bugging the cable is also difficult. Optical Fiber can also meet

TEMPEST security specifications, and ruggedized fiber have also proven extremely durable in severe environments.

5. Cost

Cost may not be the deciding factor for fiber deployment at a tactical level, but as the price comes closer to actual cost of copper, the benefits of the fiber will make it much more appealing for installation. In fact it is not the price of the fiber cable that makes it expensive. It is the elector-optical interfaces that is responsible for the higher cost. Nevertheless, fiber cable is beginning to compete on an equal basis with coaxial cable in LAN installations.

Rising sales of FDDI interfaces and the recent development of a less refined version of FDDI that uses shielded twisted pairs copper cabling has had a major impact on prices in the optical market. In the last two years the price for FDDI adapter card (interface) has declined from \$15,000 to \$3,500. Though the price reduction has been dramatic, it is still higher than the older LAN technology, which commonly costs under \$600 per workstation. Different vendors of FDDI products, like IBM, National Semiconductors, and Advanced Micro Device Inc. (the first FDDI chip supplier) expect the FDDI desktop interface to reach a more reasonable price level in the near future, as shown in Table 3-4 [Ref. 35].

Table 3 - 4. PROSPECTIVE FDDI COMPONENT PRICE AND LOWEST END-USER PRICE

| Component cost of end-user price | 1990 Fiber user | 1994 Volume Workstation-user | 1994 Volume PC-user |
|---|------------------------|-------------------------------------|----------------------------|
| FDDI chi set or chip | \$350-400 | \$150 | \$99 |
| PDM | \$350 | \$50 | \$25 |
| Omer Component | \$100 | \$60 | \$30 |
| Lowest card price user | \$3,750 | \$1,300 | \$770 |

6. Station Management

Station Management (SMT) specifies all of FDDI's built in management services. SMT initializes links between nodes, inserting and removing nodes dynamically as the network configuration changes in ordinary use. It monitors each link for fault conditions and

automatically reconfigures around any problematic link. It provides statistical monitoring of performance analysis, error detection and fault isolation. Filling a critical need of network managers, SMT provides the ability to control FDDI LAN, setting LAN operating parameters and policies, and controlling station configuration. No previous LAN standard has included such a complete set of management capabilities as FDDI.

C. COMBAT SYSTEM CONFIGURATION USING FDDI

The basic design approach was to create a Local Area Network (LAN) architecture that physically connected all the components of the combat system. The proposed real-time combat system encompasses the use of physically distributed microprocessor-based computers in arrangement with the equipment they support. Interdependent activities that are executed on different stations (nodes) communicate via the network. In this proposal, a LAN based on a dual ring of optical fiber and the FDDI networking standard will provide the interconnections between stations.

The system configuration developed with the various components is designed to address the flow of information through the combat system, along with its operational requirements placed on the system. Figure 3-2 depicts the combat system configuration using FDDI. Integral to the system is a real-time database of geographical and intelligence information. The combat system is organized in a detect-control-engage sequence. Because information is transmitted to multiple locations, the dual ring architecture supports an integrated detect function. Likewise the use of weapon systems are coordinated through the network by manual or automatic doctrines.

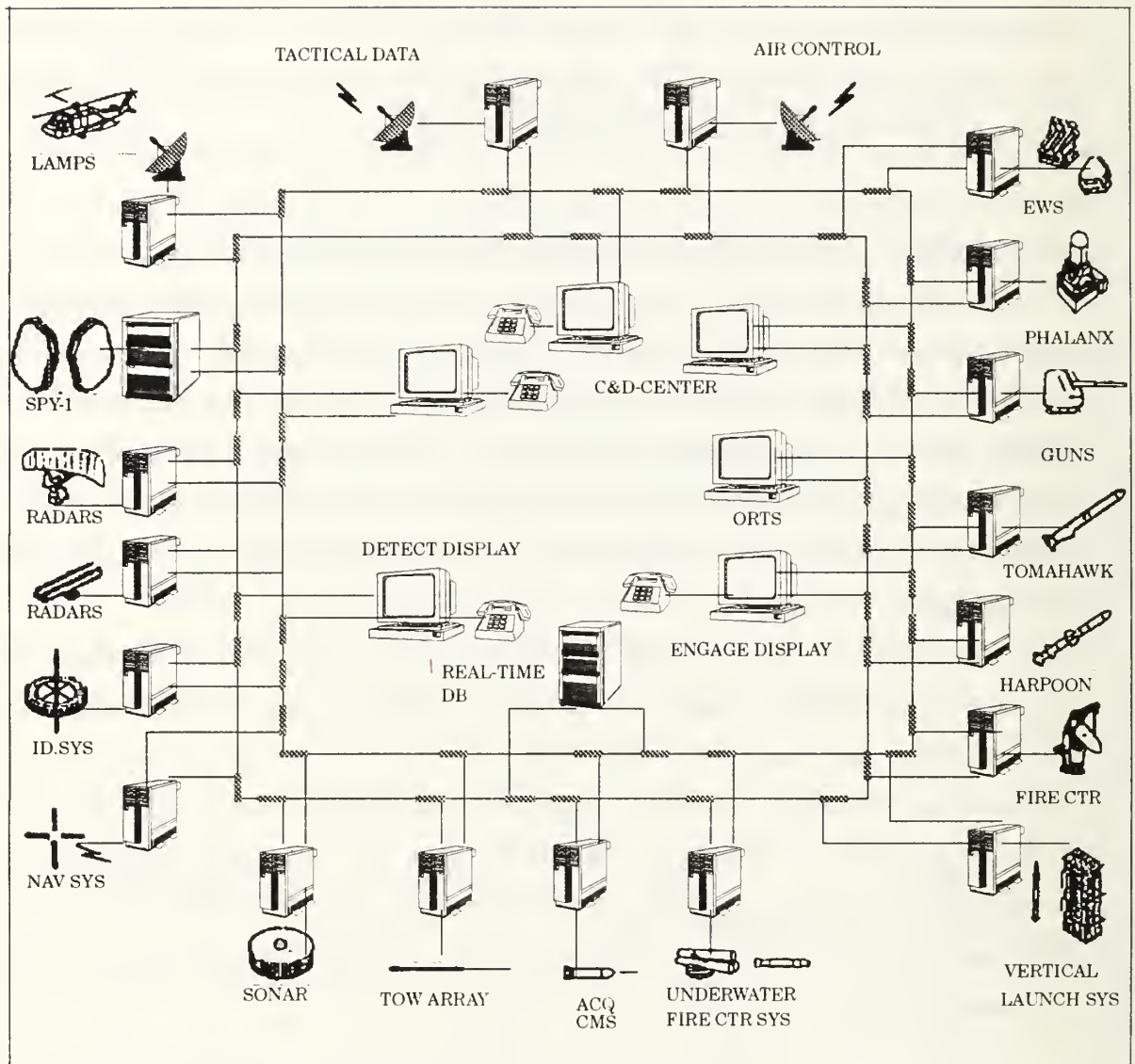


Figure 3 - 2. Combat System using FDDI

IV. IMPROVING THE HOSPITAL HEALTH CARE SYSTEM WITH HIGH SPEED NETWORKS

This chapter investigates the possibility of replacing the low speed networks currently used throughout the Hospital Health Care system with high speed networks. The high speed network would then interconnect the medical hardware, electronic equipment and computers into one interhospital communication network, possessing a simple topology, higher data transfer capability, and improved reliability. The external network would be connected to an array of potential sources as well as customers of the hospital.

Section A surveys the Hospital Health Care system. The modern hospital can be accurately described as one of the most complex organizations in existence. The typical hospital pursues ongoing research relating to the disease process, constantly monitors the effectiveness of drug therapies, assesses the different modes of delivering services and seeks economically feasible means of integrating and fully utilizing new technologies.

Clinically oriented information systems are proliferating in hospitals and clinics. Hospitals are employing Hospital Information Systems (HIS), Picture Archiving and Communication Systems (PACS), Information Management and Communication System (IMAC), etc. Ancillary departments are managing their diversified information systems. As new networks are being developed, the hospital information system and departmental systems are being interconnected. The proliferation of information and image management has resulted in creating a vast quantity of data that has to be transported between computers. Section B investigates whether a metropolitan and wide area network, based on optical fiber, can provide sufficient interconnection to support the expectations of flexibility, reliability and higher throughput rates for the system.

Section C presents the configuration of a Hospital Information System high speed networks. The internal network chosen uses a fiber optical dual bus technology, as specified by the IEEE 802.6 standard (Distributed Queue Dual Bus). The DQDB protocol has been chosen for its high bandwidth and the ease of migration with which it can interface with a *wide area network* (WAN) specified by a technique called SONET/ATM. Technological advances in SONET/ATM standards have made image communication practical when transmitted through the public switched network over fiber.

A. THE HOSPITAL HEALTH CARE SYSTEM

Hospitals, or their precursors, have been in continuous operation since antiquity. Among the Greeks the dedication of certain temples to the specialized practise of caring for the sick stretches back into the mist of prehistory. During the middle ages religious communities established hospitals to care for the sick who were impoverished or lacked family members to provide care. Because of the high incidence of contagious and often deadly disease, people with means avoided the rudimentary hospitals of plague savaged Europe at all costs and hospitalization became synonymous with the "underclass." The age of enlightenment and the rekindling of interest in the scientific method was directly reflected in the hospitals of the time as institutions were established with the objective of learning more about the nature of disease and ways to cure and control it.

The division of labor in these hospitals was typically organized into three major positions: physicians, nurses and pharmacists. The conceptualization of the hospital as the workplace for this trio of caregivers established the prototype for the modern hospital, which could be described as a factory for the production of health care goods.

As the industrial revolution came of age in the 19th century prominent community leaders and successful industrialists began to establish hospitals motivated by a desire to create greater stability and predictability within the work force. A new style of health care resembling military organization became fashionable. With the new emphasis on a military style hierarchy, the role of the physician became preeminent as virtually all decision making and information gathering, as well as diagnostic procedure and treatment were clearly placed in the physicians sphere of responsibility.

The temporary devaluation or displacement of the nurse as an esteemed member of the trio of caregivers was soon to be corrected by another event of the industrial revolution, the enhanced lethality of military weaponry. In distinct contrast to the almost sacrificial level of fatalities due to wound trauma, experienced during the American Civil War, the care that nurses provided in World War I proved to be of incalculable value in saving lives, thereby firmly establishing nursing as a necessary component of hospital care.

The modern hospital can be accurately described as one of the most complex organizations in existence. The hospital staff not only seeks to save lives and reduce suffering, but is also

actively engaged in preparing for the future. The typical hospital pursues ongoing research relating to the disease process, constantly monitors the effectiveness of drug therapies, assesses the different modes of delivering services and seeks economically feasible means of integrating and fully utilizing new technologies. In addition, many hospitals serve as education and training centers for doctors, nurses and other health care personnel.

New knowledge constantly reshapes the tasks of diagnosis and treatment, making it difficult to keep up with current developments in the respective fields of medicine. Part of the complexity of hospitals can be explained by the types of services provided. Hospitals have traditionally been categorized according to whether they provide service for all types of patients (general hospital) or a special type (specialized hospital). From the point of view of resource allocation, it is usually known that, during a particular period, a certain numbers of doctor-hours, nurse-hours, imaging-units, surgery-units etc., will be available. Difficulties arise when attempting to disentangle the enormous number of service mixes and organizational arrangements that might be derived from the resources. This complex web of interacting parts are found in almost every country. Although the organizational structure, principles of financing, and so on may differ from one country to another, the basic functions are more or less the same everywhere.

During the late 19th and early 20th centuries, technological advances made it possible to perform more precise diagnosis and treatment and to standardize surgical procedures. The invention of the X-ray machine improved diagnosis, enabling the physicians to see bones that were broken or in the process of healing. Anesthesia made surgery more manageable, while techniques established to prevent sepsis (infections) made it possible to save lives that previously would have been lost.

As early as the mid 1960s some visionaries saw the computer as a solution to some of the problems confronting the health care systems. The computer could store and retrieve data much more efficiently than people could. Diagnostic imagers with a digital output would eliminate improper exposures and delays due to film developing. Besides digitized images, the computer system could handle patient recording, surgery-assistance, billing and reporting, teaching, decision making, and administration. Increasing standards of patient care demands instantaneous access to critical information. An additional challenge is the use of long-haul

telecommunication networks to shuttle health care information around the country, and automation of mandatory reporting.

For the purpose of the present thesis it is convenient to divide hospital health care into a clinical segment and an administrative segment. In the administrative segment computer systems support such functions as accounting and management, material management, office automation, and administrative decision making. In the clinical segment computer systems support patient care, diagnosis, surgery, pharmacy, and medical decision making. Computer systems may also support clinical education and medical research. In this thesis the administrative areas will not be explored in detail, since extensive commercial information is available. Figure 4-1 depicts the functional areas supported by an integrated computer system.

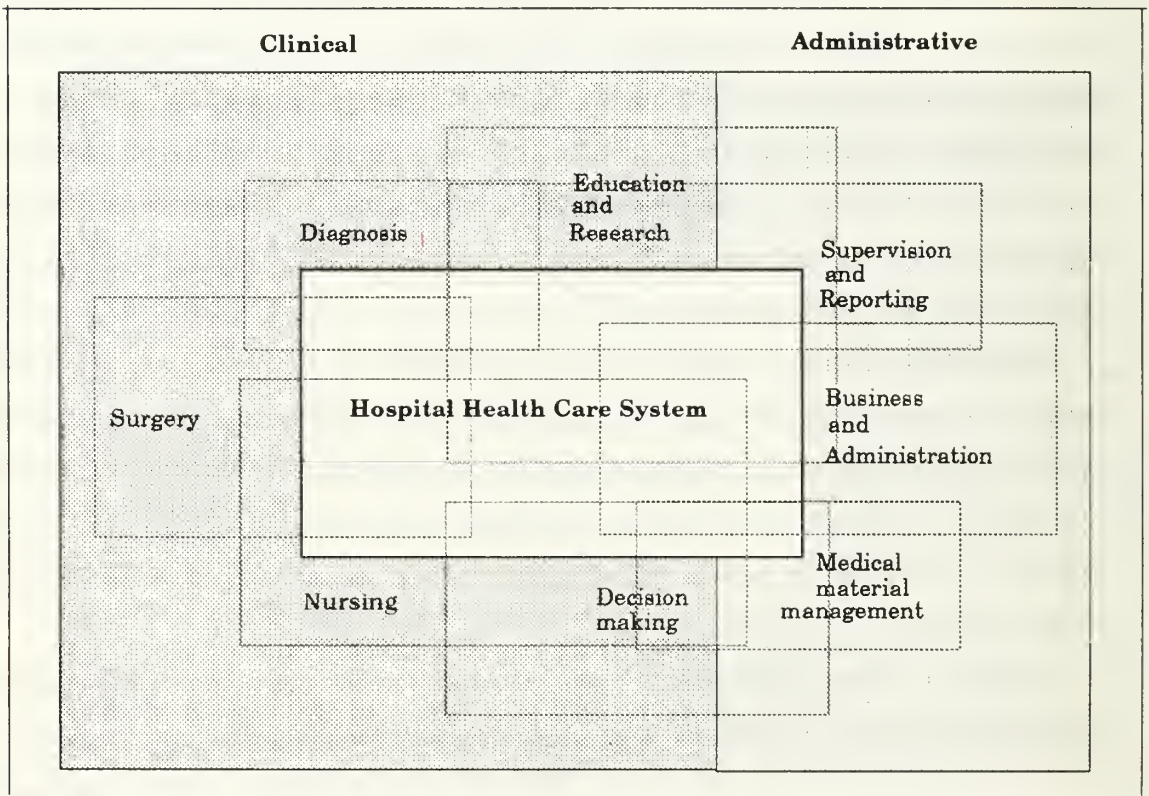


Figure 4 - 1. Functional areas in a hospital health care system

1. Diagnosis

Accurate diagnosis is of central importance for good medical decision making. Diagnosis can be complex, particularly as the volume of knowledge accumulates and a patient's history becomes more complex. Researchers have therefore been attempting to develop computer assisted diagnostic tools to aid physicians in this task. Integrating fiber optics and digital technology allows transmission of digitized images throughout the hospital, making them readily accessible to physicians, radiologist, pathologist, nurse, etc. Since the 1970s computed imaging systems that produce cross-sectional images of internal parts of the body have appeared, with rapid progress in the sophistication of the technology being made at an extraordinary pace. These include X-ray computed tomography (CT), ultrasound (US), magnetic resonance imaging (MRI), and nuclear medicine imaging (NMI).

a. Computed Tomography

X-ray computed tomography (CT) promises extensive applications for medical diagnosing because of its ability to provide non-destructive, cross sectional imaging of the internal structures of a patient. CT uses X-rays to produce thin transverse sectional images of the body. The modern CT-scanner uses a fixed set of detectors surrounding the patient and a moving X-ray tube. In this manner, the X-ray beam can pass through the body from a variety of angles. The array of detectors and their associated electronics convert incident X-Ray energy into a variable signal that is then processed and reconstructed to form a visual image through the aid of a computer system. Scanning the X-ray beam across the acquisition area produces a series of one-dimensional profiles. Each profile is composed, and together these provide the raw data that will be processed into an image. *Synchrotron radiation*, which makes high intensity, tunable monochromatic X-ray beams, provides a CT scanner with high spatial resolution.

Less than 10 years ago, CT was considered the ideal method for examining the central nervous system. Magnetic resonance imaging (MRI) has since taken the lead in that role. Today, CT is still the preferred technology in studies of the abdominal cavity and the joints of the body. However, reductions in scanning time coupled with improvements in contrast enhancement are transforming MRI into a technology highly suited for cardiovascular, abdominal and orthopedic exploration, edging into the functions that were once exclusively CT procedures.

Nevertheless, CT technology holds an advantage in pricing (CT scans range from \$300 to \$450, compared to a current cost of \$750 for a MRI examination) and is still considered to be the best available method for producing three dimensional images on more than one plane. A new CT processing technique enables interactive and almost real-time reconstruction, producing a 3-D image with realistic shading, composed of 320 pixels and 30 slices, in 1.3 to 2.0 seconds [Ref. 15]. There are some instances however where MRI's high performance resolution may well be worth the added expense, and currently both technologies complement each other in many hospitals equipment inventories.

b. Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) makes use of the magnetic field and radio frequency (RF) waves to generate intensity-modulated images from specific sections of the body. Signal intensity is measured by placing the patient in a strong magnetic field, irradiating the region of interest with RF waves, and recording the radiation emanating from the patient. The intensity of a point within an image is determined in a complicated fashion by the number of hydrogen nuclei (protons) at the corresponding point in the patient and also the chemical makeup of the tissue at that point. Various imaging techniques can produce drastic differences in imaging appearance by emphasizing different aspects of the chemical structure.

Most MR images are two-dimensional cross-sectional slices about 5 mm thick. To obtain high resolution of three dimensional from 2-D sections, slices down to 1 mm can be taken. The expense of 3-D imaging arises from the processing time. The commercial MRI model takes measurements every 10 ms, making it possible to acquire a 3-D image in five to ten minutes. Real-time imaging is also possible, but research aimed at establishing the threshold for the power levels needed to produce detailed imagery without endangering the patient is still ongoing. The use of MRI for detecting phosphorous and other elements in tissue, known as magnetic resonance spectroscopy (MRS), may have found its first clinical applications in diagnosing coronary artery diseases. MRI 3-D reconstruction is proving to be more valuable than CT reconstruction because besides distinguishing bone from tissue, as CT does, MRI can also distinguish the different types of tissue, such as fat or lesions, and fluids. Recent interest has focused on MRI modifications that would allow laser surgery to take place inside the scanner.

c. Ultrasound

Ultrasound imaging (US) instruments employ the pulse echo method. The image is composed of a multiplicity of lines, each of which depicts the stream of ultrasound echoes received after the emission of a single pulse. The location of dots along each line is determined by the time intervals in which the echoes are received, and hence display the depth at which the echo producing structures are located. For simplicities sake, the images formed from the combination of these lines are regarded as a “picture” or acoustic photograph of the insonated tissues.

Ultrasound imaging has been in use for some time, but recent advances in sensor technology and its relatively low costs compared to CT and MRI has opened up new areas for its application. Since the traditionally X-Ray anginography necessitated injected a radio-opaque iodine dye directly into the blood stream, the non-invasive character of ultrasound imaging makes it particularly preferable over the traditional procedure. Using a technique that directs ultrasound waves, through the skin, at the blood vessels the Doppler sensors can detect the variations in blood velocity and the return frequency is the tissue-encased peripheral vessels.

d. Nuclear Medicine Imaging

In positron emission tomography (PET) gamma rays are used to produce images of human body organs. The gamma rays are produced by a positron emitting tracer that is injected into the patient. An emitted positron annihilates when it contacts with a negative electron producing two gamma rays. The several million gamma rays that result from the annihilation are transformed into three dimensional image of the tracer distribution with the aid of an image reconstruction algorithm and processing hardware. Since the tracer is typically associated with particular metabolic functions in the body, the reconstructed density distribution may be used to study chemical and metabolic activity. The tomograph consists of a ring of detectors surrounding the patient which feed timing signals to the processing hardware. Single photon emission computed tomography (SPECT) uses a data collection and reconstruction process that separates the underlying and overlying distribution of radioactivity from the region of interest by generating images of cross-sectional slices. This is accomplished by using a scintillation camera coupled to a computer. To obtain multiple views,

the camera is rotated around the patient and computerized reconstruction techniques generate the cross sectional images [Ref. 61].

PET and SPECT technologies are beginning to be applied in areas of neurological and cardiological diagnosis where ultrasound and MRI have been dominant or preferred technologies, but the higher expense associated with its use, coupled with a general unfamiliarity with the new technology may preclude it from having significant impact on the market in the short term.

e. Biomagnetism

There is at present a growing excitement in the medical community because of recent developments in the application of biomagnetic technology. The techniques employed show the capacity for sensing the tiny magnetic fields emanating from the heart and brain and therefore hold great promise for diagnosing disorders of those organs. Even though the fields at the surface of the head are only one millionth of the earth's magnetic fields, the sensors referred to as SQUIDS (superconducting quantum interference devices) can localize brain activity with a spatial accuracy of a few mm [Ref. 39]. Cross talk among the sensors has proven to be an obstacle in applying the technology, and most recent measurement systems employ as many as 37 sensors. Nonetheless the promise of gathering crucial data from very specific locations would be a vast improvement over electroencephalogram (EEG) which only provide generalized information on brain activity. The biomagnetic techniques also have the needed advantage of being completely non-invasive.

f. Pathology and Laboratory Imaging

A histological image and ECG are the two most common types of image based information in pathology and laboratory medicine. A histological image is usually based on real material such as specimen dyeing from hematoxylineosin. In order to enhance contrast, a specimen normally requires some manual preparation before it is placed under the microscope. The image is projected from under the microscope onto a high resolution color monitor to assist the pathologist in his analysis. Moreover real-time stage movement and magnification changes are required in order to achieve a thorough survey of the specimen prior to diagnosis. A spatial resolution of minimum 1000 lines (pixels) approximates the quality of microscope [Ref. 59].

In the clinical laboratory, the use of computers enable the laboratory to do more tests, at a lower cost per test, and achieve more rapid reporting [Ref. 6]. In effect, the computer allows clinicians to surpass the limitations of scale while using familiar techniques and tools. That is, the computer system facilitates operations that would not be practical using manual methods.

2. Surgery

Presurgical planning is quickly evolving from a qualitative art into a quantitative science. Especially in the area of posttraumatic reconstruction, sophisticated computer graphics based on MRI and CT images are beginning to be used to tell the surgeon the exact dimensions of bone grafts, and to design custom implants produced by numerically controlled machine tools. The greater spatial resolution of MRI (now less than 1 mm), as well as improved three-dimensional reconstruction of MR images, have enabled physicians to rely more heavily on the images for presurgical planning. With the advent of low cost workstations networked to the diagnostic imaging tools, a plastic surgeon will soon be able to predict a patient's postoperative appearance with a much higher degree of precision, and achieve better symmetry when reconstructing damaged facial structures. These same computer-based tools are already assisting neurosurgeons. Computer assisted surgery (CAS) is a new navigation aid for skull surgeons. The combination of 3D coordinate measurement techniques, voxel processing methods, and pseudo 3D-imaging supports preoperative planning, path-finding during the operation itself, and postoperative therapy control. The 3-D images help the surgeon to navigate the best pathway into the brain, avoiding the motor cortex, and to calculate the volume of tumors and other abnormalities [Ref. 3].

Before the introduction of instrument navigation, an aircraft pilot had to abandon his mission whenever weather conditions deteriorated beyond the point when he/she could expect to securely arrive at the destination using visual orientation alone. This is somewhat comparable or parallel to the status of today's surgery. CAS will introduce instrument navigation into the surgeon's daily practice by providing 3D position-measurement techniques for the theater. The surgeon's map will be a pseudo 3D presentation of the patient, charted from CT images, MR images, etc. A measuring system capable of determining an instrument's position with respect to the patient will be the navigation guide.

Lasers, coupled with fiber optic and computer hardware, are finding application in the surgical field. Especially ophthalmic surgery, urology and gynecology, blood vessel suturing, and photodynamic therapy for cancer. Inactivation of viruses in transfusable blood products is a promising area. The potential for laser angioplasty, the use of light energy to blast a way through arterial plaque, has also captured the imagination of research engineers. The ultimate goal of opening coronaries by sneaking a laser bearing catheter into the heart is still to come.

3. Nursing

Computer system can also bring improvement to the nursing ward. Instead of having a nurse manually monitoring vital signs, a "smart" bed may actually record and monitor them directly, alerting the nurse to exceptions, making the process simpler and more accurate. Patient surveillance, therapeutic decision making and treatment can be supported by computer systems. A challenge is presented in that nurses and physicians need cogent and relevant information rather than raw data, so highly sophisticated "knowledge-based" systems must be developed and customized for the hospital ward environment. The system must not only be capable of thoroughly monitoring the patient, but also presenting its results in a meaningful and comprehensible way.

Radiation therapy is one of the three currently recognized methods for treating a patient with a tumor. The other two are surgery and chemotherapy. The process of designing a radiation treatment for a patient is known as radiation treatment planning. A computer system that would provide the basis for interactive responses in the treatment plan as the treatment status changes throughout the course of its application (e.g., intensity, shape or radiation source) may greatly improve the final determination of the treatment. A 3-D image could provide vital information in regard to the dosage various organs and tissues are receiving and also provide a dynamically evolving illustration in regard to the efficiency of the treatment regime being followed [Ref. 48]. Though such a system would obviously be of significant utility, making the transition from vision to working prototypes requires overcoming engineering problems of tremendous complexity. Calculating the volume distribution of radiation dosage as it interacts with the patients anatomy and then display the information pushes forward frontier of computational complexity. The complexity factor is accelerated further by the need

of interactive feedback in near real-time in order to closely monitor the effect of changes in the treatment protocol.

For each patient, hospital operations generate a large number of data sets of different types and formats. These data sets include handwritten reports, typed forms, computer based data, voice messages and reports as well as diagnostic images. The patient files are really multimedia documents, and therefore require the use of multimedia communication and storage technologies. Recent development in high speed communications technology have resulted in some interesting new applications for distributed computing systems (DCS). A DCS is generally comprised of s groups of workstations and shared input/output (I/O) devices interconnected by a local area network (LAN). The advent of fiber optics and broadband integrated service digital networks (BISDN) has extended the potential of these systems by providing high speed, low bit error rate and multimedia transmission. One primary beneficiary of this technology is the distributed multimedia information system. In a general multimedia environment, databases would contain various type of information such as text, video, images, and full motion video. An integrated transmission system permits efficient delivery of multimedia information to many different locations and terminals. Users may communicate via telephone, personal computer or workstations, health function monitor, and the like.

The development of optical storage technology will have a major impact on the development of the medical communication network. The problem of storage and retrieval of patients' records are being eased with the availability of high capacity magnetic disks and optical disk technologies. Laser based optical disks may become the primary method for the storage of image archives or databases in almost all medical imaging applications.

4. Supervision and reporting

Digital networks based on fiber optics which can carry voice, video and data transmission are able to move a large volume of messages rapidly, inexpensively and over long distances. This will enable physicians to conduct consultations from remote institutions and municipal or private offices. Teleradiology is one aspect of such a networks' power. For example, by using the networks, physicians will be able to access test results remotely by computers. The solution doesn't lie in the computers but in use of the networks. Health care telecommunication fills a need for information exchange, and may create an increasingly

independent health care community. Hospitals may find themselves fulfilling the function of active information hubs. Eventually, certain facilities might develop into "service bureaus" serving as health care information centers for entire regions.

One of the most important segments of the health care delivery system is the clinical decision making process that is exercised during the diagnostic and therapeutic phases. With the capacity to support remote medical consultation, expectations for higher quality, efficient resource use, and more homogeneous care might be met. Since vision is by far the sense that processes and interprets the greatest volume and widest range of information, the diagnostic results will rely heavily upon the quality of the images remotely displayed.

In most countries physicians are required by law to report certain types of infectious diseases to the principal health authority. Likewise several country have established national databases for vaccination records. This is due to the effort of the world health organization (WHO) in defining the levels vaccination coverage that are needed to safeguard against epidemic contagion of certain diseases. In those countries where health services are provided by a central social security apparatus, there are numerous patient transactions between hospitals and municipal communities. Furthermore when a patient is confirmed to be ill, he is often entitled to a social security payment.

5. Education and research

The computerized mannequin is just one example of the growing number of sophisticated teaching tools available to nurses, medical students and physicians. The computer devices attached to the mannequin monitor the patients medical status and respond with feedback to the students treatments. Patient simulations offer students the opportunity to learn clinical techniques without involving risk to a real patient [Ref. 32]. And for physicians, patient simulators, like flight simulators for pilots, offer valuable crisis medical training. At medical schools students are finding that computers can make learning easier and more fun. Realistic learning can be facilitated by use of high speed networks. Students may view a display of 3-D images with an overlay of voice or text for diagnosis, and have access to a real time monitor display of a surgical procedure. Dynamic tutorials incorporating elaborate graphics, animation and self-tests; programs ask students to make clinical decisions and instantly display the consequences of their choices (interactive learning). The computer can

compress hours of experience into 15 minutes of computer time, and provide individual feedback as well. The computers may not take over the teaching role, but a large portion of medicine is focused toward processing information, and computers are very good at teaching the processing of information. Computer literacy is becoming essential in day-to-day medical practice. Physicians not only use them to store and manage patient information, but they are used extensively in diagnosis and are becoming more frequently used in surgery. "In five years, students won't be able to become effective doctors without knowing something about computing" [Ref. 32].

Continuing education and research requirements can also be supplemented by teleconferencing. With high speed networks communications for education and research, hospitals can reduce travel expenses for their employees and the time spend away from work. It also gives the hospitals a chance to increase a number of educational programs offered to their employees.

6. Future health care concepts

Patient consumerism, new technologies, cost containment and outpatient care are trends in health care that have permanently altered hospital management practices and methods of care. Besides these very fundamental changes in our system of health care, we may also expect to see changes in the physical form of hospitals. The forces of a new marketplace may no longer be contained within the walls of the older institutions. The patient/customer will shop for cost, quality, and convenience in health care services. Responding to this new marketplace, hospitals of the future will architecturally alter their physical plants to resemble commercial and retail centers. The new age health center will be the connecting point for a variety of different services including, imaging clinics, laser clinics, regeneration centers, biotechnology research, birth centers, hospice and self-care. To accommodate the rapidly changing medical technologies MRIs, lithotripters, lasers, and cardiac catheters labs will be built into room-sized modules and interconnected with high speed networks. Convenient, self-service medical malls will offer a wide variety of ambulatory-care services at health shops and wellness programs. Outfitted with miniaturized scanners and imaging equipment, mobile diagnostic clinics will travel throughout the country. Their highly equipped field staff will be connected via satellite to diagnostic computers and specialists at medical centers if necessary.

B. A HOSPITAL HEALTH CARE SYSTEM USING HIGH SPEED NETWORKS

This section presents some general ideas as a rationale for the introduction of *high speed networks* (HSN) into the health care system. Traditionally, the introduction of any new technology into medical practice had to be clearly premised upon a sound prospect of greater profitability. As the technological innovations of the last 30 years have impacted the population with the means to access them, a gross and apparent disparity has developed between the haves and have nots in regard to the quality of health care that each receives. This disparity has pressed open a world-wide debate as to whether health care is purely commodity of the market place or possesses some characteristic of a human rights. Without delving too deeply into that question and its far-reaching moral and philosophical implications, it is quite evident that the quality of health care is hard quantifiable in purely economic terms to the individual who needs it. The implementation of high speed networks can be justified by other parameters than pure cost effectiveness, such as significantly enhanced operational and clinical performance. For reason of simplicity this section has been divided into internal and external segments. We shall however integrate the two aspects of health care in the final proposal for a networked, high speed hospital information system.

1. Internal hospital network issues

In order to appreciate the impact of high speed networks in the hospital environment, a comparison is needed with how operations are structured out with or without HSN. As the most general of benefits HSN will certainly impact and improve the flow of operations by reducing the element of time lag in virtually every aspect of information processing, and therefore should at least exhibit an inferential improvement in the effectiveness of medical treatment. In order to test this hypothesis however, a close examination of HSN processing compared to the low speed networks (LSN) already operating needs to be conducted. Systems such as CSMA/CD and 802.5 Token ring (maximum transport capacity 10 Mb/s) currently handle communications in numerous hospitals, and perhaps a number of functions, such as, simple patient records, word processing and various laboratory and pharmacy inventories, etc. could be adequately supported by an LSN system. The transportation capacities of these LSNs are completely inadequate however as support for

technologies that would actualize image communication, interactive learning and video conferencing.

The quality of the medical imaging data is extremely important for proper diagnosis and treatment of patients. Having images with larger amounts of information (better resolution), images from other modalities displayed simultaneously, etc. will be conclusive to better decision making. The availability of images in terms of the time needed to retrieve them is a distinguishing feature of HSN. The rapid availability of images induces a particularly progressive benefit in that it facilitates consultations between colleagues and departments. At 512 pixels/line the scan lines can normally be seen on the monitor. The move up to 1024 pixels/line represents a major step in clarity, but in future medical applications true resolution of 2048 pixels/line or 4096 pixels/line may be required [Ref. 9, 41]. The contrast resolution represents the number of gradations of gray or number of colors that can be displayed at each pixel. The range varies from 256 colors with 8 bits (b)/pixel to billions of colors for 32 b/pixel. Diagnostic quality when compared to medical films requires at least 8 b/pixel, but future applications may require true color from 16 or 24 b/pixel. The amount of information bits contained in an image is a function of the spatial resolution (image length times images width in pixels) and contrast resolution (bits per pixel). The data rates the network must support for two-dimensional images are depicted in Table 4-1.

Medical video-conferencing could well be a useful application, with implementation of HSN. This can be implemented using workstations with the ability of presenting one or more incoming full-motion video signals (30 frames per seconds) with high quality audio. HDTV quality (1125 * 1920 pixels resolution) which adds additional picture detail, better color and larger screen will make video-conferencing even more productive.

Data acquisition modalities, including computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and single photon emission computed tomography (SPECT), all have the potential for producing three-dimensional arrays of values [Ref. 47]. Computer generated imaginary offers an effective means for presenting

three-dimensional medical data to the clinician. Table 4-2 depicts the information contents in megabits (Mb) for some 3-D images.

Table 4 - 1. 2D-IMAGE SIZE AND TRANSMISSION CHARACTERISTICS

| Application | Image size (pixels) | Contrast Resolution (bits/pixel) | Information Contents (Mb) | Compressed Contents (Mb) w/ratio 10:1 |
|---|----------------------------|---|----------------------------------|--|
| CT MRI | 1,024*1,024 | 8 | 8.40 | .84 |
| | | 16 | 16.80 | 1.68 |
| | | 32 | 33.60 | 3.36 |
| US NMI Digitized X-Ray (2-D Images) | 2,048*2,048 | 8 | 33.60 | 3.36 |
| | | 16 | 67.20 | 6.72 |
| | 4,096*4,096 | 32 | 134.40 | 13.44 |
| | | 8 | 134.40 | 13.44 |
| | | 16 | 268.40 | 26.84 |
| Video-telephony Motion Video (30 f/s), HDTV | 1,125*1920 | 32 | 536.80 | 53.68 |
| | | 8 | 518.40 | 51.84 |
| | | 16 | 1,036.80 | 103.68 |
| | | 24 | 1,555.20 | 155.52 |

Table 4 - 2. 3D-IMAGE SIZE AND TRANSMISSION CHARACTERISTICS

| Application | Volume size (voxel) | Contrast Resolution (bits/voxel) | Information Contents (Mb) | Compressed Contents (Mb) w/ratio 10:1 |
|-------------------------|----------------------------|---|----------------------------------|--|
| CT MRI | 256*256*256 | 8 | 134.22 | 13.43 |
| | | 12 | 201.33 | 20.14 |
| | | 16 | 268.44 | 26.85 |
| US NMI 3-D Images | 512*512*512 | 8 | 1,073.74 | 107.37 |
| | | 12 | 1,610.61 | 161.06 |
| | | 16 | 2,147.48 | 214.75 |
| | 1,024*1,024*1,024 | 8 | 8,589.93 | 858.99 |
| | | 12 | 12,884.90 | 1,288.50 |
| | | 16 | 17,179.87 | 1,717.99 |

Success in developing networks, as with other computer applications, ultimately depends on software. Much attention is being paid to HSN protocols, such as the Fiber

Distributed Data Interface (FDDI) and Distributed Queue Dual Bus (DQDB). FDDI suits the high speed connection of computers and peripherals using fiber-optic media. The FDDI network is designed for an effective data transfer rate of 100 Mb/s. FDDI is based on a dual ring topology. Ring activity is based on the token-passing protocol. Recent work on improvements to the performance of FDDI indicates that a throughput of 300 Mb/s or more may be possible [Ref. 42, 43]. A further increase in transmission speed will lead to the incorporation of a single-mode fiber and Laser Diode (LD), which is what the ANSI X3T9.3 has suggested for the 800 Mb/s FDDI [Ref. 23]. DQDB is standardized by IEEE (802.6), and defines a MAN using fiber optic transmission medium that operate at a speed of 155 Mb/s. DQDB is based on two unidirectional buses that may be deployed in an open bus or looped bus (physical ring) topology. Bus activity is controlled by a "head-end" station (or stations), which generates a frame synchronous pattern.

The time required to access an image over a communication network can be calculated by dividing number of bits in the 2-D or 3-D image and the speed of the network. The access delay may be different from application to application. In a surgical environment near real-time images may be needed to support the surgeon. These images may need to be generated at a sequence of five to twenty frames per second. In the following computations only still images are considered. With suitable algorithms, data compression can reduce the information contents in bits significantly. A compression of image data to one tenth is already in practical use, and is incorporated in the computations. In video telephony it is more a question of, if the network can support the required data rate for real time motion (see Table 4-3).

2. External hospital network issues

We can hardly imagine the banking or the airlines industries without simultaneously thinking of the intense communication and information management systems they depend upon to operate. These models can be used as models of what the medical industry might aspire towards. A tele-medicine network is a vehicle for providing health care services to remotely located and underprivileged sections of society [Ref. 9]. The rural areas are often plagued by a shortage of health care providers and lack access to the quality health care resources found in urban areas. The interpretation of radiographic images is often necessary

for providing timely treatment. A diagnostic radiology service at a medical care facility without proper expertise, means a delay while films are transferred between the base and medical centers. A medical network is also useful in the field of pathology, where treatment is dependent upon an analysis of tissue or fluid. This means that for any remote patient, the waiting time is often days and possibly weeks. A tele-medical network would allow the radiologist, pathologist, and other specialists to be figuratively in two places at once, by communicating video images to a physicians workstation located at any remote site [Ref. 16].

Table 4 - 3. ACCESS TIME WITH DIFFERENT LOCAL AND METROPOLITAN NETWORKS

| Approximate Access Time in seconds/Sufficient bandwidth | | | | | | |
|---|--------------------|---------------------|------------------|----------|------------------|----------|
| Application | Image/Volume size) | Ethernet 10 Mb/s | DQDB 155 Mb/s | 100 Mb/s | FDDI 300 Mb/s | 800 Mb/s |
| 2-D Images | 1,024*1024 | .08 | 01 | .01 | 0 | 0 |
| | | .17 | .01 | .02 | .01 | 0 |
| | | .34 | .02 | .03 | .01 | 0 |
| | 2,048*2,048 | .34 | .02 | .03 | .01 | 0 |
| | | .68 | .05 | .07 | .02 | 0 |
| | | 1.35 | 09 | .14 | .05 | .02 |
| | 4,096*4,096 | 1.35 | .09 | .14 | .05 | .02 |
| | | 2.69 | .18 | .27 | .09 | .04 |
| | | 5.37 | .35 | .54 | .18 | .07 |
| 3-D Images | 256*256*256 | 1.34 | .09 | .14 | .05 | .02 |
| | | 2.02 | .13 | .21 | .07 | .03 |
| | | 2.69 | .17 | .27 | .09 | .04 |
| | 512*512*512 | 10.74 | .70 | 1.08 | .36 | .13 |
| | | 16.11 | 1.04 | 1.62 | .54 | .20 |
| | | 21.48 | 1.39 | 2.15 | .72 | .27 |
| | 1,024*1,024*1,024 | 85.90 | 5.55 | 8.60 | 2.87 | 1.08 |
| | | 128.85 | 8.31 | 12.89 | 4.30 | 1.62 |
| | | 171.80 | 11.09 | 17.18 | 5.73 | 2.15 |
| Video- telephony | 30f/s*1,125*1,920 | No | Yes | Yes | Yes | Yes |
| | | No | Yes | No | Yes | Yes |
| | | No | No | No | Yes | Yes |

With the type of carrying technology presently configured as the basis for the telephone networks, it is difficult to envision transmission of the vast amounts of data bits that

would be needed to shuttle medical images through the system. Moving medical images through the system requires transmission speeds at least two orders of greater magnitude than the T1 (1.544 Mb/s) private line service currently operating on the ISDN network which will soon be put on line.

Teleconferencing, accompanied with real time high resolution images is also precluded from wide-spread utilization because of the inherent incapacity to transmit the quality of necessary data. As a simple response to pressure within the marketplace for wide-spread commercial access to sophisticated teleconferencing forms, the public network will be forced to adopt a broadband integrated service digital network (BISDN). BISDN will be capable of carrying voice, video and data simultaneously, thereby opening the pathway for transmitting medical images. The BISDN might be aided in its transmission by a technique known as Synchronous Optical Network (SONET). SONET facilitates circuit switching by use of time division multiplexing (TDM) techniques. Two interface rates are currently being defined: a low speed interface at approximately 155 Mb/s and a higher speed interface at approximately 622 Mb/s. One view is that the 622 Mb/s pipe could be multiplexed into four channels of 155 Mb/s each [Ref. 4]. The first three would carry circuit oriented Broadband services of the continuous type, such as high definition video services (HDTV and teleconferencing). In addition to providing services such as on-demand entertainment, this would allow a physician to call a medical monitoring unit at a patient's bedside equipped with an HDTV camera and observe treatment. The remaining 155 Mb/s channel could carry a vast number of services operating at wide variety of speeds, from low speed voice circuits to switched multimegabit per second services capable of carrying services like medical images. The SONET framework allows higher speed interfaces to be defined. For example, 2.4 Gb/s SONET transmission facilities are already available on the market, and the evolution towards BISDN interface at that rate may prove to be relatively simple.

In Europe, a packet technique known as Asynchronous Transfer Mode (ATM) seem to be preferred for BISDN services. ATM provides a low-delay, packet-like-switching and multiplexing for various service types. At the interface, user information will be converted into short fixed length packets, called cells. The cell is attached to a header in order to indicate to the terminal equipment which service (and which terminal equipment) the cell of data should be directed to. There is a great deal of flexibility in the ways the basic transmission services

may be used, beginning with its use for STM, through a variety of hybrid schemes for mixed ATM and STM, to dedicated use of ATM. The hybrid solution may bring forward some advantages. SONET can use synchronous techniques to multiplex the overhead and payload yet still permits ATM techniques for multiplexing the user channel. In near future we may also see BISDN support the same services as presently supported by LANs, and as an alternative to other HSNs. Table 4-4 depicts the access delay for the T1 carrier and various SONET/ATM network speeds.

Table 4 - 4. ACCESS TIME WITH DIFFERENT WIDE AREA NETWORKS

| Approximate Access Time in seconds/Sufficient bandwidth | | | | | | |
|---|--------------------|--------------------------|-----------|----------|------------|------------|
| Application | Image/Volume size) | T1 carrier 1.544 Mb/s | SONET/ATM | | | |
| | | | 155 Mb/s | 622 Mb/s | 1,244 Mb/s | 2,488 Mb/s |
| 2-D Images | 1,024*1024 | .55 | 01 | 0 | 0 | 0 |
| | | 1.09 | .01 | 0 | 0 | 0 |
| | | 2.18 | .02 | 0 | 0 | 0 |
| | 2,048*2,048 | 2.18 | .02 | 0 | 0 | 0 |
| | | 4.36 | .05 | .01 | 0 | 0 |
| | | 8.71 | 09 | .02 | .01 | 0 |
| | 4,096*4,096 | 8.71 | .09 | .02 | .01 | 0 |
| | | 17.39 | .18 | .05 | .03 | .01 |
| | | 34.77 | .35 | .09 | .05 | .03 |
| 3-D Images | 256*256*256 | 8.71 | .09 | .02 | .01 | 0 |
| | | 13.05 | .13 | .03 | .02 | .01 |
| | | 17.39 | .17 | .04 | .02 | .01 |
| | 512*512*512 | 69.55 | .70 | .18 | .09 | .05 |
| | | 104.32 | 1.04 | .26 | .13 | .07 |
| | | 139.09 | 1.39 | .36 | .18 | .09 |
| | 1,024*1,024*1,024 | 556.35 | 5.55 | 1.38 | .69 | .35 |
| | | 834.53 | 8.31 | 2.08 | 1.04 | .52 |
| | | 1,112.69 | 11.09 | 2.76 | 1.38 | .69 |
| Video- telephony | 30f/s*1,125*1,920 | No | Yes | Yes | Yes | Yes |
| | | No | Yes | Yes | Yes | Yes |
| | | No | No | Yes | Yes | Yes |

3. A Hospital Information System using DQDB and SONET/ATM

Though hospital information system are becoming increasingly dependent on the technology they utilize, in the final analysis, the technology itself is only a tool or means to expedite their objectives. Knowing the limitations and appropriate uses of tool is of equal importance to understanding its potential advantages if a task is to be accomplished efficiently, with the desired results. Hospitals are steadily moving towards an environment where computers will be exploited as source of clinical information. The information system must provide image, text and voice data in an integrated manner that facilitates the physician's task of correlating the data and making patient care decisions in a timely and accurate way. The system is oriented towards providing the treating physician with a complete view of patient data. For multimedia data types, there is a unique set of requirements imposed on the communication component due to the size and characteristics of multimedia objects (see table 12). For some types, delayed data is of little or no use for multimedia application. Voice and video require real-time delivery, whereas text and images merely require timely delivery. Voice and video data can suffer errors in transmission without major degradation in service, depending on coding algorithm. For data transfer (text and numeric) errors cannot be tolerated. Table 4-5 depicts characteristic parameter values for some services [Ref. 25].

Table 4 - 5. TRAFFIC TYPES: CHARACTERISTIC PARAMETER VALUES

| Service | Maximum delay (seconds) | Average throughput (Mb/s) | Acceptable packet error rate |
|----------------------|-------------------------|---------------------------|------------------------------|
| Voice | .25 | .064 | $< 10^{-1}$ |
| Video (TV quality) | .25 | 100 | 10^{-3} |
| Compressed video | .25 | 2-10 | 10^{-9} |
| Data (file transfer) | 1 | 2-100 | 0 |
| Image | 1 | 1-1100 | 10^{-9} |

Critical to overall network composition are the factors of communication delay distribution and reliability. Effective communication protocols need to be provided by a spectrum of reliability levels and real-time characteristics to support a wide range of quality of service levels indicated by each media type and dictated by individual multimedia application. Currently DQDB guarantees the highest transmission rate (155 Mb/s). The DQDB technology by using a maximum of three set of countdown counters assures that the data from numerous

stations, and with varying priorities can be carried on the shared dual bus of a distributed network. Each subscriber is assured the most efficient queuing and minimum delay for its traffic. In short, one station will not "hog" the network and the user with soft real-time requirements can be assured that their needs will be met. A network based on FDDI (100 Mb/s) does not have the same bandwidth, but can guarantee hard real-time constraints, fairness among stations, and better reliability. Another advantage of DQDB besides high bandwidth is its slot (cell) structure which is similar to the SONET/ATM cell. This particular construction facilitates migration between the two networks [Ref. 62].

To achieve greater network reliability (e.g., protection against equipment failure or cable cuts) the buses can be deployed in a looped or ring topology. The slot generators of the two buses are physically placed in the same location. Note that the optical fibers are physically deployed as a ring, but logically, the system remains a Dual Bus. In the event of disruption in one of the buses, the system can be reconfigured so that a slot generator function can be moved to another physical location and the system remains operational [Ref. 4].

Recently developed technology permits fiber based image communication through the public switched network. The fiber based SONET/ATM network utilizes the bandwidth of fiber to communicate medical images and video to remote locations. This network architecture holds the promise of integrating voice, data, image and textual information. The SONET/ATM architecture takes advantage of the superior transmission characteristics of the fiber optic medium and eliminates the need for error correction. Another critical advantage is that the dramatic reduction in the rate of delay that this system is capable of achieving, creates the prospect of making real-time communication a reality.

Optical fibers are also ideally suited for use in electronically noisy environments. Electromagnetic interference can be a problem in hospital environments, particularly around machinery, medical hardware and other high-powered electrical systems. Optical fibers however are immune to those affects.

C. CONFIGURATION OF A HOSPITAL INFORMATION SYSTEM

As shown in Figure 4-2, the hospital information system consists of internal and external connectivity. Within the hospital, the medical imaging modules (such as CT, MRI, X-ray, US, Laser scanner equipments, etc.), image workstations, pathology and laboratory modules,

surgery modules, research modules, educational modules, physicians offices, nursing wards, administrative operational modules, and storage devices are all connected to the network. The proposal encompasses the use of physically distributed microprocessor-based computers, arranged with the medical equipment they support or as stand alone multipurpose computers. The hospital information system should run on any workstation, personal computer (PC), etc. Concentrators will connect the workstations, PC, etc., that logically belongs to a group, to the network. The star concentrator topology has been chosen for improved reliability and simplified maintenance.

Data processing is distributed among the machines in a client-server fashion, so that the applications and databases are located on different network stations. The Distributed Queue Dual Bus (DQDB) protocol is used to communicate between the stations across the internal net. The clinical (patient) files are stored on gigabyte file servers that employ a multimedia database structure to capture image, voice and text. The image workstation, PCs are client to the image servers, and provide an integrated display of multimedia information to physicians, pathologists, nurses, etc. Workstations are located in all the departments and patient areas. Image input stations are installed in image collection areas. The image display stations will be installed in patient treatment areas.

Figure 4-2 depicts the potential of a full application of the broadband integrated service digital network SONET/ATMs capability to interhospital medical information transmission. A main hospital, remote hospital, private physicians, image centers, etc. could be linked by the network. On ambulatory units and communities without fixed telephone networks (like ships), satellite transmission can be effectively implemented. Medical image transmission by satellite communication is now commercially available in USA [Ref. 29].

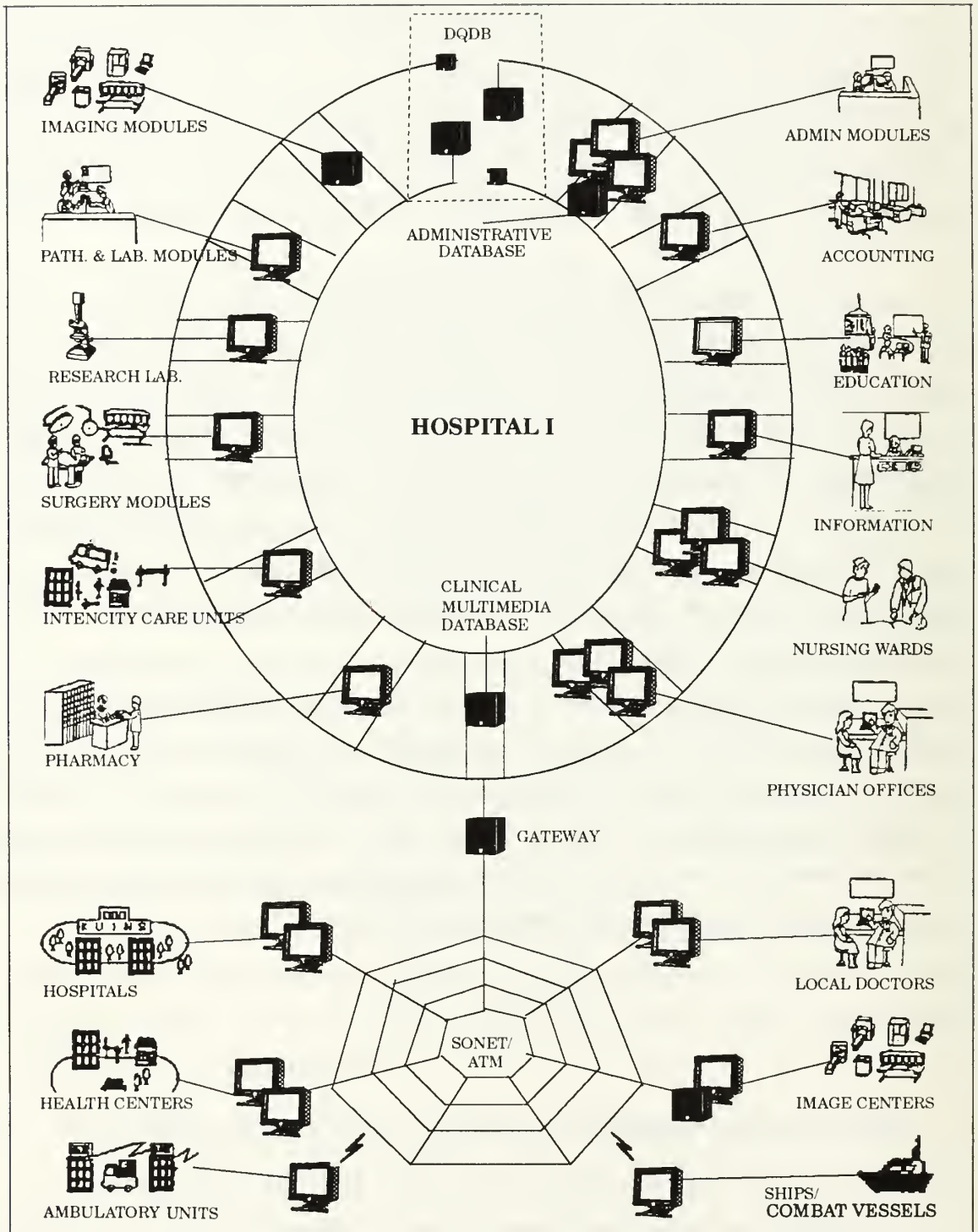


Figure 4 - 2. Hospital information system using DQDB and SONET/ATM

V. CONCLUSIONS

A. SUMMARY

This thesis has examined the feasibility of replacing the current Aegis communication system with an FDDI optical fiber network and the implementation of optical fiber communication in a hospital information system, employing DQDB and SONET/ATM techniques respectively for interhospital and external communication.

Estimates and expectations of Aegis performance requirements were compared to the functional capabilities of FDDI. The comparison resulted in a conclusion that the implementation of FDDI would not only sufficiently fulfill the performance requirements, but would also introduce a significant elevation in operational efficiency.

The ability to predict, determine and guarantee response time is imperative to a real-time combat system. FDDI offers both very high data transmission rate and a predictable, guaranteed access time. The high throughput of FDDI potentially enables combat system personnel to base their decisions on a greater pool of information. FDDI can also support the quantity of data transmission that is necessary to effect automatic doctrines in a combat system. The maximum time it takes for a station to transmit its data can be accurately determined, and guaranteed.

FDDI is also very reliable. Damage to the ring will not interrupt data transmission in the combat system, since the second ring or a ring wrap-around can be automatically configured.

The hospital can be segmented into functional areas that have specific needs in regard to computer integration and communication. Imaging, and particularly the rapid development of 3D imaging techniques, necessitates new and more efficient methods of communication.

The objective and motivation of the high speed networks architecture proposed within the hospital segment has been directed toward improving the quality of operations and thereby improving clinical performance. Employing high speed networks can result in expanding the base of patients a hospital serves, along with providing additional services for its current patient base, automate offices and nursing wards, and improve administrative efficiency.

The practice of medicine can also be directly impacted and improved. A high speed network can produce more rapid test results and expand and improve the basis of diagnosis

and surgical procedures. It can also facilitate the dissemination of specialized expertise among physicians and provide a forum for real-time consultation that otherwise would not exist.

B. GENERAL APPLICABILITY OF RESEARCH

Though the architectural configurations of high speed networks were presented for use in specific applications, the configuration techniques can be useful in other domains as well. In fact the configuration models can be utilized as the basis for the communication of many distributed systems. Since the configuration models span a variety of underlying communication mechanisms, such as hard real-time, high bandwidth, reliability, local or wide area topology, etc., other distributed systems (applications) may be grouped according to which network configuration would best serve their requirements.

C. DIRECTIONS OF FUTURE WORK

This thesis could only attempt to discuss the general impact of high speed networks applications in terms of the broadest perspective. In fact an extraordinary revolution in communication is beginning to emerge that will make the current technologies, and computer uses as antiquated as the abacus in a short time. The trend towards optical fiber all the way to the subscriber introduces the prospect of mass linkage between computers on a virtually international level.

The raw speed the new networks will increase the potential for information exchange a hundred fold. But proceeding beyond the issue of speed, the new technologies can also provide the more significant benefit of making expertise and state of the art knowledge and information available to a wide cross-section of population. Much forethought is called for in organizing these technologies so that their impact can be fully exploited for the public benefit.

In regard to the naval and hospital applications, there are several topics, such as employing optical sensors and an FDDI network to efficiently control the ship, an integration of the control and combat element of the ship, the economical aspect of an high speed network in hospital environment and reconfiguration of a hospital into functional modules supported by a high speed network that beg for future exploration. Unfortunately, it was beyond the scope of the present work to do justice to these areas of investigation, hence, they are left for future research.

APPENDIX A LIST OF ACRONYMS

| | |
|---------|---|
| AAW | Anti Air Warfare |
| ASUW | Anti SURface Warfare |
| ASW | Anti Subsurface Warfare |
| ANSI | American National Standard Institute |
| APD | Avalanche photodiode |
| ATM | Asynchronous Transfer Mode |
| BBC | Bandwidth Balancing Counter |
| BISDN | Broadband Integrated Services Digital Network |
| C&D | Command and Decision |
| CAE | Computer Assisted Engineering |
| CAD | Computer Assisted Design |
| CAS | Computer Assisted Surgery |
| CATV | CABLE TeleVision |
| CBR | Cambridge Backbone Ring |
| CCITT | Consultative Committee International du Telephone et Thelegraph |
| CD | Compact Disc |
| CDC | Count Down Counter |
| CG | Class Guided |
| CIM | Computer Integrated Manufacturing |
| CODEC | COder-DECoder |
| CSMA/CD | Carrier Sense Medium Access/Collision Detection |
| CT | Computer Tomography |
| DAC | Dual Attached Concentrator |
| DAS | Dual Attached Station |
| DCS | Distributed Computing Systems |
| DQDB | Distributed Queue Dual Bus |
| DS-1 | Digital line System-1 |
| EEG | Electron EncephaloGram |
| EMI | Electro Magnetic Interference |

| | |
|-------|---|
| EMP | Electro Magnetic Pulse |
| EW | Electronic Warfare |
| FDDI | Fiber Distributed Data Interface |
| FDMA | Frequency Division Multiple Access |
| HDTV | High Definition TeleVision |
| HELWS | High-Energy Laser Weapon System |
| HIS | Hospital Information System |
| HRC | Hybrid Ring Control |
| HSN | High Speed Network |
| I/O | Input/Output |
| IMACS | Information MAnagement and Communication System |
| ISDN | Integrated Services Digital Network |
| LAN | Local Area Network |
| LD | Laser Diode |
| LED | Light Emitting Diode |
| LION | Logical Integrated Optical Network |
| LLC | Logical Link Control |
| LSN | Low Sped Network |
| MAC | Medium Access Control |
| MAN | Metropolitan Area Network |
| MRI | Magnetic Resonance Imaging |
| MRS | Magnetic Resonance Spectroscopy |
| NMI | Nuclear Medicine Imaging |
| NNI | Network Node Interface |
| NRZI | Non Return to Zero Inverted |
| NTSC | National Television System Committee |
| OC-1 | Optical Carrier-1 |
| PACS | Picture Archiving and Communication System |
| PDU | Protocol Data Unit |
| PET | Positron Emission Tomography |
| PGM | Precision Guided Missile |

| | |
|-------|--|
| PIN | Positive Intrinsic Negative |
| REQC | REQuest Counter |
| RF | Radio Frequency |
| RFI | Radio Frequency Interference |
| SAR | Synthetic Aperture Radar |
| SAS | Single Attached Station |
| SMT | Station Management |
| SONET | SYNchronous Optical Network |
| SPE | Synchronous Payload Envelope |
| SPECT | Single Photon Emission Computed Tomography |
| STM | Synchronous Transfer Mode |
| STS-1 | Synchronous Transport Signal-1 |
| T-1 | Transmission-1 |
| TDMA | Time Division Multiple Access |
| TTR | Timed Token Rotation |
| TTRT | Target Token Rotation Time |
| UNI | User Network Interface |
| US | Ultra Sound |
| VCI | Virtual Channel Identifier |
| VLS | Vertical Launch System |
| VPI | Virtual Path Identifier |
| VT | Virtual Tributary |
| WAN | Wide Area Network |
| WCS | Weapon Control System |
| WDMA | Wavelength Division Multiple Access |
| WHO | World Health Organization |

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