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FIBER OPTIC SENSORS AND NETWORKS FOR  
U.S. NAVY SHIPBOARD TESTS AND TRIALS

by  
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FIBER OPTIC SENSORS AND NETWORKS FOR  
U. S. NAVY SHIPBOARD TESTS AND TRIALS

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(ABSTRACT)

After a U. S. Navy ship is built but before it is placed into service, many performance tests of all shipboard systems are conducted. These tests vary greatly in who performs the test, the purpose of each test, which system or systems are being tested, and the duration of each test. As naval warfare ships become increasingly complicated, the performance tests that are conducted also become numerous and complex. The current test philosophy prescribes that for each test and test organization, telemetry cables for electrical sensors are strung throughout the ship immediately prior to the test being conducted. As the shipboard tests and trials become more numerous and complex this philosophy becomes expensive from a labor and materials point of view.

This thesis proposes an economical solution to the current test and trials problem by offering a fiber optic network with optical sensors. The fiber optic network will be designed to accommodate as many different users as possible, and it will be installed once, during the new ship construction. Prior to the network design, optical fiber sensor schemes are discussed. One sensing scheme, using quartz crystal oscillators, looks promising for the test and trials application. This one sensing method can be applied to acceleration, velocity, displacement, temperature, current, and voltage. Thus economies can be realized by using one network and sensor type for the majority of tests and trials applications.

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# CHAPTER 1

## 1.0 Introduction

After a U.S. Navy ship is built but before it is placed into service, many performance tests of all shipboard systems are conducted. These tests vary greatly in who performs the test, the purpose of each test, which system or systems are being tested, and the duration of each test. All shipboard tests have one common element, however, the transfer of test data from the sources such as sensors to a common collection point such as a recorder or data multiplexer unit. As naval warfare ships become increasingly complicated, the performance tests that are conducted also become more numerous and complex. Two of the most technically complex ships currently being built for the U.S. Navy are the CG 47 (Ticonderoga) class guided missile cruisers and DDG 51 (Arleigh Burke) guided missile destroyers. Both employ the advanced AEGIS weapons systems and are similar in displacement, size, propulsion, weaponry, and threat detection equipment. The Navy is currently in the middle of a twenty-seven ship production run for the Ticonderoga class ships and is just beginning the production of approximately the same number of Arleigh Burke class ships.

This thesis will propose a fiber optic-based test data network for the transfer of test data for these advanced surface ships. The fiber optic data transfer network consists entirely of passive components; fiber, cable, connectors, junction boxes, and couplers. This design will not only accommodate current data transfer requirements for conventional (electrical) sensors, but will accommodate anticipated advances in shipboard tests and trial technology including the use of fiber optic sensors and increased data rates. Thus, design considerations include current and anticipated data transfer rates, data multiplexing schemes, and data signal conditioning and recording requirements. The actual network design will be based on the test data requirements, available fiber optic components, and the most efficient cable plant layout. The final network design is intended for Arleigh Burke-class ships, but can be modified for Ticonderoga-class ships since these two ship classes are of similar design. Indeed, the design is basic enough that it can be applied to most ship classes.

## 1.1 Current Test Philosophy

There are 21 proposed tests and trials scheduled for the DDG 51 class ships once a ship is delivered to the Navy but before the ship is cleared for unrestricted service to the fleet. These 21 tests are conducted by 10 different Navy organizations, primarily the Navy laboratories. There are basically three classifications of tests: combat systems, ship systems, and fleet training/crew evaluation tests. The latter involves little in the way of data transfer and will not be considered in this paper. The primary test for combat systems is the Combat System Ship Qualification Trials (CSSQT, pronounced sea-squat) that are conducted over an eight week period at sea in several test operating areas. Other combat systems tests and trials include evaluation of the shipboard electronics system, various gun systems exercises, weapons systems accuracy, and Electro-Magnetic Pulse (EMP) testing.

Shock Trials are the primary ship systems test. It is also an eight-week event that is conducted at-sea and in-port. The purpose of the shock trials is to test the response of the ship and crew to a series of underwater blasts of increasing intensity. The most recent shock test on an AEGIS ship was conducted on CG 53 (USS Mobile Bay)[1]. This test required that almost 750 data channels be installed for monitoring velocity, acceleration, strain, relative displacement, and pressure. By the end of trials, over 12,000 data records were processed. To handle this amount of data efficiently, the data acquisition system is modularized; there were eight substations that multiplexed the data to a single recording station near the stern of the ship. This is indeed one of the largest tests conducted on Navy ships in terms of time, equipment, and manpower. Acoustic trials, and ship standardization and tactical maneuvers trials are several of the other ship systems tests.

The 21 tests and trials are conducted consecutively over the course of about 23 months. Availability of the ship to the Navy labs is not under the control of any given lab; one lab will not have access to the ship at one time to conduct all of the tests and trials that that particular lab needs to accomplish. Subsequently, there is a great deal of equipment moving and instrumentation set-up for each test. All tests require data transmission from sensors to the recording equipment, so copper cable (usually 2-wire twisted pair) is strung throughout the ship for each organization each time a test is conducted. Cable-pulling on a Navy ship after the ship has left the builder is a very labor-intensive, time-consuming, disruptive, and expensive endeavor.

## 1.2 Need For Universal Test Data Network

A universal data transfer network is proposed to handle the majority of test data that is generated on the ship during the various tests and trials. A dedicated network that is accessible to all labs for data transfer is better than all labs installing cable for individual applications.

It is important to discuss some of the major characteristics of the data network system. The first characteristic is that the entire system will be fiber optic. Fiber optics will provide the necessary bandwidth capability for present and future data transfer rates. It is well known that other benefits of fiber optics include light weight and immunity to Electro-Magnetic Interference (EMI). Since this data network will become a permanent system, it is important that it be light weight so that there is minimum impact on the ship design.

The system is designed to be installed as the ship is being constructed. This reduces the cost of installation since it is a greater expense to install cable after completion of ship construction. This is especially true for the Arleigh Burke class of ships; this class of ships will be outfitted with the “collective protection system” that provides defense against nuclear fallout, and biological and chemical agents. The interior of the ship will be positively pressurized to keep out contaminants and all incoming air will be filtered. A cable plant design that is installed as the ship is being built can accommodate the requirements of the collective protection system more easily than installing test cable for each test after the ship has left the builder. Installation of test cable after the ship is completed almost always involves cutting holes in bulkheads or leaving hatches open to gain access to certain areas for instrumentation. Hence, the integrity of the collective protection system must be tested and maintained after the ship tests have been completed; an expensive and time consuming operation once the ship has left the shipbuilder.

Finally, the entire data transfer network is designed to be as modular as possible. Easy access to the network is accomplished by placing network nodes in locations where large sensor concentrations are anticipated. The network is required to accommodate as many labs and as many different tests as possible. While all components of the network cannot be moved once installed, the individual fiber channels can be routed and configured many different ways allowing the test technicians several options in how data is transferred from one location on the ship to another location.

One major drawback of this proposal is that it forces the Navy labs participating in the tests and trials to access the fiber optic network with the proper equipment. On one hand this may not seem difficult as an increasing number of vendors are offering fiber optic options on sensor and data acquisition equipment. But there is a reluctance on the part of managers and technicians in most of the Navy labs who conduct these tests to use fiber optics since it is perceived to be unreliable and not rugged enough to withstand the typical naval environments in which these tests are conducted. It is also very expensive to purchase the fiber option, as well as to train the test personnel in the rudiments of fiber optic technology. Pentagon mandates in the use of fiber optics in the Navy, as well as successful tests that have been completed on experimental fiber optic sensors and data transfer networks, are slowly working to dispel the apprehensions of universally employing fiber optics on Navy ships.

### 1.3 Previous Work

Although the Navy has been slow to employ fiber optics in ship systems, there have been a few experiments with significant results to demonstrate the viability of fiber optics in data transfer systems.

One of the first demonstrations of a fiber optic data transfer system aboard a Navy ship was an experimental telephone system installed on the USS Little Rock in 1973 [2]. This system, designed and installed in a six-month period, provided secure voice communications between six stations. Once installed and tested, the system performed well, requiring only routine maintenance.

The Intercompartmental Cable Service (ICCS) has been one of the most thoroughly tested shipboard fiber optic cable networks to date. This network is a series of point-to-point links that connect strategic ship compartments. The first ICCS installation was the AEGIS test platform USS Norton Sound (AVM 1). Testing and evaluation of the ICCS was conducted between 1983 and 1986 [3]. The first AEGIS cruiser to be outfitted with the ICCS was CG 50 (USS Valley Forge). One of the applications that used the ICCS was transferring generator performance information to remote locations of the ship.

The latest ship to have the ICCS installed was the USS Mobile Bay (CG 53). It is significant that CG 53 was selected as this ship also underwent shock trials, a series of four

underwater explosions of increasing intensity for the purpose of testing the ship's capability to maintain its warfighting stance during simulated tactical conditions [4]. The shock trials not only provided an opportunity to test the network in a tactical situation, but to test other prototype fiber optic systems as well, including [3] a generator performance monitoring system, a video display system, a damage control sensor system, a shaft torsionmeter system and a pressure transducer system. The ICCS as installed on CG 53 is shown in Figure 1.3.1.

One of the most important tests of the Mobile Bay shock trials was the performance monitoring of the ICCS itself [4]. The ICCS consisted of approximately 2 kilometers of 100/140 micron fiber working at a wavelength of 850 nanometers. Four fiber optic circuits of the ICCS were tested during all four shock trial shots. Each circuit contained at least seven connections in cables that were located in areas of the ship that were expected to receive the greatest shock and stress. Two circuits were tested by monitoring the output of an optical receiver to determine any change in optical power as a result of connector losses resulting from the shock. One circuit was monitored by filming the real-time Optical Time Domain Reflectometer (OTDR) oscilloscope trace. Finally, an integrity test was developed to monitor selected circuits of the ICCS using a multiple scan OTDR approach. The block diagram for this OTDR and data acquisition system is shown in Figure 1.3.2. This method was able to determine the shock effect on the entire optical circuit, not just the cables and connectors alone, as well as provide data showing exactly where transient losses occur. During the shock, the system recorded almost 100 scans per second. Post-trial analysis indicated that there was almost no effect on fiber optic circuit performance as a result of the shock. The experience of the ICCS tests provides the confidence that a useful sensor data network can be designed and implemented.

## 1.4 Overview

The current test methods for conducting tests and trials on new construction ships has become increasingly time-consuming and expensive. This thesis proposes a product to satisfy the need for a more efficient test methodology: a fiber optic network capable of data transfer for fiber or electrical sensors.

This thesis will discuss different fiber sensor designs and their suitability to this particular Navy application, fiber optic network components, a design for a fiber network, and discussion of network performance including integration with fiber optic sensors.

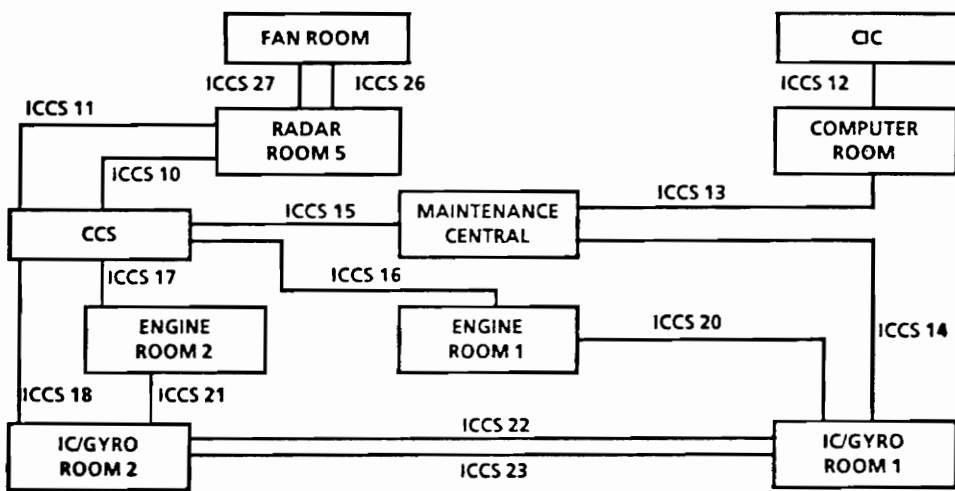


Figure 1.3.1  
USS Mobile Bay Intercompartment Cable Service

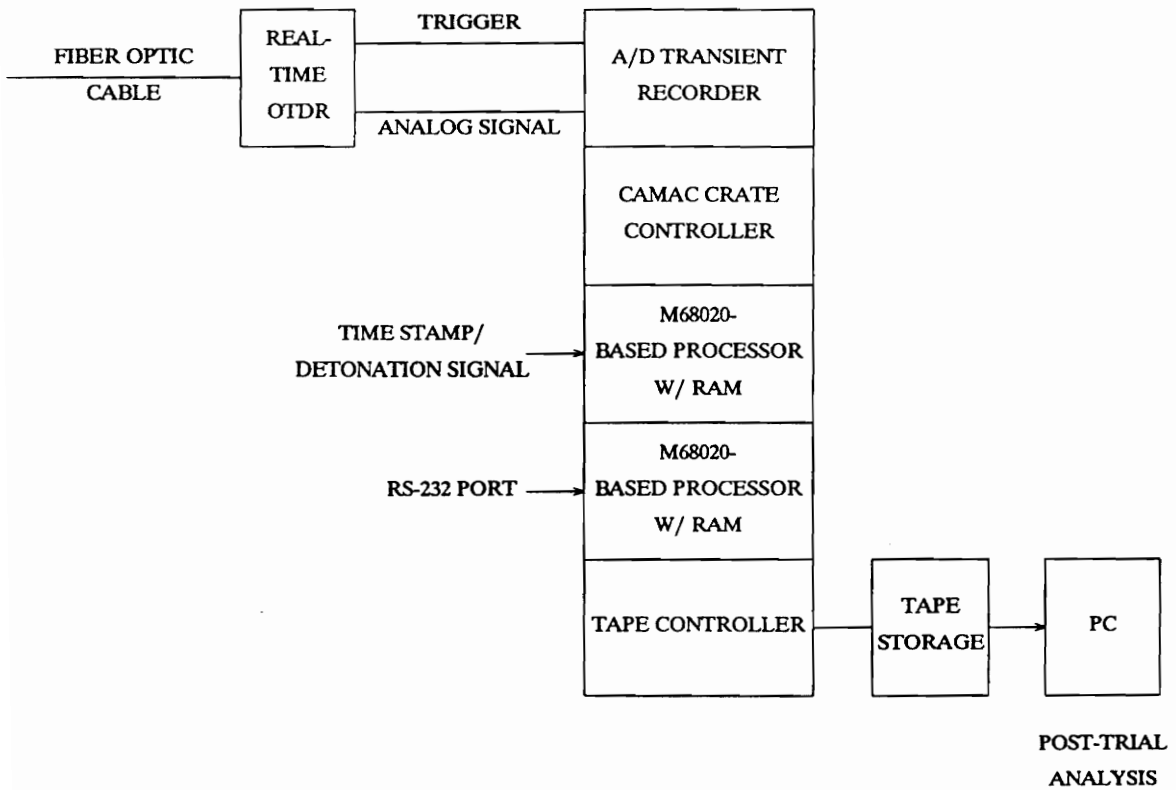


Figure 1.3.2  
ICCS Performance Test

# CHAPTER 2

## 2.0 Principles of Fiber Optic Sensors

This chapter reviews the various methods of sensing using fiber optics, characterizing each method in relation to Navy requirements for shipboard sensors for tests and trials. In particular, intensity modulated, interferometric, chemical, and crystal-based sensors are discussed. It is the optical signal characteristics of these sensors that dictate the characteristics of a fiber optic network used to support sensor data transport.

Sensor research and development is currently one of the fastest growing segments of fiber optic technology. Fiber optics technology offers some distinct advantages over traditional sensor technologies: small size and weight, increased sensitivity, immediate compatibility with current fiber telemetry systems, immunity to electro-magnetic interference, and the ability to operate in corrosive and flammable environments. These characteristics are just some of the advantages that fiber optic sensors offer the wide variety of Navy sensor applications. Applications for fiber optic sensors appear to be limitless. Measurement of electric and magnetic fields, acoustic waves, pressure, temperature, acceleration, rate-of-rotation, displacement, fluid level, torque, current, voltage, and strain are just some of the more traditional applications for fiber optic sensors [5], while new applications include chemical identification.

Almost all of the fiber optic sensors that have been developed attempt to exploit some property of optical waves and materials including intensity, phase, polarization, frequency, and wavelength. Each of these sensors, in turn, can be classified as extrinsic, where the optical fiber path is used for the transfer of the signal information from a remote sensor; intrinsic, where the fiber is specifically suited to measure a particular environmental condition; or evanescent, where the core of the fiber is exposed to the environmental condition and the electromagnetic wave is allowed to interact with the environment. This chapter will focus on the principles of fiber optic sensors and how the intensity, phase, and polarization properties of the light and fiber characteristics are exploited for the various fiber sensor designs. The advantages and disadvantages for each sensing method will be discussed, as well as suitability of each particular sensor to Navy applications.

## 2.1 Intensity Modulated Sensors

The intensity of light is one of the easiest properties of optics that can be exploited for fiber optic sensors. For these sensors, the change in optical intensity is a function of the quantity being sensed. Intensity modulated devices can be classified into two categories, sensors where the light does not leave the fiber and those sensors where it does leave the fiber. One type of each of these sensor will be discussed here.

### 2.1.1 Microbend Sensor

Simply put, a microbend sensor is one where a stress is applied to a fiber causing a number of small bends in the fiber. As the fiber bends, light is coupled to higher order modes from the core to the cladding, where it eventually exits the fiber. As shown in Figure 2.1.1.1, a typical microbend sensor employs few and simple optical components. The characterization of this type of sensor is from Reference [5] and is summarized in the following paragraphs.

A performance parameter that can be defined for any optical sensor is a normalized modulation index which can be expressed as

$$Q = \frac{\Delta I}{I_0 p} , \quad 2.1.1.1$$

where  $\Delta I$  is the change in optical intensity,  $I_0$  is the applied optical power and  $p$  is the applied pressure to the sensor. For a microbend sensor that employs a set of plates with periodic ridges as shown in Figure 2.1.1.1, the modulation index can be written as

$$Q = \frac{dT}{dx} \left( \frac{dx}{dp} \right) , \quad 2.1.1.2$$

where  $T$  is the fiber transmission and  $x$  is the displacement of the plates. This equation shows that the modulation index is dependent upon two parameters, the fiber properties ( $dT/dx$ ) and the mechanical design of the sensor ( $dx/dp$ ).

For a periodic distortion with wavelength  $\Lambda$ , it has been shown that the power coupled between modes with propagation constants  $\beta$  and  $\beta'$  follow

$$\beta - \beta' = \pm \frac{2\pi}{\Lambda} \quad . \quad 2.1.1.3$$

The difference in adjacent longitudinal propagation constants is given by

$$\delta\beta = \beta_{m+1} - \beta_m = \left( \frac{\alpha}{\alpha+2} \right)^{\frac{1}{2}} \frac{2\sqrt{\Delta}}{a} \left( \frac{m}{M} \right)^{\frac{\alpha-2}{\alpha+2}} \quad , \quad 2.1.1.4$$

where  $m$  is the mode label,  $M$  is the total number of modes,  $\alpha$  is the fiber geometry constant,  $\Delta$  is the normalized difference in refractive index between core and cladding, and  $a$  is the core radius. For parabolic index fibers ( $\alpha = 2$ ), Eq. 2.1.1.4 reduces to

$$\delta\beta = \frac{(2\Delta)^{1/2}}{a} \quad , \quad 2.1.1.5$$

and from Eq. 2.1.1.3,

$$\Lambda_c = \frac{2\pi a}{(2\Delta)^{1/2}} \quad . \quad 2.1.1.6$$

This value for the periodicity of the spatial modulator is typically in the millimeter range. This solution holds for parabolic index fibers only, where  $\delta\beta$  is independent of  $m$  and all modes are equally spaced.

The advantages of these types of sensors are that the light does not exit the fiber, and they employ inexpensive optical components. Some of the disadvantages of these sensors are that they are generally of low sensitivity, they lack an easy means of self-calibration, the sensor materials may suffer long-term hysteresis effects, the constant stressing of the fiber may reduce its lifetime, and other portions of the sensor system (sources, connectors) may be susceptible to optical intensity fluctuations that may not be compensated (lead sensitivity).

## 2.1.2 Diaphragm Sensor

An example of an intensity modulated sensor where the light temporarily exits the fiber is the diaphragm sensor shown in Figure 2.1.2.1 [6]. For fibers with core radii  $r$  and numerical aperture NA, no light is coupled from one fiber to another if  $d < a/2T$ , and the core

of the output fiber is completely filled with reflected light when  $d > (a+2r)/2T$ .

( $T = \tan[\sin^{-1}NA]$ ,  $d$ =distance from fiber ends to diaphragm, and  $a$ =spacing between input and output fibers.) This defines the range of  $d$ , and therefore the operating range for this type of sensor. The amount of light that is coupled between fibers for this range of operation is determined by the amount of overlap of the reflected image back into the output fiber as shown in Figure 2.1.2.2.

The fraction of the core surface that is illuminated by the reflected image is given by

$$\alpha = \frac{1}{\pi} \{ \cos^{-1}\{1-\rho\} - (1-\rho) \sin(\cos^{-1}(1-\rho)) \} \quad , \quad 2.1.2.1$$

where  $\rho$  is the ratio of the distance that the image overlaps the output fiber core to the fiber core radius ( $\delta/r$ ). This ratio is also defined by

$$\frac{\delta}{r} = \frac{2dT - a}{r} \quad , \quad 2.1.2.2$$

and the fraction  $F$  of the incident optical power intercepted by the output fiber is then

$$F = \alpha \rho \left( \frac{r-a}{2dT} \right)^2 \quad . \quad 2.1.2.3$$

These calculations are based on the assumptions that there is a uniform power density in the input fiber, there is 100% reflection at the diaphragm, and that the diaphragm is perfectly perpendicular to the fibers.

Culshaw [6] has shown that the intrinsic resolution for this type of sensor is better than 1 nanometer for step index fibers with core radius  $r=100 \mu\text{m}$  and NA of 0.5, fiber separation of  $a=100 \mu\text{m}$ , and a 10 W LED source with a sensor bandwidth of 10 kHz.

These types of sensors have similar operating characteristics as microbend sensors; they consist of simple components, yet must be made lead insensitive. Other disadvantages of these sensors are that proper alignment between the diaphragm and fibers must be maintained and the reflection surface must remain clean.

## 2.2 Interferometric Sensors

Optical fiber sensors that detect a change in the optical phase in a fiber as a result of environmental modulation are intrinsically highly sensitive, therefore high resolution measurements are possible with these types of sensors. The phase of the light travelling in a fiber is influenced by two properties of the optical fiber; the fiber dimensions (length and geometry) and the index of refraction of the fiber. In turn, these two waveguide properties are influenced by three distinct environmental effects on the fiber; strain, pressure, and temperature.

Sensors that rely on phase changes require interferometers and complicated electronics to accomplish the phase detection. A common interferometer scheme that is used for sensing environmental conditions such as temperature, strain, and pressure is the Mach Zehnder interferometer. This type of interferometer that employs all fiber components is shown in Figure 2.2.1. Three distinct sections make up the Mach Zehnder interferometer; electronics, reference arm, and the signal arm. The electronics consist of the source, usually a single-mode laser diode, a photodetector, and some signal processing electronics. The reference arm contains a reference modulator that provides a certain frequency adjustment which depends upon the method of phase detection, either homodyne or heterodyne. Finally, the signal arm can be custom designed for the specific application to maximize sensitivity.

### 2.2.1 Phase Detection

All fiber optic interferometric sensors employ either a homodyne or (more often) a heterodyne phase detection scheme. The principle of coherent detection for these two schemes is shown in Figure 2.2.1.1. From the basic interferometer diagram it was seen that the reference and signal arms are combined and this signal is input to a photodetector. The signal field is given by  $E_s \exp j(\omega_s + \phi_s)$  where  $E_s$  is the amplitude of the signal electric field,  $\omega_s$  is the frequency of the signal, and  $\phi_s$  is the phase of the signal. Similarly, the reference field is given by  $E_r \exp j(\omega_r + \phi_r)$ . The photodetector acts as a power or “square law” detector and the output of the combined reference and signal fields is

$$P(t) = E_s^2 + E_r^2 + 2E_s E_r \cos[(\omega_s - \omega_r)t + \Delta\phi] \quad , \quad 2.2.1.1$$

where the quantity  $(\omega_s - \omega_r)$  is known as the intermediate frequency,  $\omega_{if}$ .

When the signal and reference frequencies are identical ( $\omega_{if} = 0$ ), the receiver functions as a homodyne device. For this phase detection scheme, the frequency and phase between the signal and reference must be controlled. Few interferometric systems employ homodyne phase detection as this method is very susceptible to thermal drifts and optical phase lock loops are difficult to design and implement.

Heterodyne phase detection techniques are more common for use in interferometric sensors. In this case  $\omega_s \neq \omega_r$ ; in fact these systems try to let  $\omega_{if} \approx 1$  GHz to take advantage of radio superheterodyning technology that has been developed since the 1920's. One drawback to this method is sensitivity degradation of 3 dB as compared to homodyne. In homodyne, the signal is always in phase with the reference so that the response at the photodetector is always maximum. In heterodyne, the signal and reference are not in phase and can be in quadrature, or exactly  $90^\circ$  out of phase. Thus for any given signal the power at the photodetector mixer for the heterodyne system will be half the power of a homodyne system.

For either phase detection method, the polarization states of the signal field and the reference field must be identical to maximize the magnitude of the combined fields at the photodetector. Random fluctuations in the state of polarization for the fields can lead to polarization induced fading of the combined signal. Employing polarization preserving fibers in the components of the interferometer is one method of ensuring the polarization states, but these fibers are very sensitive to external perturbations and alignment with other optical components is difficult. Kersey, et.al. [7] have shown that active control of the state of polarization for the input fiber (via a feedback loop) is sufficient to limit polarization induced fading.

## 2.2.2 Properties of Interferometric Sensors

Interferometric sensors are attractive candidates for various multiplexing schemes as single sensors do not use all of the available bandwidth that the single mode fiber has to offer. There are three methods used to multiplex interferometric sensors; coherence, time, and frequency division multiplexing [8]. Coherent multiplexing requires two interferometers, sensing and receiving. The path imbalance of the sensing interferometer must be greater than the coherence length of the source laser. Phase information is then recovered by balancing the path difference at the receiving interferometer. The applications for this method are limited by excess phase intensity noise and the complication of each sensor requiring a separate receiving interferometer. Frequency division multiplexing involves the use of slightly unbalanced interferometers and sources that are modulated at different frequencies allowing the demodulation for all sensors to be accomplished by the demodulation circuitry for just one sensor. A high duty cycle time division multiplexing method also requires only a single demodulation interferometer and also reduces the laser source coherence length restraint [9]. As with all interferometric sensing schemes, phase induced intensity noise and sensor crosstalk are important design considerations for this method.

Besides enhanced sensitivity and ability to be multiplexed, there are other advantages to interferometric sensors. As mentioned earlier, the sensing arm can be configured in such a way to maximize the sensitivity to the applied measurand while being desensitized to other effects. Different interferometer designs also lend themselves to be implemented as integrated optical components, especially in  $\text{LiNbO}_3$  [10]. Finally, phase detection technology that is being developed by the long-haul telecommunications companies to increase their capacity may be modified for the use with phase detection sensors.

There are some major drawbacks to interferometric sensors that need to be considered before they are marketed. The reference arm is sensitive to the same environmental conditions (temperature, strain, pressure) as the signal arm and must be shielded effectively or compensated [11]. Lead sensitivity can be overcome using sources of specified coherence length. Finally, these sensors are of a high level of technological sophistication and are therefore priced accordingly. Until inexpensive methods of phase detection are developed interferometric sensors will be limited to those applications where the sensor's superior performance warrants the high cost.

## 2.3 Chemical Sensors

Although almost all chemical sensors use the general property of intensity modulation, these sensors are considered apart from those discussed in Section 2 because they use the optical properties of the chemical to accomplish the modulation. Chemical sensors generally fall into the categories of extrinsic or evanescent type.

### 2.3.1 Optical Methods for Chemical Sensing [12]

Chemical sensors use one of three material properties to accomplish their mission; absorption, fluorescence, and phosphorescence. Absorption occurs when the chemical under test absorbs radiation of a specific wavelength. The amount of absorption depends on the absorption cross section of the molecule being sensed, the optical path length in the material, and the illumination wavelength. For a typical sensor shown in Figure 2.3.1.1, the output optical intensity  $I(z)$  is related to the input intensity  $I_0$  by the relation

$$I(z) = I_0 \left( \frac{r_2}{r_1 + z \tan \phi} \right)^2 e^{-\alpha z} \quad , \quad 2.3.1.1$$

where  $\alpha$  is the absorption coefficient and is equal to  $c_s c_m / N$ , where  $c_s$  is the absorption cross section of the molecule,  $c_m$  is the concentration of the absorbing molecule, and  $N$  is Avogadro's number. This equation is a first order approximation for uniform illumination.

The chemical and its concentration must be carefully selected so that the difference in transmitted light intensity for minimum and maximum concentrations is large enough for adequate sensitivity and that the amount of optical absorption for the greatest absorption condition is still large enough to maintain an adequate signal to noise ratio. In order to implement this sensor more easily, it is desired to have a single-ended sensor rather than the double-ended sensor shown in Figure 2.3.1.1. This can be accomplished by using membrane sensors where a reflective membrane is impregnated with the reagent or by using a scattering cell where the reagent is mixed with a solution containing scattering particles.

Fluorescence is the process of absorption of optical energy and the immediate re-emission of radiation at a slightly longer wavelength. This process lasts on the order of one nanosecond and the difference in peak wavelengths (known as the Stokes shift) is from 10

to 20 nanometers. The advantage that fluorescent sensors have over absorption sensors is that there is no need for membranes or scattering cells since the probability of re-emission is equal in all directions since the fluorescing molecule undergoes Brownian motion (random walk) during the process. Phosphorescence is a process similar to fluorescence but the excited state does not follow quantum mechanical transitions and therefore can remain in an excited state for a greater length of time. The advantage of this over fluorescent sensors is that the reagent can be illuminated for a short time and then removed. The phosphorescent light can be detected more accurately while source effects can be neglected, resulting in better sensor performance.

## 2.4 Crystal-Based Sensors

The concept of crystal sensors extends over a broad spectrum of sensor types, but all employ optical crystals, either as discrete components or as a substrate upon which the sensor is based (integrated optics). Three types of crystal based sensors will be discussed; those employing integrated optics, polarization sensors that employ crystals having electro-optic or photoelastic properties as the sensing element, and a quartz crystal sensor that has an inherently digital output.

### 2.4.1 Integrated Optic Sensors

It has been only in the last few years that integrated optical circuits have been investigated and have shown the potential to revolutionize the field of optics, just as the integrated circuit has done for the electronics industry. The materials that are most often used in integrated optics are glass ( $\text{SiO}_2$ ), crystals ( $\text{LiNbO}_3$ ) and semiconductors ( $\text{InGaAsP}$ ). Efforts in the last few years have concentrated in  $\text{LiNbO}_3$  technology because it uses established manufacturing processes and shows great promise for a variety of applications.

$\text{LiNbO}_3$  devices are manufactured by indiffusing a thin (20-70 nm) titanium film into a polished, clean  $\text{LiNbO}_3$  substrate. The indiffusion process is accomplished in 5 to 8 hours at about  $1000^\circ\text{C}$ . The process results in a waveguide with a refractive index difference ( $\Delta$ ) of 0.005 or less. The optical losses for these devices is on the order of 0.1 dB/cm.

A very useful integrated optic design is a Mach Zehnder interferometer like the one described in Section 2.2. Since the source is the same for both arms, the two waves will be coherent; interference will occur as long as the difference in the length of the two arms is less than the coherence length of the source laser. When the two waves recombine, three conditions can occur: if the waves are in phase there is constructive interference and all light will be coupled into the output port, if the waves have a phase difference of  $0 < \phi < \pi$ , there is partial destructive interference and only a portion of the light will be coupled into the output port, and if the waves have a phase difference  $\pi$  there is complete destructive interference and no light will be coupled to the output port.

Since  $\text{LiNbO}_3$  has a very large electro-optic coefficient, a  $\text{Ti:LiNbO}_3$  Mach Zehnder integrated optic circuit makes an excellent voltage or electric field sensor, or a simple, reliable and repeatable fiber optic switch.  $\text{LiNbO}_3$  requires only a few volts to accomplish a  $\pi/2$  phase shift. Sensors for detection of magnetic and acoustic fields can also be realized with the appropriate choice of integrated optic materials.

Evanescent sensors can also be employed in a Mach Zehnder integrated optic arrangement by allowing one arm of the interferometer to be exposed to the environment. This method allows for the identification of chemical species from their refractive index [12]. For this type of sensor the ratio of input intensity to output intensity is

$$\frac{I}{I_0} = \frac{1 + \cos\phi}{2} \quad , \quad \text{where} \quad \phi = 2\pi \left( \frac{L_2 n_2 - L_1 n_1}{\lambda_0} \right) \quad , \quad 2.4.1.1$$

and  $L_n$  is the optical path length of the two interferometer arms.

## 2.4.2 Polarization Sensors [12]

As mentioned in the introduction, the polarization of an electromagnetic wave is one property that can be utilized for fiber optic sensors. Although silica fibers themselves have birefringent properties, it is birefringent crystals that form the sensing element for the great majority of these sensors. It is for this reason that polarization sensors are discussed here.

Birefringent media can be characterized by their properties of linear or circular birefringence. Circular birefringence can be caused by the application of a magnetic field (Faraday rotation) or an electric field (electrogyration). The majority of developments in

polarization sensors have used materials with linear birefringent properties. There are several classes of these materials based on the environmental condition that influence the degree of birefringence. Electric fields, stress, and acoustic waves are some of these environments. In the electro-optic effect, the index of refraction of the material changes differently for different polarization directions. When this effect is directly proportional to the applied electric field, this effect is known as the Pockels effect. This effect is dependent upon the direction of wave propagation through the crystal. These crystals also require relatively high fields to produce effective results and are also very temperature sensitive. Generally these crystals are also piezoelectric and therefore are pressure sensitive as well. The Kerr effect occurs when the electro-optic effect is proportional to the square of the applied electric field. This effect is common in many materials but is usually very weak. The Kerr effect does not rely on the symmetry of the crystal, nor is this effect influenced by temperature. Some materials that exhibit useful electro-optic properties include  $\text{LiNbO}_3$ , KDP, quartz, GaP, and GaAs.

Just as an electric field can induce linear birefringence in certain crystals, so, too, can stress that is applied to particular crystals. Generally this stress is applied to the crystal in a direction perpendicular to the direction of light propagation. Some materials that have useful photoelastic properties include fused quartz,  $\text{LiNbO}_3$ , and  $\text{PbMoO}_4$  (lead molybdate).

It is clear that electric field, magnetic field, voltage, pressure (and variants such as acceleration and vibration) and temperature sensors can be developed from these crystals. The most common scheme of employing these types of sensors is shown in Figure 2.4.2.1. A polarizer is placed in front of the crystal to fix the polarization and an analyzer is placed after the crystal to convert the signal to one that is intensity modulated by an amount proportional to the applied field or stress. The figure shows that the analyzer can be placed either immediately in front of the detector (which requires polarization maintaining fiber) or inside the sensor head. Both result in a sensor with decreased performance since polarization preserving fiber is very susceptible to external stress and the intensity in a normal fiber can be influenced by changing environmental conditions.

### 2.4.3 Quartz Crystal Sensor

Up to this point, all sensor schemes have some drawbacks: interferometers are complicated and sensitive to other environmental conditions, and intensity and polarization based sensors both suffer from lead sensitivity that may be complicated to compensate. Fortunately there is a type of sensor that shows promise of being relatively simple and is inherently digital so that lead sensitivities can be ignored. This sensor is based on a vibrating quartz crystal [13].

This sensor, whose basic design is shown in Figure 2.4.3.1, employs a quartz crystal designed to resonate at a particular fundamental frequency under external modulation. As pressure is applied to the cantilever beam, the quartz crystal is stressed. This stress causes the fundamental frequency of the crystal to increase linearly with increased load. Determining the change in fundamental frequency is accomplished through optical interrogation of the crystal and the use of a phase lock loop and frequency meter. The crystal acts like a shutter; a light beam that passes through the shutter is modulated at a frequency proportional to the stress applied to the crystal. This results in an inherently digital signal.

The heart of this sensor design is the dimensions of the quartz crystal. The one described in [13] is a triple bar structure as shown in the figure. The fundamental resonant frequency of a rectangular bar clamped at both ends is

$$f_0 = 1.028 \frac{t}{l^2} \sqrt{\frac{E}{\rho}} \quad , \quad 2.4.3.1$$

where  $E$  is Young's modulus in the length direction,  $\rho$  is the density of the material,  $t$  is the thickness, and  $l$  is the length between the clamping points. When a tensile stress ( $\sigma$ ) is applied, the resulting resonant frequency is now

$$(f'_0)^2 = (f_0)^2 + \frac{\sigma}{\rho L} \quad , \quad 2.4.3.2$$

where  $L = \frac{4}{3l}$ , and the fractional change of frequency per unit stress,

$$\frac{df_0}{d\sigma} = f_0 \left[ \frac{0.266l^2}{Et^2} \right] , \quad 2.4.3.3$$

shows that this change in resonant frequency is predominantly a function of the length and thickness of the crystal. Typical unstressed resonant frequencies for these types of quartz crystals range from 10 to 50 kHz.

There are two problems that would need to be corrected in order to make this a truly exceptional sensor technology. The current design requires a photovoltaic conversion at the sensor head in order to vibrate the piezoelectric crystal. A photothermally driven system would be preferred. Finally, a second crystal might be necessary for thermal compensation of the crystal.

## 2.5 Sensors for Navy Applications

The requirements for any type of sensor that is used for Navy applications are very demanding. These sensor must be inexpensive, easy to use and calibrate, immune to EMI and RFI, small and lightweight, consume low power, rugged and accurate. Any type of sensor that exhibits lead sensitivity would be inaccurate and difficult to calibrate. This chapter has indicated that interferometric and crystal based sensors are best suited for Navy applications. However, until easy and inexpensive methods of phase detection are developed, interferometric sensors have limited use in large scale sensing systems and would not, therefore, be considered to replace the conventional sensors used for the tests and trials discussed in this thesis.

In addition to these requirements, the sensors must be easy to integrate with the fiber network. Intensity-based sensors, although simple in design, require individual signal conditioning and multiplexing units. This is required by polarization-based sensors as well. Interferometric sensors can be optically multiplexed, but require sophisticated signal conditioning equipment. The process of matching the coherence length of the laser source to the interferometer arm length for making the sensor lead insensitive becomes complicated when this type of sensor is integrated into a fiber network. Quartz crystal oscillator sensors can be frequency multiplexed rather easily (see Ch. 4) and require

common, simple signal conditioning equipment for all types (pressure, temperature, etc.) of sensors.

Crystal based sensors, especially those with inherently digital outputs, show great promise to replace conventional sensors such as pressure, acceleration, and vibration that are widely used in shipboard tests and trials. The optical characteristics of these sensors, including their ease of multiplexing, are to be considered when developing a fiber optic data transfer network in support of these sensors.

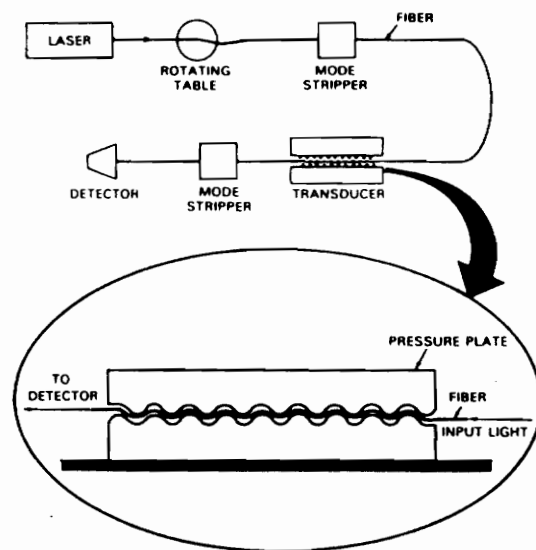


Figure 2.1.1.1  
 Fiber optic microbend sensor (from [5]).

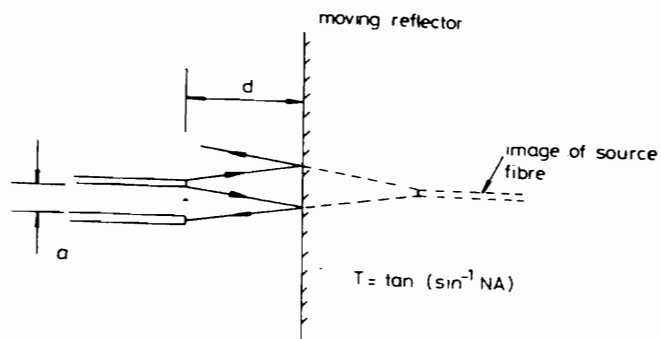


Figure 2.1.2.1  
Diaphragm or moving reflector fiber optic sensor (from [6]).

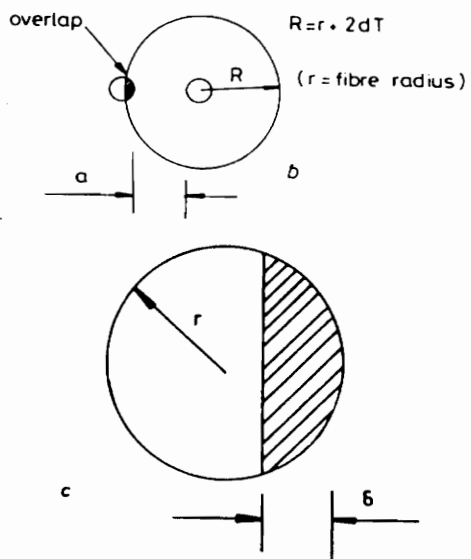


Figure 2.1.2.2

End view of fibers for a diaphragm sensor showing the overlap of reflected light (from [6]).

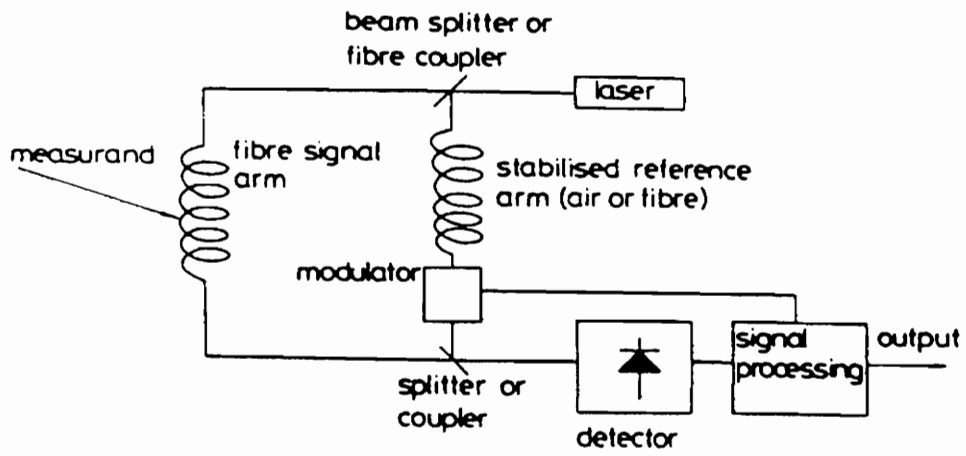


Figure 2.2.1  
All fiber Mach Zehnder interferometer (from [6])

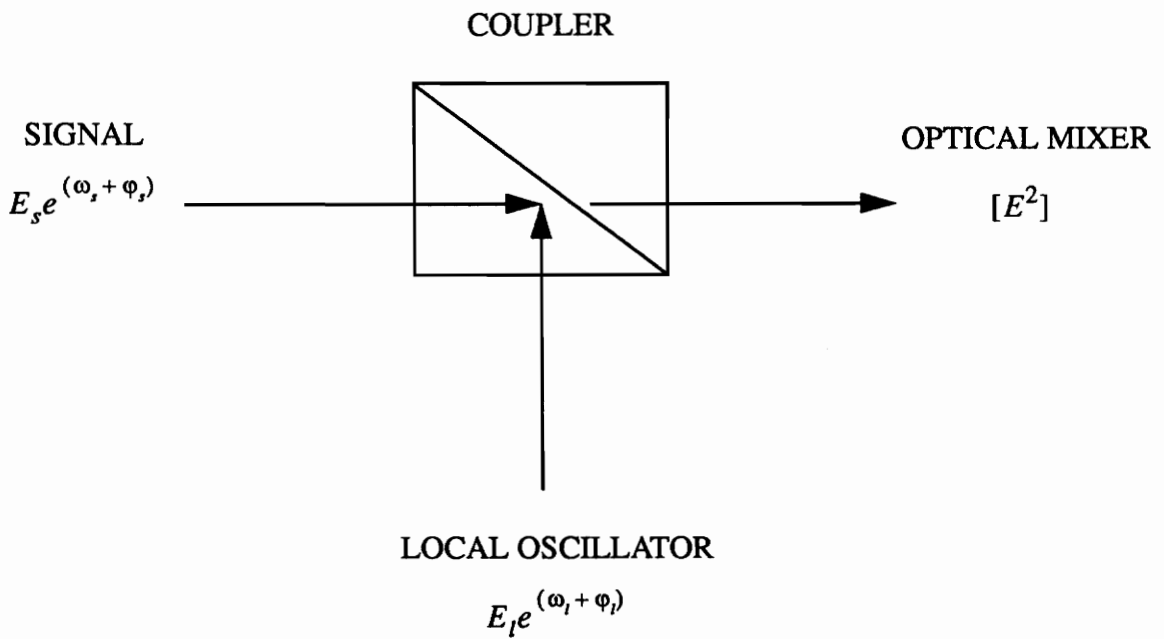


Figure 2.2.1.1  
Principle of coherent detection.

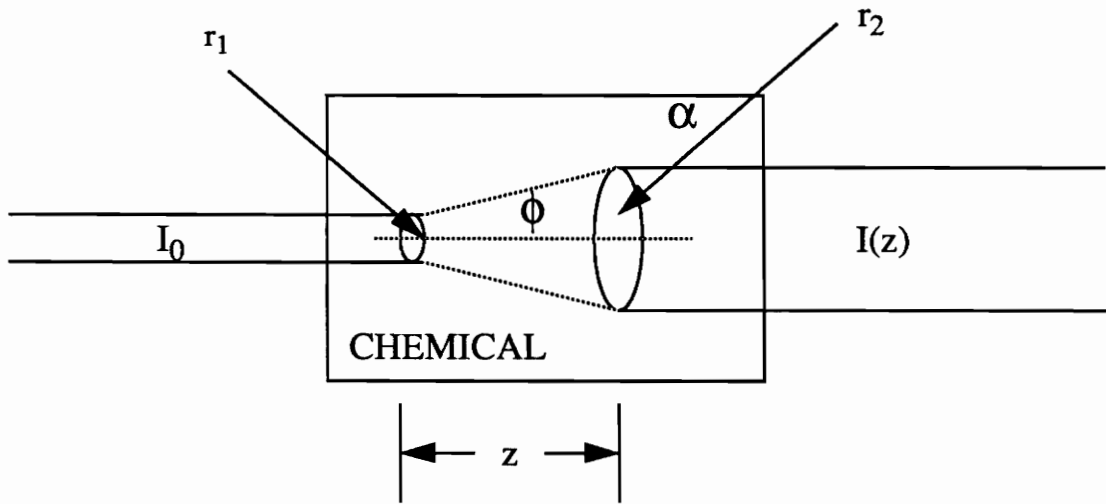


Figure 2.3.1.1

Double-ended design for a chemical sensor using the principle of absorption. The radii of the transmitting and receiving fiber are  $r_1$  and  $r_2$  respectively.

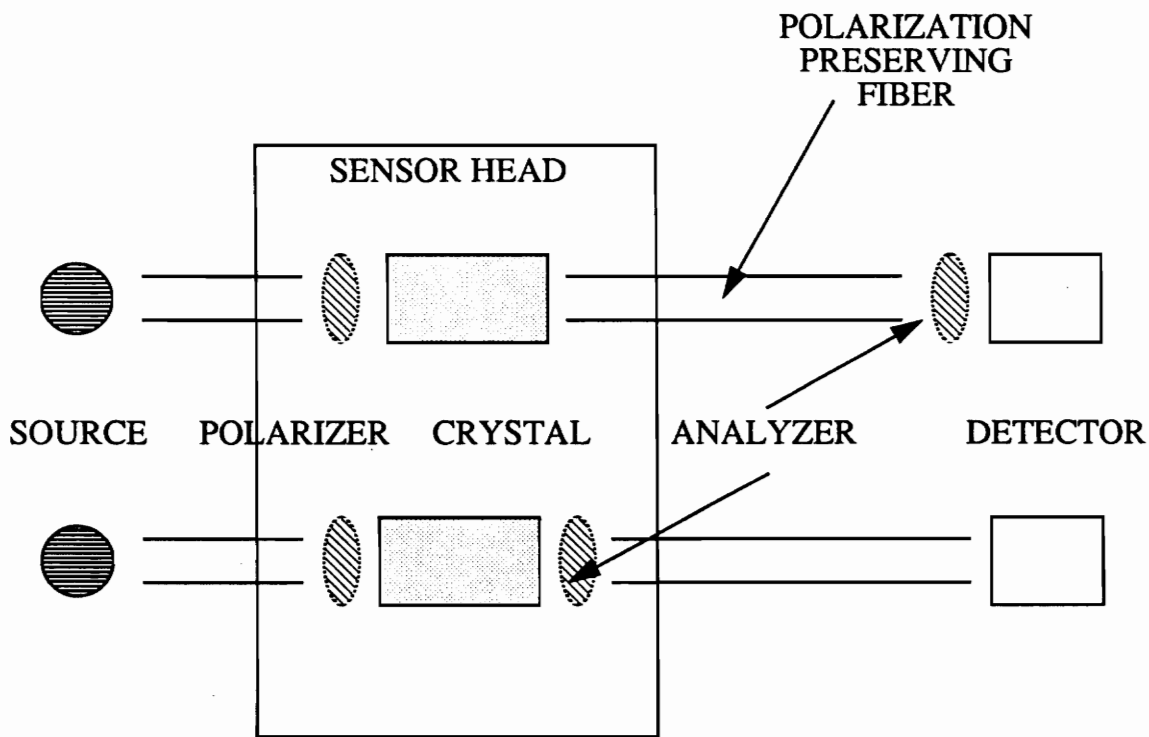


Figure 2.4.2.1

Two methods for extracting signal information from a polarization based optical fiber sensor. The top method requires the use of polarization preserving fibers.

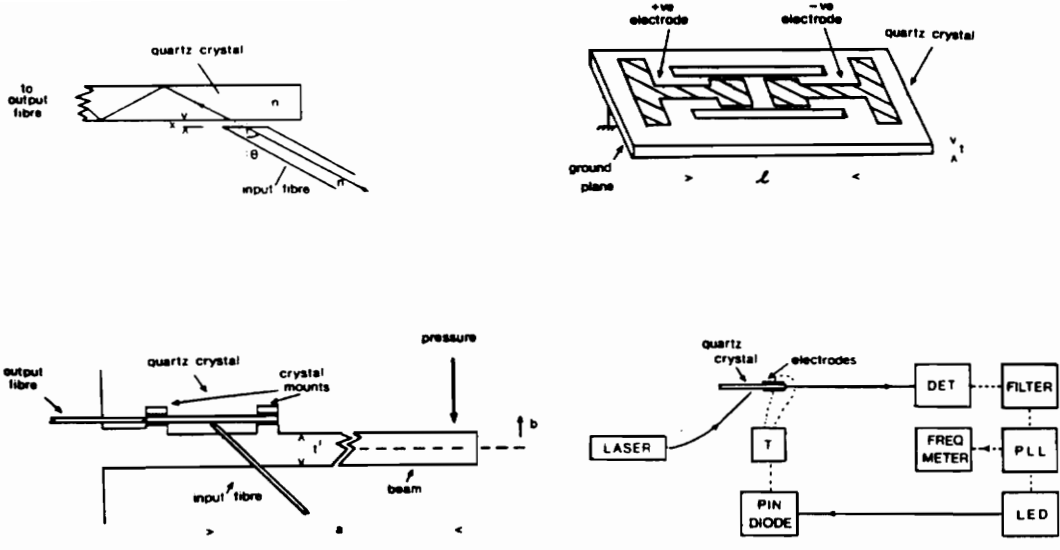


Figure 2.4.3.1  
 Vibrating quartz crystal sensor showing (clockwise from top left) coupling between fiber and crystal, quartz crystal with electrodes, mounted crystal, and electronics system (from [13]).

# CHAPTER 3

## 3.0 Data Network Description

Five basic fiber optic hardware components comprise the data network; fiber, cable, interconnection devices, couplers, and junction boxes. All fiber optic hardware components will be in compliance with the standards that have been developed by the Naval Sea Systems Command (NAVSEA). Standard part numbers allows for the simplification of procurement and repair procedures and reduces the amount of a diverse inventory that would normally be required.

This chapter will discuss the important properties of the five fiber optic components, discuss in detail the design considerations that influence the final network design, and present a possible cable plant layout based on probable design optimization parameters.

## 3.1 Network Component Descriptions

### 3.1.1 Fiber

Except for special circumstances that will be discussed later in this paper, the data network will utilize multimode, graded index fiber. The exact specifications for this fiber may be found in MIL-F-0049291 (NAVY). Some important characteristics of this fiber are listed here.

Table 3.1.1.1  
Network Fiber Characteristics

| Fiber Characteristic     | Value                      |
|--------------------------|----------------------------|
| Core Diameter            | $62.5 \pm 3.0 \mu\text{m}$ |
| Cladding Diameter        | $125 \pm 2.0 \mu\text{m}$  |
| Core Non-circularity     | $\leq 6 \%$                |
| Cladding Non-circularity | $\leq 2 \%$                |
| Core/Cladding Offset     | $4.0 \mu\text{m}$          |
| Attenuation (at 1310 nm) | 1.0 dB/km                  |
| Bandwidth (at 1310 nm)   | 350 Mhz-km                 |

### 3.1.2 Cable

The fiber optic cable that will be used in the data network will conform to MIL-C-0085045(NAVY). Each cable will contain 2, 4, or 8 optical fibers depending on the location of the cable in the network. The cable design is shown in Figure 3.1.2.1. The optical fiber cable component (OFCC) consists of the buffered fiber, a strength member (usually Kevlar) and an outer jacket. The proper number of OFCCs are then helically wound around a central strength member. A water blocking agent is added along with more Kevlar, and finally the whole cable is covered with an outer jacket. The cables are designed to be as chemically inert as possible; the amount of smoke, acid gas, and other toxic gasses are restricted when the cable undergoes a flame test; even the amount of flame propagation is limited. These cables are designed to be as safe as possible in the event of a shipboard fire.

The optical loss of the fiber, once it is cabled, cannot exceed 0.5 dB/km beyond the original attenuation rate of the uncabled fiber. Mechanical stresses (bending, torsion, etc.) cannot impart a loss greater than 0.2 dB on any part of the cable, and any environmental stress cannot impart losses greater than 0.3 dB on any part of the cable.

### 3.1.3 Connectors

To make the entire network as flexible as possible, only connectors will be used for the termination of fiber optic cable. MIL-C-0028876(NAVY) is the military specification that describes the shipboard connectors. The connectors will be single-fiber type compatible with the multimode fiber. Since all connections will be made inside interconnection (junction) boxes, the connectors are designated light duty. Also included in the specification is a description of a coupling device that is used to mate two connectors together.

The specification states that the insertion loss per fiber path shall not be greater than 1.0 dB, and the change in optical transmittance during or after any specified environmental or mechanical test must not be greater than 0.5 dB. These connectors have a bayonet-style mounting mechanism, and are very similar in design to the ST style commercial grade fiber optic connector.

### 3.1.4 Couplers

Fiber optic couplers will be installed inside each junction box in order to implement a broadcast method of data transfer. The couplers to be installed are specified in MIL-C-0024621A(NAVY) as multimode, stand-alone components whose outputs are non-uniformly distributed. Each coupler will have one input and two outputs and the splitting ratio will be 10/90 between the two.

### 3.1.5 Junction Boxes

The purpose of the junction boxes is to provide a convenient method of organizing the optical pathways at the junction of two or more terminated fiber optic cables, as well as to offer protection of the components mounted inside. The shipboard junction boxes are designed to hold not only connectors but splices (mechanical and fusion) and couplers as well. It is very important that the inside of the junction box be easily accessible and well organized since placement of the box may be inconvenient. Junction boxes are one of the last items installed in a newly constructed ship and therefore may be mounted on the deck, overhead, or bulkhead in any available location. It is very rare to have a junction box that is bulkhead mounted at chest-height.

## 3.2 Design Considerations

Before a cable layout design for the data network can be developed, a number of considerations must be explored in order to determine the best possible design. These considerations primarily deal with how the network can be used to its fullest extent with appreciation for the ease of use and ease of installation of the network. Since this network is to satisfy the data transfer requirements of a great number of applications, certain assumptions or rules need to be established.

Various tests and trials each require different types and number of sensors. Some tests, like shock trials, require a great number of sensors, while most tests require only a few sensors. Few sensor tests are typically employed for an extended period of time while tests requiring a large number of sensors last only for a few seconds, as with the shock trials. The discussion of design considerations in the following sections can apply to systems that employ conventional or fiber optic sensors.

### 3.2.1 Design Considerations for Many Sensor Tests and Trials

For applications where a large number of sensors are deployed, it will be assumed that there will be one central recording and data processing location. This may be expanded to two locations if there is an unusually large number of sensors or there are other factors that require more than one recording location. This assumption is based on the observation that this is a more efficient means than to distribute recording or data processing equipment around the ship. Indeed, the Navy laboratory that does the data acquisition and processing for shock trials houses all recorders and computers in an instrumentation shack that is located on the helo deck or fantail of the ship.

It is obvious that some degree of multiplexing will be necessary for tests that use a large number of sensors since the network designed to accommodate a large number of point-to-point circuits would become large and cumbersome. Several methods of multiplexing may be employed including frequency division multiplexing of electrical signals before they are converted to optical signals and having local recorders at several locations around the ship that are under the control of a central computer and data processing equipment. Figure 3.2.1.1 illustrates these two methods.

Another feature that is required in the final network design is a broadcast ability from the central data processing location to substations where recording equipment will be established. This feature is important in applications where accurate timing information needs to be established between such equipment, as well as providing a means for a broadcast voice system to all parts of the ship that is independent of the ship's Interior Voice Communications System (IVCS).

A suggested scheme for the data acquisition of a many sensor system is modeled after one that is currently being developed by David Taylor Research Center for copper based transmission media. This system employs a combination of local transient recorders and the IEEE-488 data transfer protocol. A fiber optic version of this method is shown in Figure 3.2.1.2. Each sensor is connected to a unique signal conditioner located near a network node. When a timing pulse is sensed (indicating event initiation), the local recorder is activated and recording takes place until the local RAM is filled. After the event, the data in the RAM buffers are downloaded to processing equipment via the IEEE-488 bus. The local recorders allow up to 16 channels of sensor recording and have an IEEE-488 interface

built in. The IEEE-488 standard restricts the number of devices (in this case local recorders) to 15, thus allowing 240 sensors for each simple bus network. By using IEEE-488 bus expanders, a total of 41 devices and 656 sensors can be accommodated on a single bus. If more sensors are required, separate busses can be implemented. The main advantage of this system is that the IEEE-488 standard is widely used and many vendors support the standard with a variety of hardware and software. Fiber optic versions of bus extenders and bus expanders are currently available with maximum data rates of less than 2 Mbits/sec, well below the fiber network capacity.

### 3.2.2 Design Considerations for Few Sensor Tests and Trials

The data network must also be able to accommodate those experiments where only a few sensors are used. In this case a direct link can be established between the sensor and recording (or display) unit (Figure 3.2.2.1). This was shown to be an effective method during the CG 53 shock trials when hydrostatic pressure data was converted to RS-232 (fiber optic) and transported to a remote display in another part of the ship via the ICCS.

As mentioned in Chapter 2, direct, analog information cannot be placed on the network unless optical amplitude fluctuations that may occur at cable junctions can be compensated. Since these fluctuations are random and compensation is difficult, it is recommended that intensity-modulated fiber optic sensors be avoided for Navy shipboard use. Those fiber optic sensors that produce inherently digital outputs, such as those mentioned in Chapter 2, would be ideal for those sensing applications where it is necessary to locate the signal conditioning electronics in a part of the ship that is far removed from the location of the sensing head.

### 3.3 Discussion of Cable Layout Design

In determining an appropriate cable layout design of the sensor data network, two approaches may be taken. The first is to accumulate all user requirements and then churn out a design that meets all of the given requirements. There are two problems with this procedure; first is that the design may end up appearing as though it was “designed by committee” and would not be an efficient and economical design, the second problem with this approach is that by the time the network is implemented, the requirements of the users will be different and the design will be obsolete.

An alternative approach in developing the network is to design an efficient system that accomplishes the following: allows full coverage of the ship in terms of location and the number of sensors, can be used easily for many different applications, and has significant capacity to fulfill any future needs. It was this approach that was used to determine the cable layout for the sensor network.

On the Arleigh Burke-class ships there are 41 areas designated “vital” spaces that are necessary in maintaining the proper operation of the ship. These spaces fall into three categories; engineering spaces (including pilot house, maintenance and repair stations, and engine rooms), combat system spaces (including radar rooms, Combat Information Center, and weapons storage spaces), and combination of engineering and combat systems spaces. These vital spaces are the ones that are most heavily monitored with sensors during any ship trials.

The entire ship can be divided into ten network service areas based on the location of the 41 vital spaces as shown in Figure 3.3.1. The figure shows the ten service areas as:

**Table 3.3.1**  
**Network Service Areas**

| Network Node Designation | Function                                |
|--------------------------|---|
| A                        | Combination (towed sonar and steering)  |
| B                        | Combat Systems (radar)                  |
| C                        | Combat Systems (CS equipment room)      |
| D                        | Engineering (transformers, pumps)       |
| E                        | Engineering (engine room)               |
| F                        | Engineering (engine room)               |
| G                        | Combat Systems (pilot house, radar)     |
| H                        | Combat Systems (CS maintenance central) |
| J                        | Combination (communications, machinery) |
| K                        | Combination (sonar, sonar dome)         |

By segmenting the ship in this fashion a cable layout design can be developed quite easily. This ensures coverage of the entire ship, lends itself to data multiplexing schemes,

and accommodates one or two central processing locations that become obvious. This general design is shown in Figure 3.3.2. Exact locations for the placement of junction boxes for each service area will be decided prior to installation. In determining the performance of the sensor data network, average or typical cable lengths will be used.

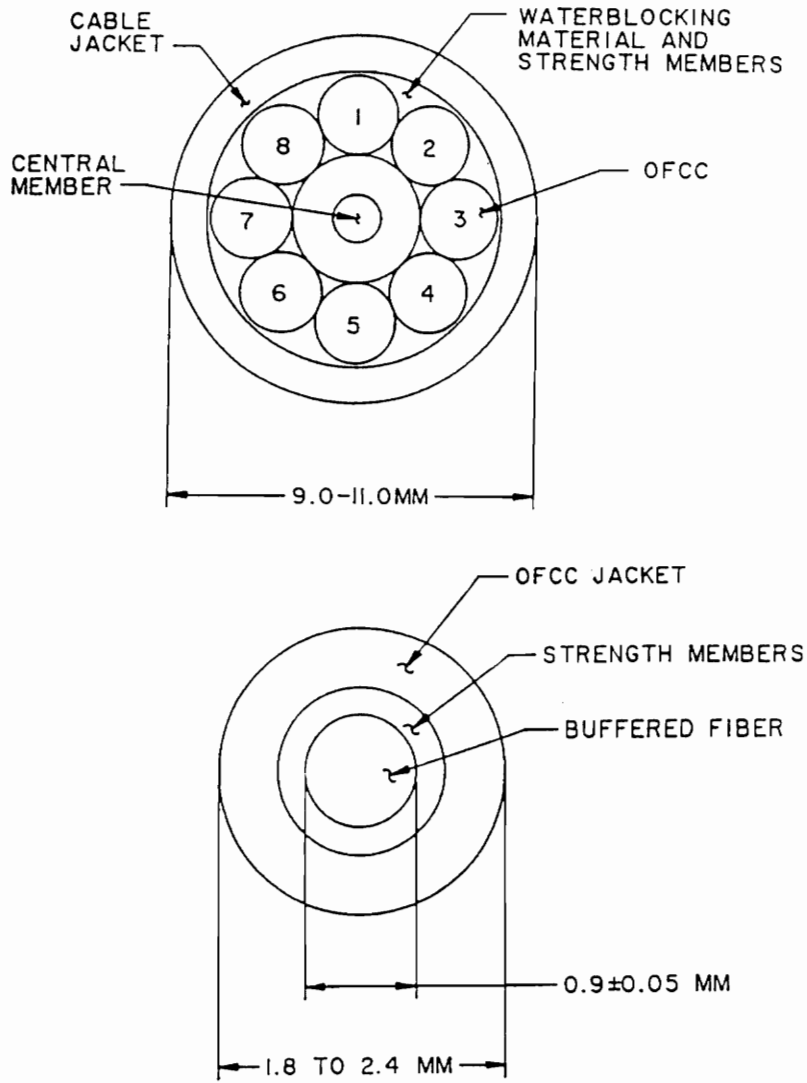


Figure 3.1.2.1  
Shipboard fiber optic cable design.

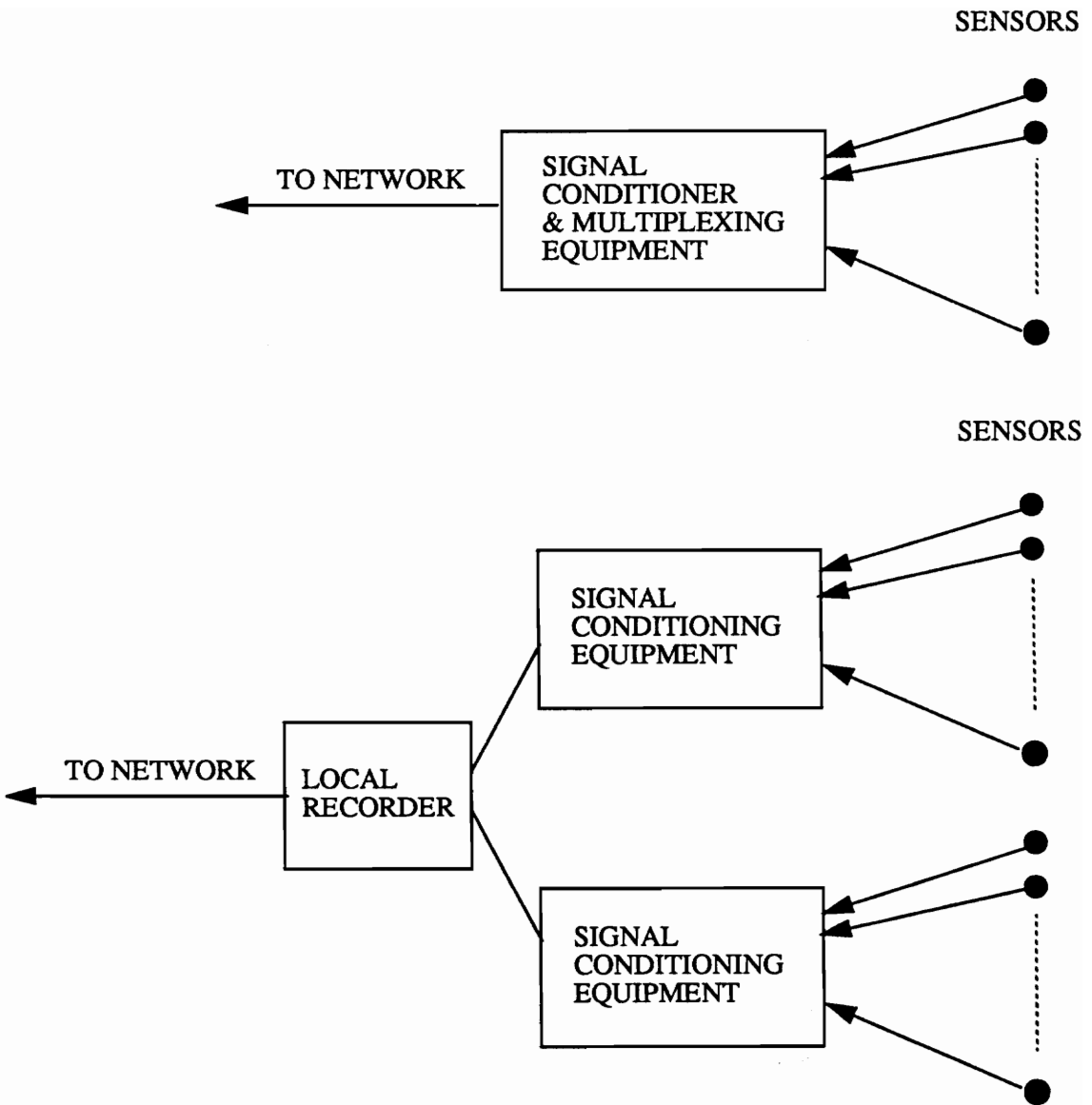


Figure 3.2.1.1  
Two methods for shipboard data transfer and storage.

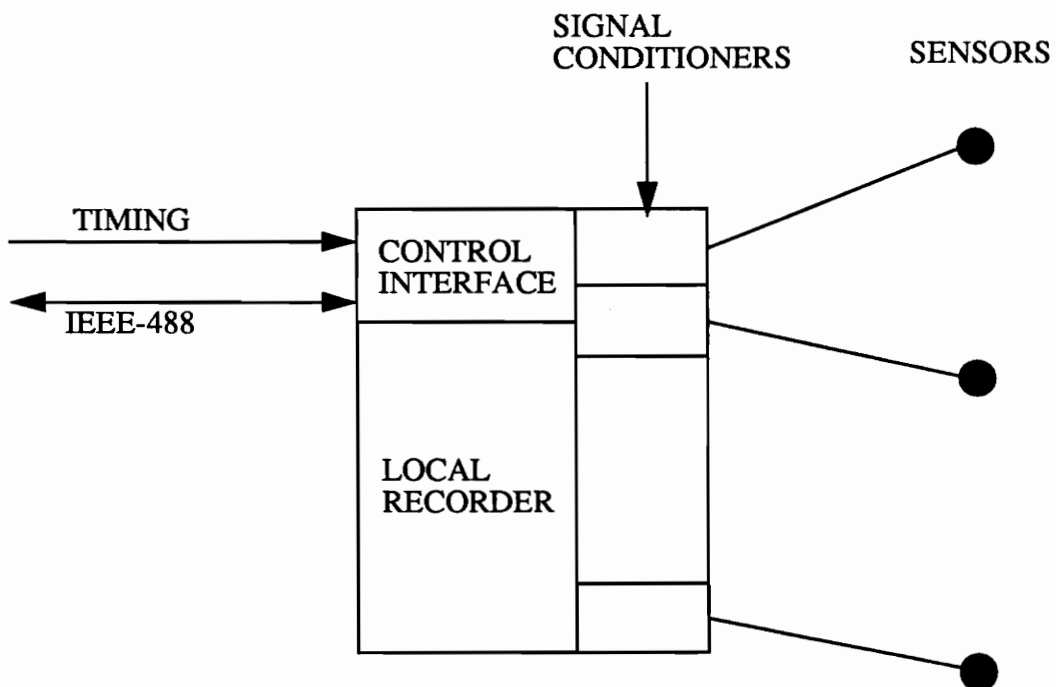


Figure 3.2.1.2  
A suggested method for shipboard data transfer and storage.

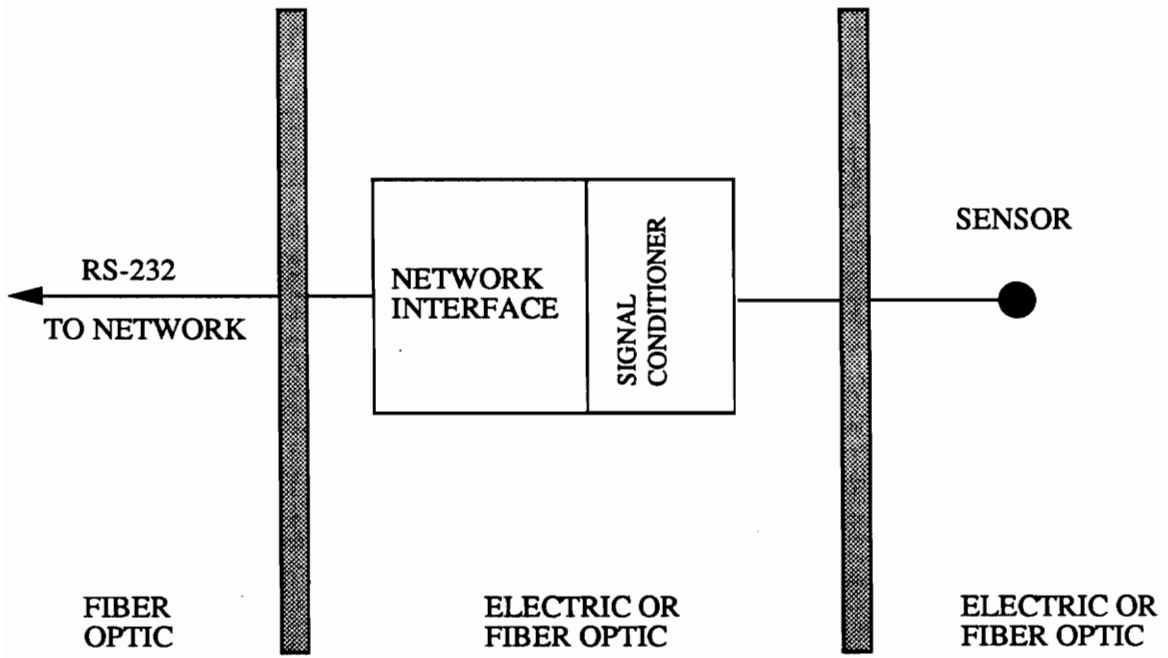


Figure 3.2.2.1  
Direct link between sensor and recording unit.

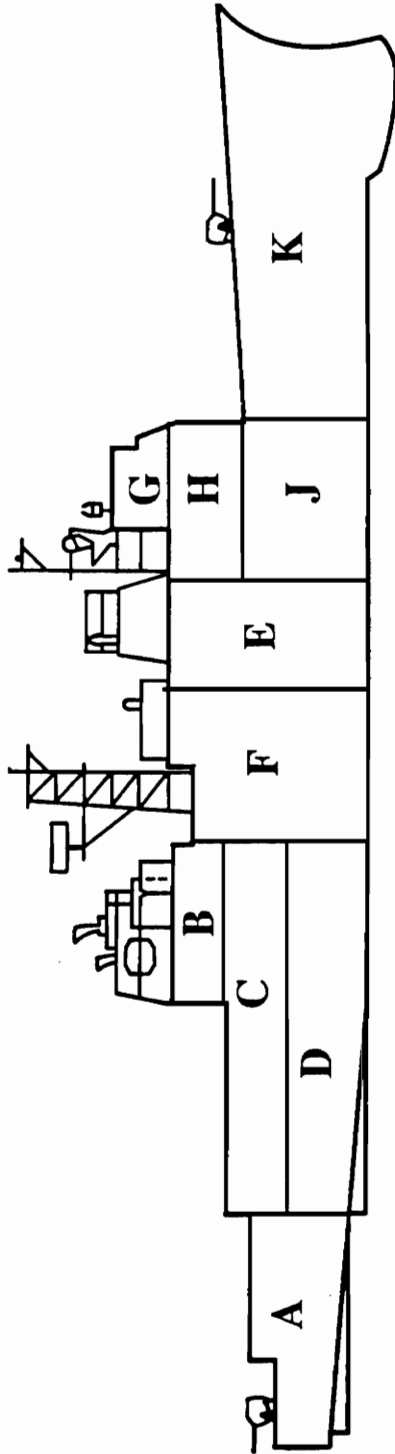


Figure 3.3.1  
Ship divided into ten network service areas.

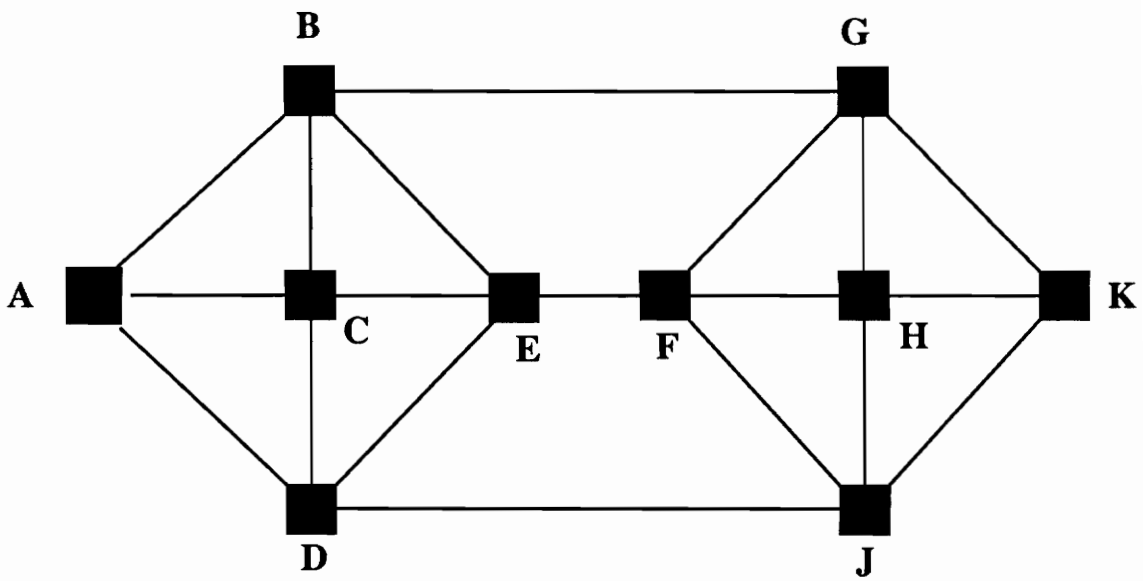


Figure 3.3.2  
General design for shipboard tests and trials data transfer network.

# CHAPTER 4

## 4.0 System Engineering Considerations and Design Examples

Implementation of fiber optics into AEGIS ships is being accomplished in a very careful and deliberate manner with consideration for the system engineering concepts of reliability, maintainability, life-cycle cost, training and human factors requirements. While these systems engineering concepts are not new to military systems, fiber optic systems will be introduced into the fleet that meet all performance requirements and are life-cycle cost effective.

Now that a potential cable layout plan has been proposed, it is necessary to determine how well the cable plant will function. This chapter will discuss the performance of the network as well as the operational requirements to maintain the network. Finally, several design examples will be explored to show how the network is used for many different applications.

### 4.1 Performance Analysis

#### 4.1.1 Point-to-Point Performance

Most applications for the sensor data network such as data transfer of multiplexed sensor channels will require a point-to-point link from one service area to another. Two of the most important performance parameters for point-to-point links are the optical loss between service areas and the bandwidth the fiber can support. The absolute worst case for analyzing a point-to-point connection in the sensor data network would be one that traverses all junction boxes, such as the path shown in Figure 4.1.1.1.

Most of the loss budget for this point-to-point link is fairly easy to calculate; the worst case fiber loss is 2.0 dB/km and there is approximately 1.04 kilometers of fiber resulting in 2.08 dB of cable loss, and there are nine connectors each with a maximum loss of 1 dB. The environmental effects on the attenuation of these components is a bit more difficult to quantify. Brown and Anderson [14] have developed a statistical method for calculating the attenuation of components in adverse environments. The mean response and standard deviation for the combined environmental conditions of temperature/humidity, shock, vibration, bending, compression, mechanical stress, EMI, and sand are given as:

Table 4.1.1.1

Component characteristics under combined environmental conditions.

| Component            | Loss       | Standard Deviation |
|----------------------|------------|--------------------|
| Multimode Cable      | 1.33 dB/km | 0.44 dB/km         |
| Light Duty Connector | 0.24 dB    | 0.08 dB            |
| Coupler              | 0.30 dB    | 0.10 dB            |

For a confidence level greater than 95% (two standard deviations) the attenuation as a result of combined environmental effects is 2.34 dB for the cable and 3.6 dB for the connectors. This results in a total loss of 17.02 dB for the entire link. This value is for the passive components only and does not include a safety margin for the aging of the active components. This is a worst case; most typical links would probably have a loss budget of less than half of this worst case value.

## 4.2 Operational Performance

### 4.2.1 Reliability

Reliability of the system and the components of the system are very important issues for any shipboard system, and for this data network system especially. This system must be able to transfer digital data to any part of the ship during the shipboard tests and trials. We have already seen that there is a 95% degree of confidence that the attenuation for a certain worst case data path will not exceed 17.02 dB.

One method of ensuring increased reliability in a system is to incorporate the use of redundancy. Up to this point, the number of fibers in each cable has not been specified. This detail will be decided very early in the design review process with representatives from all potential users. It is felt that the minimum number of fibers for each cable is as shown in Figure 4.2.1.1. This configuration accomplishes the following; only two junction boxes are required to be traversed from any service area if the central recording locations are in

service areas A or K, and this configuration allows 24 independent circuits between service areas A and K (provided that a broadcast scheme is not used).

Another method of ensuring high system reliability is the use of components with high reliability. Using components that are manufactured and tested to military specifications generally guarantees high component reliability and will provide a source of standardized components, making the system easier to maintain. Expected system reliability can be calculated only when the system component reliabilities are known. For all fiber optic systems that are being considered for installation on the Arleigh Burke-class ships, system reliability will be calculated using reliability data supplied either by the component manufacturer (when available) or from the U.S. Navy. The reliability data supplied from the U.S. Navy is shown in the following table.

Table 4.2.1.1  
Fiber Optic Component Failure Rates

| Component               | MTBF (millions of hours) |
|-------------------------|--------------------------|
| 1300 nm LED             | 0.574                    |
| 1300 nm LED Transmitter | 2.22                     |
| 1300 nm Laser Diode     | 0.010                    |
| 1300 nm Photodiode      | 1.25                     |
| 1300 nm Receiver        | 1.90                     |
| Fiber (per km)          | 0.705                    |
| Cable (per km)          | 0.162                    |
| Splices (fusion)        | 1.687                    |
| Couplers                | 0.260                    |
| Connectors              | 1.7                      |

These values are derived from field data acquired from military and commercial installations and from laboratory experimentation. Based on the data from the table, the reliability of a fiber optic point-to-point link consisting of 500 meters of cable and four mated connector pairs is 0.99585 for a mission time of 2000 hours.

By employing redundant telemetry paths, the reliability of the system is increased. The redundant path is considered to be in standby, ready to be manually switched into operation if the primary path fails. The increase in reliability follows a Poisson distribution,

$R(t) = e^{-\lambda t} + (\lambda t) e^{-\lambda t}$ , for one standby with a failure rate equal to the primary. From the preceding calculation ( $\lambda=2.0795 \times 10^{-6}/\text{hr}$ ,  $t=2000$  hrs,  $\lambda t=0.004159$ ), the reliability is increased to 0.999991375.

#### 4.2.2 Maintainability and Life-Cycle Support

The data network, as designed, is easy to maintain and support. There are only a few components that make up the network; junction boxes, connectors, couplers, and cable. There is only one type of junction box and once they are installed are expected to never require maintenance. There is only one style of connector in the network and fiber optic repair kits on the ship make replacing connectors a simple task. Only one type of coupler is specified as well. Repair for these components can be accomplished by either civilian technicians or shipboard personnel. There are three types of cable specified for this network, their only difference being the number of fibers in each cable. Redundancy in the cable network will allow any severe cable damage to be bypassed until cable replacement can be accomplished in port.

The anticipated service lifetime for the test data network is approximately 30 months. This is from the time the network is installed to the time the ship is released for unrestricted service. It is expected that during this time the network will be maintained by the design agency. Trained personnel will repair components as well as make periodic measurements of the cable system in an attempt to quantify the aging process of passive fiber optic components installed on Navy ships. After the ship is released for unrestricted service the network will be maintained by shipboard personnel. The network will then be available for ship system upgrades. Training for shipboard personnel in fiber optic technology will be instituted by the time the first network is installed.

#### 4.3 Design Examples

This section will discuss how a number of fiber optic sensors can be multiplexed together so that the information from many sensors can be transferred along a single fiber. This section will assume that the fiber optic sensors being used are the quartz crystal

sensors discussed in section 2.4.3, since these types of sensors have been identified as the most promising for use in this particular Navy application. Since this sensor is inherently frequency-based, it is only natural that frequency division multiplexing techniques be considered.

### 4.3.1 Frequency Division Multiplexing of Fiber Optic Sensors

The principle of frequency division multiplexing of telephone circuits can be applied directly to frequency based fiber optic sensor system. In this multiplexing scheme, a baseband signal with a well defined center frequency and spectral width is modulated with a fixed frequency from a sine-wave oscillator [15]. Figure 4.3.1.1 demonstrates this heterodyning technique. The multiplication of two sinusoids with different frequencies will then yield new sum and difference frequencies. These are known as the upper side band and lower side band, respectively. Usually one of the side bands is filtered since both side bands contain the same information. The upper side band maintains the order of the low-to-high frequency components that correspond to the baseband signal.

An example of how this multiplexing technique can be used for this fiber optic sensor application is shown in Figure 4.3.1.2. After the conversion of the optical signal to an electrical signal with the corresponding frequency components, each sensor output is mixed with another constant sinusoid with frequency  $2\pi f_0 x$ . These signals are then combined and the lower side band is filtered. This combined signal is then converted back to an optical signal for transfer to a remote demultiplexer and data acquisition system.

Suppose ten sensors were to be multiplexed together ( $n=10$ ), and each of these sensors had a center frequency of 40 kHz with an 8 kHz spectrum. The frequencies of all signals, once mixed together, would range from 50 kHz to 140 kHz, if  $f_0 = 10$  kHz. The total sum of frequencies for these ten sensors is 950 kHz, which does not even begin to approach the transmission capacity limit for telecommunications grade optical fiber.

Although the hardware for this type of multiplexing scheme is relatively simple, it does require the sensor signal to move between the optical and electrical domains several times. However, there is a multiplexing scheme that allows the sensor signal to remain in the optical domain until the information is processed.

### 4.3.2 Sensor System Employing Self-Multiplexing Sensors

As mentioned in section 2.4.3, quartz crystal based sensors have a resonant frequency that is a function of the crystal dimensions and composition. This fact can be used to develop a series of standard sensors, each operating at a different resonant frequency, that allow a system that is self-multiplexing. This concept is shown in Figure 4.3.2.1. A high powered source is used to impart a continuous wave optical signal into a 1x8 fiber optic coupler. These eight leads are then connected to eight crystal quartz sensors, each with a unique resonant frequency ( $\omega_n$ ,  $n = 1$  to 8). These outputs are then coupled back into a single optical fiber for transmission to an optical/electrical converter, a series of bandpass filters, and finally to the data acquisition system. A typical frequency spectrum for the mixed signals is shown in Figure 4.3.2.2, where  $f_c$  is 10 to 80 kHz, and each sensor has a spectrum of 8 kHz.

The obvious advantage to this multiplexing scheme is the simplicity of hardware as compare to the previous multiplexing method. However, the self-multiplexing scheme require a series of sensors, each with very low optical loss. The technician installing this type of system is required to know that eight sensors, each with a unique resonant frequency, are required for this system to operate properly. The previous system required a standard resonant frequency for all sensors. The trade-offs for these two multiplexing methods are simplicity of hardware versus standard parts.

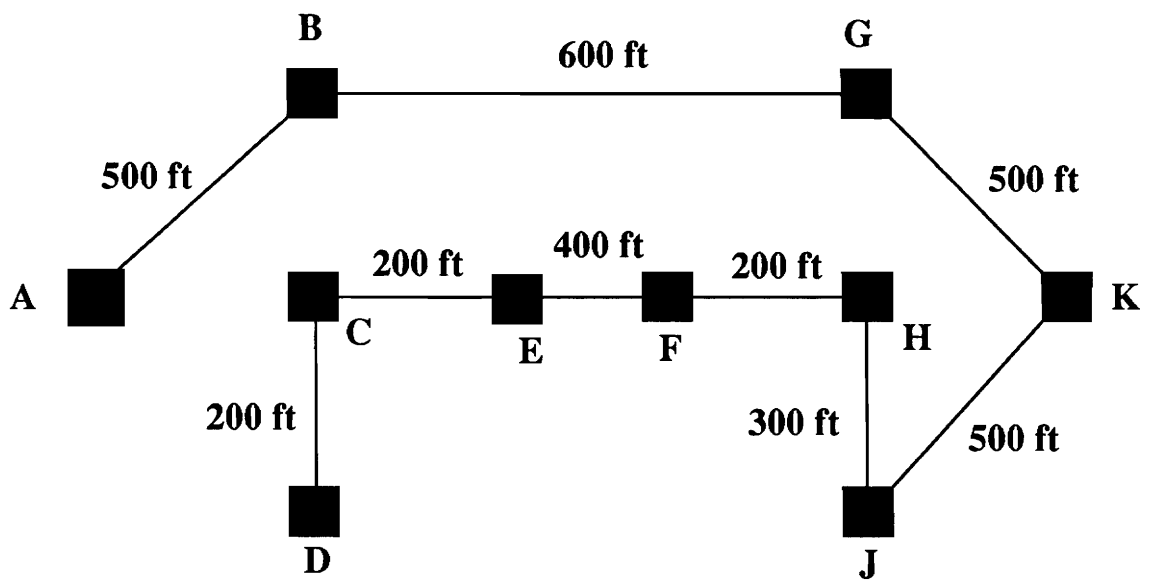


Figure 4.1.1.1  
Network configuration for worst case point-to-point performance

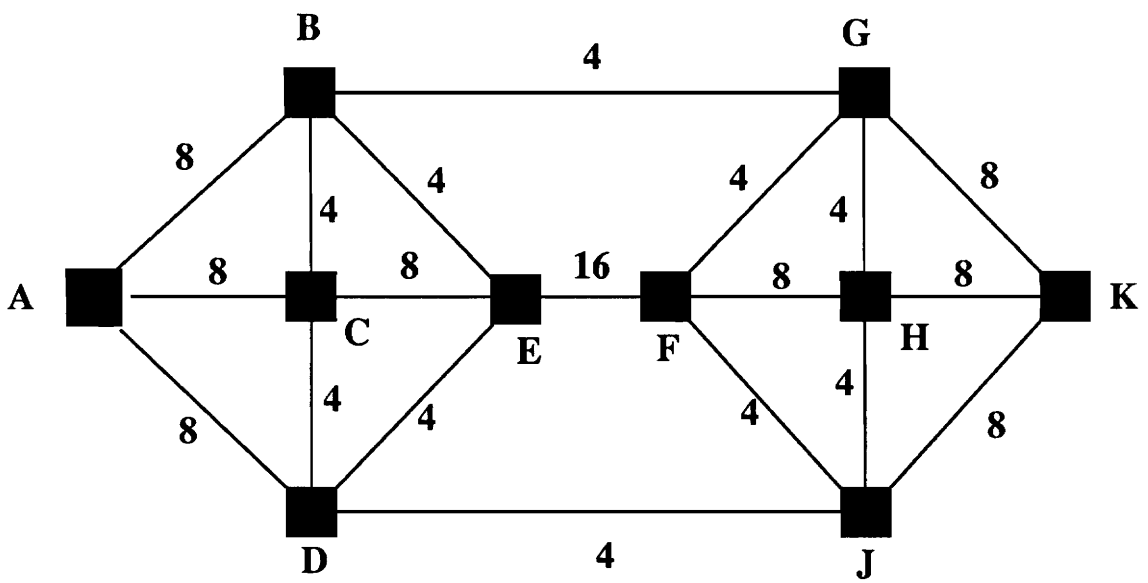
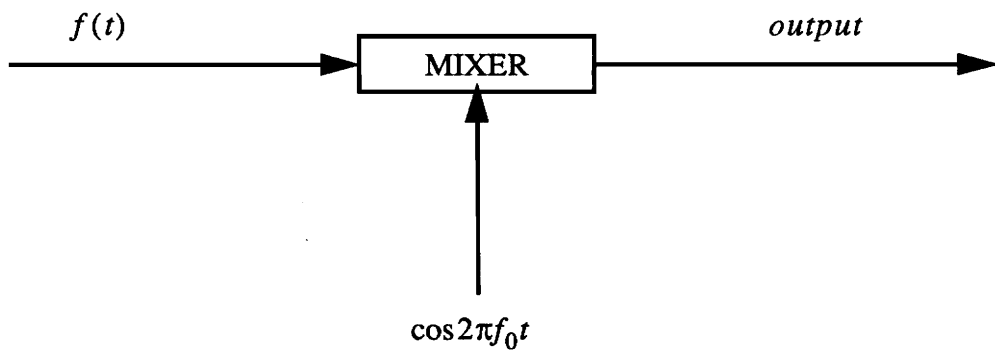


Figure 4.2.1.1  
 Network showing minimum number of fibers per cable.



$$\cos f(t) \cos 2\pi f_0 t = \frac{1}{2} [\cos (f(t) + 2\pi f_0 t) + \cos (f(t) - 2\pi f_0 t)]$$

Figure 4.3.1.1  
Frequency shifting of a sinusoidal signal.

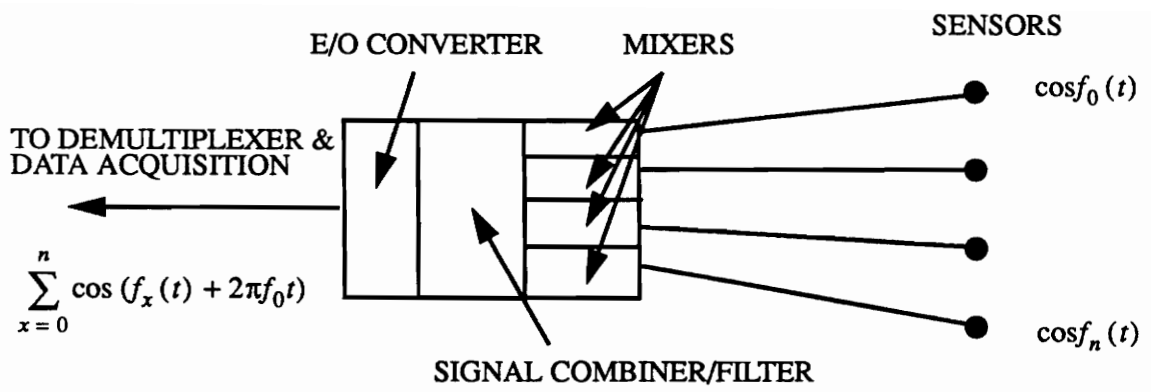


Figure 4.3.1.2  
 Multiplexing sensor data using heterodyne techniques.

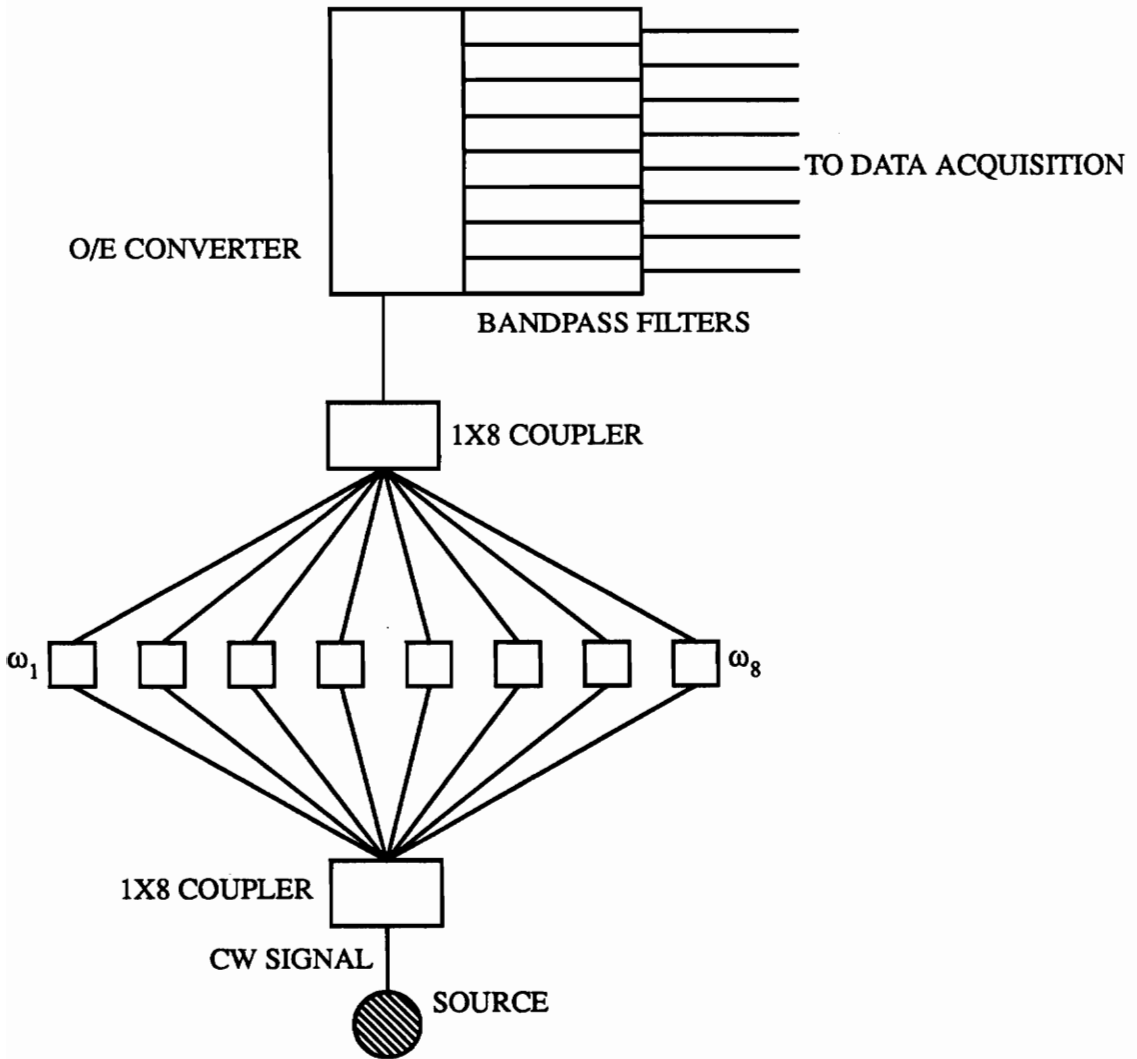


Figure 4.3.2.1  
Self-multiplexing fiber optic sensor system.

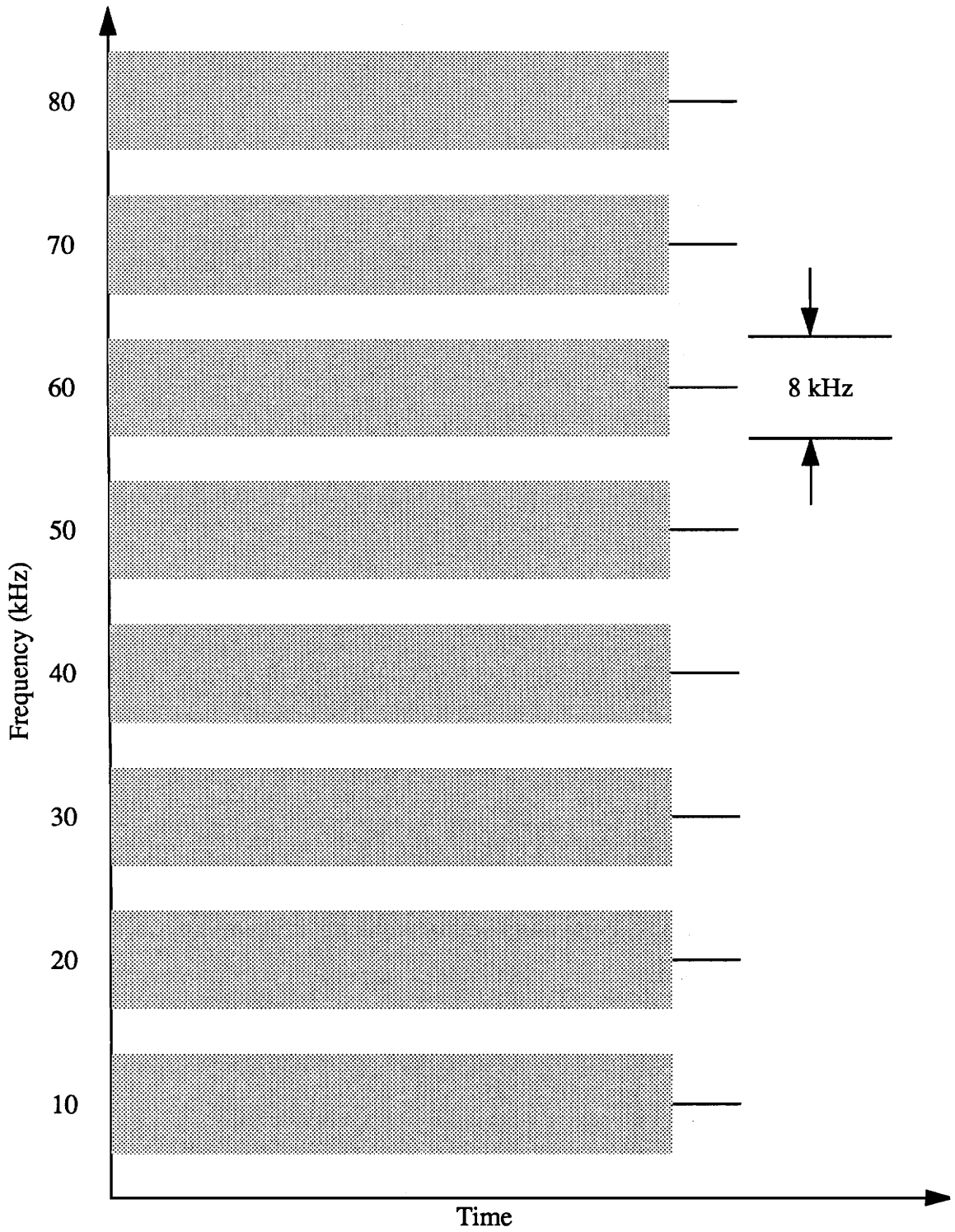


Figure 4.3.2.2  
Constituent frequencies of the self-multiplexing sensor system.

# CHAPTER 5

## 5.0 Conclusion

A concept for a data transfer network for use by shipboard tests and trials personnel has been provided. The network consists of fiber optic cable and connectors that link ten service areas around the entire ship. This network is more economical than the repetitive installations of copper networks for the different tests and trials. This network is simple and easy to use; it consists of simple and standardized components, provides easy access to the network throughout the ship, and is designed to accommodate most applications for data transfer. A discussion of various fiber optic sensors was also included; interferometric sensors may be used in applications where their sophistication and sensitivity are necessary while those crystal based sensors with inherently digital outputs show the most promise for shipboard tests and trials applications.

The following recommendations are provided as guidance in developing a system of fiber optic networks and sensors for fleet use. Since the network is intended to become part of the ship configuration, it must meet all of the standard Navy equipment/system procurement requirements. These recommendations provide direction for the natural evolution of network development, integration of a fiber network with conventional sensors, and fiber optic sensor development. These recommendations are:

- develop a detailed specification for a demonstration system, and identifying a platform for installation. By installing a demonstration systems that closely resembles the final product, systems engineering requirements data, such as component reliability, spare parts inventory, number and types of maintenance actions, mean time to repair, etc., can be generated;
- identify, procure, and test the interface equipment that is required by the current conventional sensor data acquisition methods for connection to the fiber network;
- continue the development of quartz crystal oscillator sensors for measuring pressure, acceleration, velocity, displacement, temperature, strain, voltage, and current. Develop a standard set of quartz crystal frequencies for the self-multiplexing sensor scheme.

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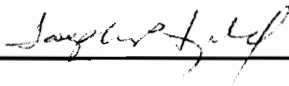
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## VITA

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