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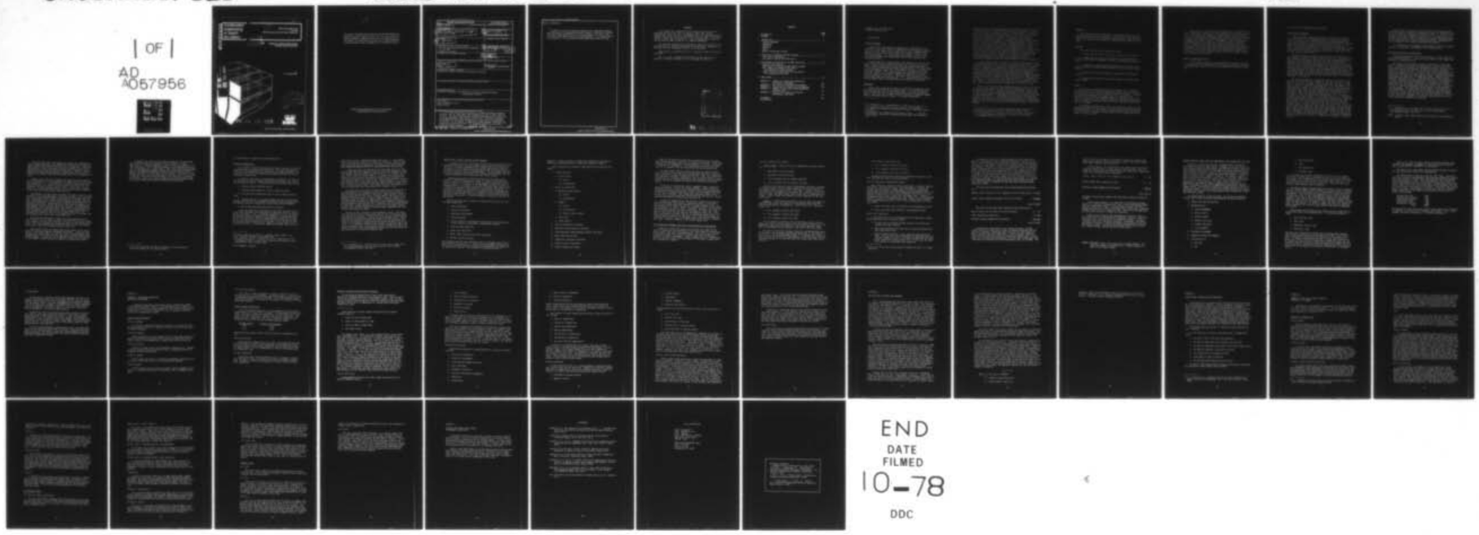

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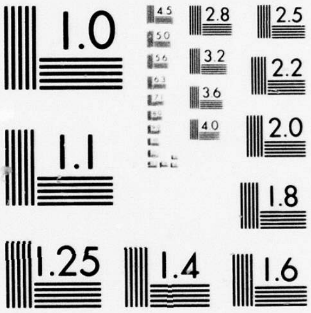
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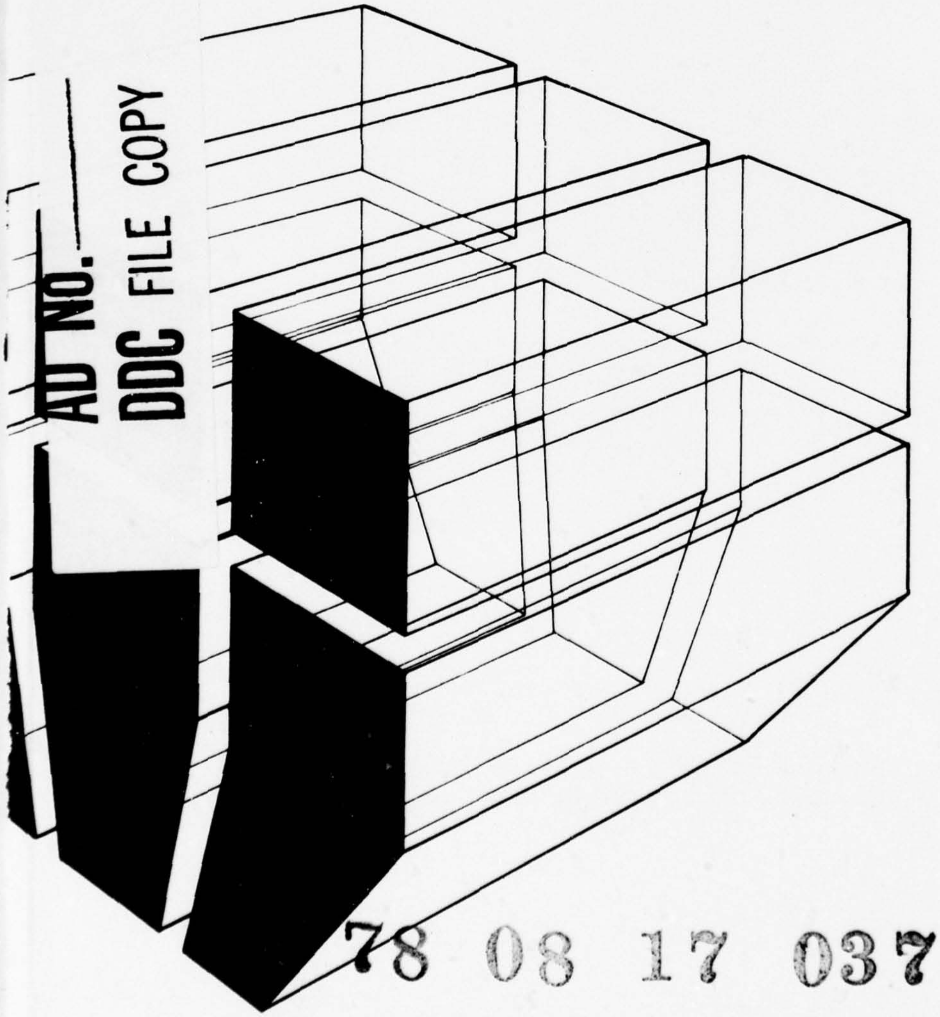
SPECIAL REPORT M-241
July 1978
EMI Circumvention by Fiber-Optic Transmission

POTENTIAL USES OF FIBER OPTICS IN ARMY FIXED FACILITIES

by
R. G. McCormack



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This report describes the results of a study performed to identify potential uses of fiber-optic data transmission links in Army fixed facilities. The uses identified are related to monitoring and controlling electrical-mechanical functions of the facility, primarily in Nuclear Electromagnetic Pulse (EMP) hardened facilities, but also nonhardened facilities. As an example, a comparison is made between fiber-optic and conventional wired data links in an automated monitoring and control system for energy control.

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Examples are given illustrating general cost comparisons between the fiber optic and conventionally wired systems. Conclusions are that fiber-optic data transmission links may be practical for use in Army fixed facilities where such links are advantageous to circumvent particular threats or in large complex systems where data rates are high.

FOREWORD

This research was conducted for the Directorate of Military Construction, Office of the Chief of Engineers (OCE) under Project 4A762719AT40, "Mobility, Soils, and Weapons Effects," Technical Area A1, "Weapons Effects and Protective Structures"; Work Unit 002, "EMI Circumvention of Fiber Optic Transmission." The applicable QCR is 1.03.010. The OCE Technical Monitor was Mr. I. Schwartz, DAEN-MCE-D.

The study was conducted by the Energy and Power Division (EP), U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. The CERL Principal Investigator was Mr. R. G. McCormack.

Appreciation is expressed to Mr. M. J. Pollock of CERL for his contribution.

COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director. Mr. R. G. Donaghy is Chief of EP.

CONTENTS

POTENTIAL USES OF FIBER OPTICS IN ARMY FIXED FACILITIES

1 INTRODUCTION

Problem Statement

Optical fiber technology has progressed in recent years to the point where fiber-optic cables can compete with conventional wiring and cabling for data transmission in applications such as communications, navigation, fire-control, surveillance, and computer terminal interconnecting systems.[1] For data transmission purposes, optical fibers have some advantages over conventional coaxial cable and shielded, twisted-pair cable.

The applicability of optical-fiber data-transmission links in the design and construction of Army fixed facilities has not been determined. However, conventional cables have some disadvantages when used in facilities hardened against nuclear weapons effects. To protect them from electromagnetic pulse (EMP) interference, they must be shielded with steel conduit. Also, long-distance data transmission using conventional cabling often requires repeaters or amplifiers to offset signal attenuation in the cable. Fiber-optic data-transmission links can overcome these and other problems. It is therefore desirable to determine whether they are suitable for use in Army fixed facilities.

Background

Experts have recognized the need to simplify the burgeoning tangle of wiring and cabling in this electronic age.[2] This need becomes evident to anyone who looks at the intricate webs of wiring and conduits used in facilities such as modern high-rise buildings, strategic command centers, and weapon-control centers. As systems become more

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[1] R. G. McCormack, W. J. Croisant and P. C. Lam, *State of the Art in Fiber Optics Communications and Data Transfer*, Interim Report E-111/ADA042579 (Construction Engineering Research Laboratory [CERL], July 1977).

[2] R. Batchelder, *The Communications Revolution 1976-(   )*, Galileo Electro-Optics Corporation, excerpted from National News Conference (April 1976).

sophisticated and missions more complex, an increasing amount of data or information must be transferred from one point to another. For many years copper wire or cable has been the accepted medium for conducting electrical signals over short distances. In the past 10 years, more than 10 billion pounds of copper have been used in constructing information transmission systems.[3] The demand for and resultant shortage of copper has caused it to become a strategic material and has caused its cost to increase sharply. Although aluminum (or other metals) may be substituted for copper, long-distance data transmission requires that losses in the transmission medium be low, in turn requiring that the metal used have a high conductivity. Examples of other metals having suitable electrical properties are (1) silver, gold, and platinum, all of which are even more expensive and scarce than copper, (2) lead, which is too heavy for cabling, (3) magnesium and sodium, which lack chemical stability, and (4) zinc, which has inadequate strength. Thus, there is an apparent need for a substantially different type of conducting medium for data transmission.

A strong contender for the role of substitute transmission medium is the optical fiber, which is made from silicon dioxide (glass), a very plentiful substance. In fiber-optic transmission lines, data signals travel as light impulses rather than as electrical currents. Optical fibers have many advantages over wire cables for data transmission, and in some applications they offer the most cost-effective approach. Expanded use of optical fibers and the resultant mass production of them will lead to further reductions in the cost of both the fibers and the hardware necessary for converting electrical signals to light pulses and vice versa. As costs decline, the importance of this new technology will increase. The state of the art and anticipated advances in fiber-optic data transmission have been summarized in a previous study.[4]

The U.S. Air Force has been investigating optical fibers for use on military aircraft, while the Navy has been studying both aircraft and shipboard applications. The Army Electronics Command has studied various applications in Army communications systems. Special studies have not been made, however, to show where and how optical fibers can be used in Army fixed facilities. Therefore, the investigation reported here addressed that question. The information gained from this study may be useful to the District and Division engineering personnel in determining whether fiber-optic data transmission links may be applied in facility designs.

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[3] *Insulated Wire and Cable*, Current Industrial Reports Series (U.S. Department of Commerce, Bureau of the Census, August 1975).

[4] R. G. McCormack, W. J. Croisant, and P. C. Lam, *State of the Art in Fiber Optics Communications and Data Transfer*, Interim Report E-111/ADA042579 (CERL, July 1977).

Objective

The objectives of this study were to identify potential uses of fiber-optic data-transmission systems in the design and construction of Army fixed facilities and to show cost and operational comparisons between data transmission by fiber-optic methods and by conventional cabling.

Approach

The study comprised the following activities.

1. Summarizing the state of the art in fiber optics technology.

2. Summarizing the technical characteristics of conventional monitoring and control instruments, sensors, and components currently in use.

3. Studying past Army construction projects so that they can be used as examples in evaluating the potential of fiber-optic data transmission.

4. Summarizing the data-transmission problem for the selected projects.

5. Comparing the required fiber-optic systems with conventional wired systems.

Scope

Specific data transfer applications addressed in this study were those pertinent to the electrical/mechanical monitoring and control of the facility and those related to security and alarm systems. Telephone or battlefield communications applications that are not the responsibility of the Corps of Engineers were not addressed at this time. The use of fiber optics for readout, inspection, and graphic display involves a different technology from that of data transfer and was therefore not addressed.

To show where and how fiber optics are potentially usable, cost and performance comparisons were made. Detailed step-by-step procedures for determining which facilities or what subsystems within facilities should use fiber optics are beyond the study scope and are intended for development in future studies.

The principles of fiber-optic data transmission, the state of the art, and potential applications of the technology are discussed in Chapter 2. The general requirements for monitoring and controlling the electrical and mechanical systems of Army fixed facilities are discussed in Chapter 3, followed by an example application of fiber optics to an automated energy control system. The example is used to compare the performance and cost of fiber-optic versus conventional wired data links. Appendix A summarizes conventional monitoring and control instruments, Appendix B discusses multiplexing techniques and hardware, and Appendix C discusses long distance transmission and repeaters. Appendix D summarizes some fiber-optic cable mechanical strength tests, and Appendix E provides information about optical fiber cable installation, maintenance, and repair.

Mode of Technology Transfer

A draft Technical Note providing procedures for design, installation, testing, and maintenance of fiber-optic data-transmission systems in hardened Army fixed facilities will be submitted for publication by OCE.

2 FIBER OPTICS TECHNOLOGY AND APPLICATIONS

Fiber Optics Technology

Fiber-optic data transmission involves transferring information over a hairlike fiber of transparent material, usually glass, quartz, silica, or plastic, with light being the form of energy transmitted. Light energy injected into the transmitting end of the fiber is retained within the fiber by the mechanism of total internal reflection. To obtain total internal reflection, the fibers are constructed with a core and a cladding of different indices of refraction, so that light beams traveling in the fiber but which are not parallel to the fiber's axis are bent radially toward the axis.

Information may be transmitted over the fiber in either analog (continuously variable) or digital (on-off pulse) form. Generally, however, analog transmission is made difficult and inaccurate by the nonlinearity of the components used (the light source and detector). Therefore, data are transmitted digitally in most current applications. If the original signal (or information) to be transmitted is in analog form but is to be transmitted in digital form, an analog-to-digital (A-to-D) converter must be used at the transmitting end of the fiber. Such a converter samples the analog signal at timed intervals and converts each analog sample to a group of binary (on-off) pulses, with the binary value of the group (or word) representing the amplitude of the signal at the moment it is sampled.

The required fiber-optic transmission system in its simplest form consists of a light source or transmitter, the optical fiber, a light detector (receiver), and power sources at each end. The typical light source is either a light-emitting diode (LED) or a laser diode. The light detector is generally a photodiode but may be a phototransistor or a photomultiplier tube. Practical systems use signal conditioning to amplify the signal from the light detector and to reconstruct the digital signal. They also incorporate some means to obtain time synchronization of the transmitter with the receiver. If it is necessary to restore the digital signal to its original analog form, a digital-to-analog converter (DAC) must be provided at the receiving end. When comparing digital data transmission in fiber-optic versus conventional wired systems, it should be noted that the wire or cable of the conventional system is equivalent to not just the optical fiber alone, but the fiber with its associated light source (including a driver and power supply) and a light detector (including a power supply and amplifier). Other components of the system may be the same whether the link is made with a fiber-optic line or conventional cable. Thus, for fiber optics to be cost competitive with metal conductors, it is generally necessary that the optical fiber be used to transmit many channels of information at once.

Optical fiber transmission lines can provide a much greater bandwidth (the range of frequencies and hence the amount of information they can carry) than that offered by conventional cables. To take full advantage of the fiber's bandwidth capability, it is generally necessary to use a multiplexing scheme, a method by which many independent signals can be transmitted over a single transmission medium. See Appendix B for a discussion of multiplexing techniques and hardware.

If transmission over extremely long distances is required, repeater stations are necessary. See Appendix C for further detail.

The State of the Art of Fiber Optics

A detailed examination of the state of the art in fiber optics has been reported previously.[5] Since that study, however, some changes have occurred, as summarized below.

The industry has continued to work on improving the fibers themselves, focusing on decreasing the attenuation, increasing the bandwidth, improving the strength, and decreasing the cost. Low-loss, step-index fibers having an attenuation of less than 2 dB/km can now be supplied in large quantities. The theoretical limit of performance has almost been reached in this area, and no significant improvements in attenuation can be expected in the immediate future. However, significant improvements have been made in graded-index fibers, which have wide bandwidths (200 mHz-km or more). Graded-index fibers with attenuations as low as 3 dB/km have become commercially available.* Furthermore, it is expected that additional improvements in the bandwidth of graded-index fibers can be attained within the next 5 years. Work is also continuing in improving single-mode step-index fibers having extremely large bandwidths. The single-mode fiber, however, is currently difficult and expensive to manufacture and has relatively high attenuation. In addition, it has a very small core (3 microns maximum) and a small acceptance angle for coupling light into the fiber, making it difficult to use. This fiber, therefore, is currently applicable only in situations where great bandwidth is essential.

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[5] R. G. McCormack, W. J. Croisant, and P. C. Lam, *State of the Art in Fiber Optics Communications and Data Transfer,* Interim Report E-111/ADA042579 (CERL, July 1977).

*NOTE: On special order these fibers may be obtained with bandwidths of Hz-km.

During the past year, the industry has pushed the development of small, simple fiber-optic transmit/receive links which can be used to replace conventional cables for digital data transmission. These systems consist of small transmitter and receiver modules which may be operated with a variety of different fiber types. Several of the commercially available systems operate at signal levels which are compatible with standard transistor-transistor-logic (TTL) integrated circuits.

Another area in which the industry has made substantial advances during the past year is the development of commercially available fiber-optic connectors. It is now possible to purchase standard connectors made specifically for several different types of optical fiber. The connectors are small and may contain an LED, a laser diode, a photodiode, or a phototransistor with provision for mating these components to the fiber to provide optimum light coupling.

Improvements in light sources have been realized as a result of refinements in LED chip technology, increasing the power output available and raising the bandwidth capability of some LEDs to greater than 300 mHz. Semiconductor laser diodes provide greater output than LEDs, and they can be modulated to provide greater information bandwidth than is possible with the LED. Widespread use of these devices, however, has been hampered by their shorter operational lifetime. Breakthroughs in semiconductor laser technology which will greatly increase diode lifetime are expected in the near future. When a long-life semiconductor laser becomes available, applications of single-mode fibers will increase, since with the laser it is possible to couple more power into the extremely small core of the single-mode fiber.

Both LEDs and semiconductor lasers can now be purchased with a short "pigtail" optical fiber attached so that the device can be optionally coupled into a system by splicing the pigtail to the system optical fiber. Splicing technology has advanced to the point that the energy loss across a splice can be kept as low as about 1 dB.

Since optical fibers are fragile and can be broken easily, the industry has developed numerous strengthening designs. In most of these designs, very tough jackets are used and internal strength members are incorporated into the cables so that they may be pulled through conduit without damage. In addition, the strengthened cables may be supported by cable hangers without protective conduit or covered cable trays.

In general, the state of the art has advanced to the point where the use of fiber-optic transmission lines is practical in many applications.[6] Telephone companies in major cities are beginning to install fiber-optic links in which thousands of voice-communication channels are conveyed over a single fiber. Fiber optics are seeing expanded use in interconnecting computer peripherals in cases where electromagnetic interference (EMI) might create problems if conventional wired systems were used. As usage continues to increase, costs will continue to decrease, and research and development will advance the technology even further. Thus, most industry experts anticipate widespread usage by the early 1980s with sales of over $100 million annually.

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[6] "Fiber Optics Systems Are Few, But Watch Out for the Explosion," *Electronic Design*, Vol 15 (July 19, 1977).

3 APPLICATIONS OF FIBER OPTICS IN ARMY FACILITIES

Potential Applications

This section identifies the broad areas where fiber optics could be considered for use in Army fixed facilities. Inter-building applications for voice communications or communications between automatic data processing units are not considered, since other Army agencies are responsible in those areas.[7]

In general, fiber optics technology has the potential for application wherever the optical fibers have inherent advantages over coaxial and twisted-pair cables. In Army fixed facilities, these areas include:

1. Hardening against EMP/EMI* threat

2. Eliminating the danger of arcing in explosive areas

3. Providing data transmission into or out of highly corrosive areas

4. Transmitting data in situations where the data rate-distance products are too high to be handled by conventional wired systems without repeater stations or excessively large cable (above 50 MHz-km).

5. Maintaining extremely high levels of security.

It has been shown that environments in which EMP (and EMI) and intense light transients are present have no measurable effect on optical-fiber transmission.[8] Thus, in EMP/EMI-hardened facilities, the threat of damage to electronic components and equipment or interference with their proper operation could be largely bypassed through use of fiber optics. In most cases, the use of fiber optics can eliminate the need for elaborate cable shielding, metal conduits, surge protectors, and electrical filters. In making cost comparisons between fiber optics and

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[7] Personal communication from Dr. L. Dworkin, DRSEL-NL-RM-1, U.S. Army Electronic Command (27 September 1977).

[8] R. G. McCormack and D. C. Sieber, *Fiber Optic Communications Link Performance in EMP and Intense Light Transient Environments*, Report E-94/ADA032126 (CERL, October 1976).

* Electromagnetic impulse.

conventional wiring in EMP/EMI-hardened facilities, it is not immediately obvious which alternative is most cost effective. General guidelines for making this determination are given in the section entitled Cost Comparisons Between Fiber-Optic and Conventional Wired Systems.

In some facilities, the design criteria may make the use of fiber optics highly desirable because of some of the stated advantages (other than EMP/EMI immunity) without considering costs. For example, the optical fiber can be used safely where it is necessary to provide data transmission into an area containing an explosive charge because the fiber provides dielectric isolation and cannot conduct charges (including lightning) which could cause arcing. Another example is a situation where cabling must be routed through areas where chemicals highly corrosive to metals are being used. Such highly corrosive environments may include underground applications where soil acidity is high.

In recent years, the need for energy conservation has resulted in the development of more elaborate monitoring and control systems for controlling electrical/mechanical functions. These systems include automated energy monitor and control systems (EMCSs), which may use minicomputers, microprocessors, or both, and which require complex transmission networks to relay all required data. The state of the art is now sufficiently advanced that fiber-optic data-transmission systems can be considered for such applications.[9] Generally, the cost effectiveness of fiber-optic systems becomes more attractive as the control system becomes larger and more complex, requiring larger bandwidths and transmission over greater distances.

Because of their immunity to electromagnetic fields, fiber-optic links are attractive for relaying data into or out of facilities where high security is required. In such facilities, secure information may be conducted by conventional cabling inside of shielded areas. These cables or the electronics systems with which they are associated may radiate electromagnetic energy from which secure information can be derived. It is therefore important that the data transmission media used to carry nonsecure data to and from the secure shielded zone not be capable of picking up the electromagnetic energy inside the shielded zone and reradiating it outside the shielded zone.

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[9] R. G. McCormack, W. J. Croisant, and P. C. Lam, *State of the Art in Fiber Optics Communications and Data Transfer*, Interim Report E-111/ADA042579 (CERL, July 1977).

Applications in Monitoring and Control Systems

In modern facilities, the process of monitoring and controlling the operational functions has become highly complex and sophisticated, especially in strategic command centers, secure communications centers, and other facilities where maintaining operational building functions is or may be critical to mission accomplishment. The requirement that the facility be hardened against EMP and/or nuclear blast normally adds considerable complexity to the monitoring and control system.

Monitoring and control systems typically use individual cables (coaxial or shielded twisted-pair cable) to transmit analog data from various monitoring instruments to either a central monitoring point or auxiliary points. In the case of the SAFEGUARD Anti-Ballistic Missile Defense facility, for example, the Missile Site Radar (MSR) complex uses a computer for automatic surveillance of the functions monitored. Essentially all quantities monitored are transmitted to the computer by individual shielded twisted pairs of conductors within cables which are generally routed through rigid steel conduits to provide EMP shielding and physical protection. Literally thousands of cables are required in the system.

Monitoring functions of interest in Army facilities fall into the following categories:

1. Level measurement
2. Pressure measurement
3. Temperature measurement
4. Flow measurement
5. Various analytical measurements obtained with instruments such as gas analyzers, pH analyzers, and humidity sensors
6. Flame and smoke detection
7. Speed (rpm) monitoring
8. Power, VARS, voltage, and current monitoring
9. Nuclear radiation sensing

Each category comprises many different types of instruments with differing principles of operation. In addition, the measurement task may vary from simple threshold detection to continuous measurement and readout of the quantity of interest. Each category is discussed briefly in

Appendix A to show the types of signals and information rates which a fiber-optic data-transmission link would be required to handle.

Control functions of interest in Army facilities include the following:

1. Liquid flow rates
    a. Valve control
        (1) On-off
        (2) Proportional
2. Gas or air flow rates
    a. Butterfly valve control
        (1) On-off
        (2) Proportional
    b. Dampers
        (1) On-off
        (2) Proportional
        (3) Electric motor control
    c. Start-stop
    d. Speed control
3. Pressure regulation (variable)
4. Generator voltage control (variable)
5. Engine-generator speed/frequency control (variable)
6. Power switching (on-off)
7. Temperature regulation (variable)
8. Humidity control (variable)
9. Battery charge rate control

Most of the functions listed may be controlled in one of several ways--through pneumatic, hydraulic, or electric controllers or such combinations as electropneumatic and electrohydraulic devices. Obviously, if fiber-optic transmission is to be applicable to a particular function, it is essential that the function be controlled electrically.

For those control functions which have only two operating modes (e.g., on-off and start-stop), the required switching rate is very low, often expressed in terms of actuations per hour. Thus, the information rate required of the data transmission links for these functions is extremely low, and literally thousands of such actuations could be handled by multiplexing the commands on standard voice-communications-grade lines.

In the case of proportional control, somewhat higher information rates are required. In most situations, however, a control would be moved directly from one position to another rather than being sequenced incrementally through each possible control position between the original and final positions. Each change would therefore require transmitting only a single binary word representing the new position, and the required information rate would again be very low.

It should be remembered that the multiplex concept could be used with a conventional wired system if dedicated coaxial (or shielded twisted-pair) cables were used instead of leased telephone lines. For most monitoring and control systems the information rates are low enough that bandwidth of a coaxial cable is adequate. Therefore, the number of cables required would be the same as the number of fibers, and it appears at this point that the material and equipment costs for a fiber-optic system would be higher than for a conventional wired system. For complex systems, however, the additional cost of the modules needed to interface the optical fiber to the EMCS system would be small (probably well under 1 percent) compared to the overall system cost.

Cost Comparisons Between Fiber-Optic and Conventional Wired Systems

Guidelines (rather than precise cost figures) for comparing the costs of fiber-optic data-transmission links with those for conventional coaxial-cable links will be presented here. Exact system costs cannot be prepared without first precisely defining the facility and data transmission system requirements. General comparisons will therefore be made on a per-unit basis, and an estimate will be given of system costs for a hypothetical example.

Costs for Coaxial Cable Systems

Coaxial Cable. Current prices for representative coaxial cabling are:

1. Type RG-58*, $.17/ft ($.56/m)
2. Type RG-8, $.36/ft ($1.18/m)
3. 1/2-in.-diameter Heliax, $.88/ft ($2.89/m)
4. 7/8-in.-diameter Heliax, $2.20/ft ($7.22/m).

RG-58 cable is typically used to interconnect electronic equipment in frequency ranges from DC through mid-VHF (0 to 100 mHz) for short runs where losses are not critical. RG-8 cable is used in similar applications but at frequencies up through 1 gHz. The Heliax cables are used for longer runs where losses are critical and at frequencies up to 10 gHz. Figure 1 shows the attenuation versus frequency for the four cable types.

Conduit. In EMP hardened structures, coaxial cables are generally routed through rigid steel conduits to provide both additional EMP shielding and physical strengthening. Current prices for rigid steel conduit are:

1. 4-in. diameter, $3.41/ft ($11.19/m)
2. 2-in. diameter, $1.10/ft ($3.61/m)
3. 1-in. diameter, $.52/ft ($1.71/m).

Cost of conduit accessories (such as couplings, unions, junction boxes, pull boxes, flexible conduit, and cast accessory boxes) will vary depending on the system configuration. For present purposes, these costs are estimated to be 25 percent of the cost of the line conduit.

The cost of installing a conduit system for non-EMP-hardened applications has in the past been estimated as being equal to the conduit material costs. For an EMP-hardened system, it is assumed that installation costs will be 50 percent higher because of the requirement that the conduits be welded at all junction boxes, pull boxes, and linear plate junctions.

Total conduit system costs are:

1. 4-in. diameter, \$7.67/ft (\$25.17/m)
2. 2-in. diameter, \$2.48/ft (\$ 8.12/m)
3. 1-in. diameter, \$ 1.17/ft (\$ 3.84/m).

Assuming that 50 coaxial cables are routed within each 4-in. conduit, the cost per cable is \$.15/ft (\$.50/m).

Cost for Fiber-Optic Transmission Systems

Many varieties of optical fibers are available, including low-loss, medium-loss, and high-loss types. These groupings are further subdivided into step-index or graded-index, multimode or single-mode, single-fiber or bundled, and strengthened or nonstrengthened types. For most EMP-hardened facilities such as SAFEGUARD, the building is large enough to allow the use of step-index, multimode fibers. Either a strengthened fiber cable supported by cable hangers or a nonstrengthened cable in a conduit or raceway could be used. International Telephone and Telegraph Corporation (ITT) lists[10] the following prices for low-loss fibers:

1. Glass step-index fiber (S-25-PS[1]), nonstrengthened, \$1.05/m
2. Glass step-index fiber (GS-02-8), strengthened \$2.30/m.

System Cost Comparisons

In evaluating the cost of conventional versus fiber-optic systems, three comparisons are of interest, namely:

1. Conventional wired nonmultiplexed systems versus fiber-optic systems using multiplexing.
2. Multiplexed systems using fiber optics versus multiplexed systems using cable links.
3. Nonmultiplexed fiber-optic versus nonmultiplexed cabled systems. This case will not be considered in making the cost comparisons, however, since it is evident that when the full bondwidth capability of optical-fiber links is not used, the fiber optic system is considerably more expensive.

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[10] *Short Form Price List* (Electro-Optical Products Division, ITT, February 1977).

To compare the costs of a multiplexed optical-fiber system with those of a conventional wired, nonmultiplexed system, consider as an example a simplified remote monitoring application at a nuclear-hardened facility. The requirement is typical of a weapon-control facility such as SAFEGUARD. The specific task is the remote monitoring of parameters from a subsystem such as an auxiliary power plant (in the case of SAFEGUARD, a 3.2 MW diesel-engine generator set.) For comparison, it will be assumed that 100 analog signals must be transmitted from measuring instruments at the power plant to the central monitoring and control location, and that the distance between the two locations requires 300 ft (90 m) of cabling. For the conventional wired system, it is assumed that individual cables are required for each analog signal and that rigid steel conduit is required for EMP shielding, with each conduit carrying 50 cables.

The costs for the conventional wired system without multiplexing are:

Conduit, 600 ft (183 m) of 4-in. diameter at \$7.67 ft (\$25.17/m) = \$ 4,602

Coaxial cable, 60,000 ft (18.288 m) at \$.17/ft (\$.56 m) = \$10,200

Total \$14,800

The costs for the fiber-optic system with multiplexing are:

Optical fiber, 300 ft (90 m) at \$.70/ft (\$2.30/m) = \$ 210

Fiber interfacing electronics = \$ 1,000

Multiplex system (commercially available) = \$14,755

Total \$15,965

Although this rough material cost comparison shows a slightly higher cost for the fiber-optic system, it should be observed that the particular multiplex system which was priced has far more capability than is required for this simple task. A special-purpose system designed for this application could be obtained at reduced cost. Furthermore, even at the prices quoted above, the fiber-optic system would have a definite cost advantage if future maintenance costs are included. The optical fiber is not subject to corrosion* and does not need periodic checking for immunity against EMP effects, whereas the conduit system would require periodic shielding tests.

In this example, the conventional wired system could also use multiplexing requiring only a single cable to relay the data. Thus, in comparing a conventional multiplexed system to a fiber-optic multiplexed system, the following figures would apply:

Conduit, 300 ft (90 m) of 1-in. diameter at $1.17 per ft	= $	351
Coaxial cable, 300 ft (g/m) at $.17/ft	= $	51
Multiplex system (commercially available)	=	$14,755
	Total	$15,157

As given in the previous example, the fiber-optic system cost would be $15,965.

In this simple example, it is seen that for multiplexed systems, the cost of fiber-optic transmission lines is only a few percent higher than for conventional cables. For more complex systems, the costs become even more nearly equal except where the coaxial cable's bandwidth becomes too narrow or its losses too high. Then it will be found that the fiber-optic system is slightly less expensive.

A major factor hindering the widespread use of optical fibers is the higher cost of the optoelectronic components required. High costs result partially from the present low production volume. As usage increases, costs will continue to decrease. Furthermore, anticipated technological advances in design and manufacturing processes will further reduce pricing. Continuing shortages and high prices of copper will tend to further increase the use of fiber optics.

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* NOTE: The optical fiber can be used with or without conduit. Wire cables are subject to corrosion even in conduit because of leaks in the conduit system.

Example Potential Application of Fiber-Optics in a Conventional Facility

An EMCS at an Army base provides an example where fiber optics technology has potential application. Although the base and the facilities involved may not be EMP-hardened, the EMCS which might be installed there might be representative of the complex monitoring and control systems in future facilities. The principles illustrated by this example could be applied to both hardened and nonhardened systems. A block diagram of a typical EMCS is shown in Figure 2. The system includes 35 data collection and transmitting units (DCTUs). Each DCTU communicates with a central processing unit (CPU) over leased telephone wire pairs, each having a 3-kHz bandwidth. The number of pairs required is dependent on the number of channels monitored and controlled by each DCTU. The system is capable of accommodating 14,000 analog, binary, or command points. Analog source scanning is accomplished at a rate of 30 sources per second. Binary (on-off) sources may be scanned at a rate of 500 contacts per second. The transmitted bit rate of each DCTU is 1200 baud (bits per second).

The system controls 13 heating plants, the electrical switching station, and 17 major buildings, performing the following functions:

1. Demand limiting-load shedding
2. Optimization of:
    a. Energy management
    b. Boiler profile
    c. Chiller profile
    d. Optimal start-stop
    e. Program start-stop
    f. True economizer
3. Maintenance management
4. Logging of trends (and summary)
5. Totalizations of:
    a. Run time
    b. Btu

c. GPM (gallons/min)

d. lb/hr

e. Analog quantities

f. Kilowatts used.

The total data transfer requirement involves the use of approximately 400 individual leased telephone wire pairs to and from the control center. Data communication is performed asynchronously using channel multiplexors, with each channel being full duplex (two-way). The multiplexing system uses digital transmission. Extra bits are transmitted to assure greater data reliability.

The heating plants, energy-controlled buildings, electric switching station, and the computer control center are spread out over a 3-square-mile area, with 1 mile being a typical distance over which data must be transmitted. Since the data rate required in this system is very low for each pair of wires, the low-bandwidth telephone wires are adequate. Telephone lines such as those on continuous property can typically be leased at a flat rate of $2.50 per month per line plus a charge of about $8.00 per month per mile of distance. Thus, the rental cost for the 400 lines (if they average 1 1/2 miles in length) would be about $5800 per month, equivalent to a 10-year present worth of $477,500 if discounted at 8 percent.

Data transmission from the various points could be accomplished by several means other than telephone lines. The available options include:

1. Special-purpose cable
2. Radio links
3. Atmospheric optical links
4. Fiber-optic links.

The first cost of procuring, routing, and installing special-purpose cable would be substantial and would depend on whether it was to be installed underground, overhead on existing poles, or overhead on new poles. If special-purpose cable was used, a single cable between each point would suffice since the required data transmission rates are low. To analyze cost effectiveness it would be necessary to compare the first cost of the special installation with the present worth of the series of anticipated leasing payments to be made for the 400 pairs of telephone cables.

The use of a radio link would require relatively expensive radio equipment and permanent assignment of a portion of the RF spectrum. Such a system would be susceptible to interference.

The optical link (laser beam) would be weather-dependent and therefore not sufficiently reliable for consideration.

The fourth option is the use of optical fiber links. Using low-loss fibers having a high bandwidth, the necessary transmission capacity could be provided by a single fiber connecting each DCTU with the CPU, thus requiring only 35 lines. To be cost effective, the initial and 10-year maintenance cost of each fiber-optic link would have to be less than or equal to $477,500 (the present worth of the telephone line rentals over 10 years) divided by 35, or $13,643. The average link would be about 1 mile long. The estimated costs for each link of a fiber-optic system (assuming that the fibers are installed on existing utility poles) are as follows:

Average fiber cost	$3745
Interfacing electronics	1000
Installation hardware	300
Installation labor	1000
Maintenance (10 years)	500
Total	$6545

Multiplying this cost by 35 lines yields a total system cost of $229,075 as compared to the $477,500 for telephone line rentals. Thus, in this example, the use of fiber optics is a feasible alternative.

4 CONCLUSIONS

Optical fibers' large data-transmission bandwidth, dielectric isolation, reduced weight and size, and freedom from EMP, EMI, and radio frequency interference (RFI) offer advantages over conventional twisted-wire and coaxial cables. With the telecommunication industry expanding its use of fiber-optic equipment, production rates are increasing and costs are dropping. As a result, the use of fiber-optic data-transmission systems will continue to expand rapidly.

In Army fixed facility monitoring and control systems, the use of fiber optics rather than conventional metallic cables can be advantageous especially in EMP-hardened facilities, in fuel and ammunition storage facilities, in highly corrosive environments, and in high security areas. In facilities that require large numbers of monitoring and control channels, multiplexing and use of fiber-optic cables for data transmission are cost-effective.

Since this new technology is growing rapidly and is expected eventually to see widespread application, the Corps of Engineers should develop criteria for the design of fiber-optic data-transmission systems and should develop detailed procedures for making tradeoff analyses between data transmission options.

APPENDIX A:

SUMMARY OF CONVENTIONAL MONITORING AND CONTROL INSTRUMENTS

A computerized heating, ventilating, and air conditioning (HVAC) system provides automatic control of the temperature and/or humidity in a space while optimizing energy consumption. The control system portion may be electric, electronic, pneumatic, fluidic, hydraulic, self-contained, or a combination of these.

Types of Control Systems

Electric Systems

Starting and stopping the flow of electricity or varying the voltage and current by means of a rheostat or bridge circuit provide control in electric systems.

Electronic Systems

These systems use very low voltages (15 V or less) and currents for sensing and transmission; these control signals are amplified by electronic circuits or servomechanisms to operate the controlled devices.

Pneumatic Systems

Pneumatic systems usually use low-pressure compressed air. Changes in output pressure from the controller cause a corresponding position change at the controlled device.

Hydraulic Systems

These systems are similar in principle to pneumatic systems but use a liquid or a gas other than air as the transmission medium.

Fluidic Systems

Fluidic systems use air or gas to transmit control commands and are similar in operating principles to electronic as well as pneumatic systems.

Self-Contained Systems

This type of system incorporates a sensor, controller, and controlled device in a single package. No external power is required; only a monitoring connection need be provided. The energy needed to adjust the controlled device is provided by the reaction of the sensor with the controlled variable.

Control System Transmitters

All of the control functions in a system depend on the monitoring (measurement) of the controlled variables. The measurement is made by a sensor, the output of which is connected to a signal conditioner. The sensor and signal conditioner together constitute a transmitter. The measured value is produced as one of the standard DC outputs of the transmitter, which fall into the following standard ranges:

Voltages (volts)	Currents (milliamperes)
0-11	1- 5
1- 5	4-20
0- 5	10-50

Transmitters may produce either analog or discrete (incremental) outputs.

Analog Transmitters

Analog devices transmit data in a linear, continuous form with the output voltage or current being proportional to the measured variable. The output signal from an analog transmitter must be converted to digital format before it can be transmitted via a digital data system such as a fiber-optic link.

Discrete Transmitter

Transmitters that indicate conditions such as stopped or started, on or off, set or reset, or a high or low limit are already in binary form. Therefore, a digital data system can transmit the data without prior conversion.

Analysis of Monitoring and Control Functions

The following paragraphs discuss some of the conventional monitoring instruments applicable to multiplexed links. Possible applications and considerations such as measurement response time, accuracy, and the resultant data transmission rates are examined to indicate those parameters which may be of importance in a system using fiber-optic transmission links.

Level Monitoring

Level detectors are used in Army fixed facilities to monitor variables such as:

1. Levels in fuel storage tanks
2. Levels in lubrication oil tanks
3. Levels in water storage tanks
4. Soil water levels.

The simplest level sensor is a float actuated switch, which senses only a threshold level. The information transfer rates required for this type of device are extremely low. In some applications, it may be necessary to detect numerous threshold levels in a tank or to provide continuous monitoring of liquid levels. If continuous monitoring is required, information rates are increased somewhat, but they are still relatively low as compared to the bandwidth of typical data-transmission channels. For example, assume that it is desired to know the tank level to within 0.1 percent. It is then necessary to differentiate between 1000 levels. These 1000 levels can be represented by 10 binary digits (bits) since $2^{10} = 1024$. If the tank could be drained in 1024 seconds (about 17 minutes), it would be necessary to transmit one 10-bit "word" each second to maintain updated information on the status of the tank level. Thus, an information rate of 10 bits per second would suffice. Typically, data transmission systems require additional data bits for framing and error checking or correction, but such bits will not normally increase the required information rates by more than a factor of 2. The required information rates are therefore low for liquid level monitoring. A conventional shielded, twisted-pair cable could carry many thousands of such channels using time-division multiplexing.

Pressure Monitoring

Pressure-measuring devices are used in Army fixed facilities to monitor parameters such as:

1. Fuel pressures
2. Coolant systems pressures
3. Differential air pressures
4. Barometric pressures
5. Manifold pressures
6. Vacuum levels.

The wide range of available pressure-monitoring instruments is capable of measuring from high vacuum pressures of up to 400,000 psig. Many of the commercially available instruments use a DC signal in the 4 to 20 milliampere range to transmit pressure information in analog form over shielded, twisted-pair cable to central monitoring points.

The rate of change of the pressures to be measured is usually low, requiring data channels with low information rates. The highest information rate likely to be encountered would be that required to monitor engine manifold pressures, where pressure variations over the full range may occur in about 1 second. If 1 percent measurement accuracy was required, the system would have to transmit 7 binary digits ($2^7 = 128$) plus framing and error correction bits. A sampling rate of 1 per second would be necessary; assuming a total of 14 bits per sample, the required data transfer rate would be 14 bits per second.

Temperature Monitoring

Temperature measurement is accomplished with a variety of devices, including:

1. Glass-stem thermometers
2. Bimetallic thermometers
3. Filled thermal-element actuators
4. Color indicators
5. Pyrometric indicators
6. Electrical resistance thermometers
7. Thermistors
8. Thermocouples

9. Quartz crystal thermometers
10. Radiation pyrometers
11. Infrared pyrometers.

Some of these devices must be read manually, while others have electrical outputs which can be transmitted over wires to a monitoring point. Most of the commercially available instruments provide a current output which is proportional to temperature.

Applications of remote temperature monitoring in Army fixed facilities include:

1. Room air temperatures
2. Outside air temperatures
3. Exhaust gas temperatures
4. Bearing temperatures
5. Lubrication oil temperatures
6. Chilled water temperatures
7. Hot water (boiler) temperatures.

In general, the temperatures vary slowly, requiring at least several minutes to change through an appreciable percentage of the measurement range. Some standard commercially available temperature monitors, however, are capable of responding in 1/5 second at accuracies of 0.2 percent of full scale. To maintain this accuracy and rate, the actual data transmission rate required may be as high as 100 bits per second. Adding framing and error correction bits may increase the required bit rate to 200 bits per second.

Flowrate Monitoring

In Army fixed facilities it is often necessary to monitor and control various liquid and gas flow rates. Commercially available flowrate measuring instruments use a variety of operating principles. Types applicable to a centralized monitoring and control system include:

1. Differential pressure sensors
2. Magnetic sensors

3. Turbine sensors
4. Swirlmeters
5. Thermal flowmeters
6. Rotating lobe sensors.

Variables which are typically monitored at Army fixed facilities include:

1. Fuel flow rates
2. Coolant flow rates
3. Lubricating oil flow rates
4. Airflow rates in cooling systems
5. Steam flow rates in heating systems.

Flow rates which may be accommodated by commercially available instruments vary from 0.03 cc per minute through 100,000 gallons per minute (378,500 liters per minute). The best accuracies obtainable are 0.5 percent; obtaining those accuracies requires a digitizer capable of producing 200 quantizing levels. These 200 levels would require 8-bit words in the digitizing process. The magnetic type of flowmeter can respond over its full range in a fraction of a second. If a PCM multiplex system were to retain a response time of 1/10 second, an information rate of 2 x 8 x 10, or 160 bits per second would be required. It is doubtful, however, that such a fast response time would ever be necessary in the conventional monitoring applications.

Electric Power System Monitoring

Electric power system monitoring includes the measurement of power flow, volt-amperes in reactive circuits (VARS), voltage, and current. These quantities are normally measured in fixed monitoring applications by electronic instruments having DC outputs proportional to the quantity being measured. In the case of precise power instrumentation, it is desirable to be able to measure the transient response of a generating system. To do so, it is necessary to obtain several measurements within a half cycle of the alternating current waveform. If the required accuracy is 0.1 percent of full scale, then 10-bit resolution is needed. If samples are required at 2-millisecond intervals, the data transmission rate is 2 x 10 x 500 or 10,000 bits per second. This rate is substantially greater than that required for most other types of monitoring and would present difficulties in framing if other channels were sampled at much slower rates. The transient monitoring would probably be best handled by a dedicated separate link. In this type of application, the greater bandwidth and lower attenuation provided by fiber optics become attractive. If several transient measurement channels are combined in a multiplexed link, the bit rates become sufficiently high that losses on conventional coaxial cables will be significant and bandwidth reduction will cause distortion of the transmitted waveshape.

In addition to monitoring the real-time transient response of electric power systems, it is also common to measure rms voltage, current, power, and VARS. Such measurements require a much lower information rate than real-time transient analysis. These other quantities would normally need to be sampled only a few times per second. The required accuracy could be as good as 0.1 percent and thus the information rate for each channel would be on the order of 100 bits per second.

Other Monitoring

Other quantities and conditions which might be monitored in an Army fixed facility include rotational speed (rpm), nuclear radiation, gas analysis, acidity analysis, humidity, flame detection, and smoke detection. Each of these quantities would vary relatively slowly and would thus require low data transmission rates, generally less than 100 bits per second per channel.

APPENDIX B:

MULTIPLEXING TECHNIQUES AND HARDWARE

One of the advantages of fiber-optic over conventional cabling is the greater information bandwidth of the optical fiber. This advantage can only be used, however, if it is necessary to send rapidly varying information. As discussed in Appendix A, most monitoring and control instruments and transducers produce slowly varying outputs which require only very small bandwidths if transmitted individually. It is possible to take advantage of the fiber's bandwidth, however, by transmitting the outputs of many instruments over a single fiber (channel). This may be done either by time sharing the channel between all the instruments or by a modulation scheme which allows the outputs of different instruments to be transmitted on different frequency bands within the channel frequency spectrum. Time sharing of a channel is called time division multiplexing (TDM), whereas frequency sharing is known as frequency division multiplexing (FDM).

It should be noted that whatever multiplexing scheme is chosen will work equally well with fiber-optic links or conventional wired links, except that the fiber-optic link will be able to handle many more monitoring and control components because of its greater bandwidth. From an economic standpoint, a multiplexed channel is superior to an individual channel system, since one transmitter and receiver are needed instead of many.

Two multiplexing techniques--frequency division multiplexing (FDM) and time division multiplexing (TDM)--are of interest. FDM, which is easily adaptable to the transmission of analog information, uses frequency modulated subcarriers to convey the information. One subcarrier is used for each analog source. Modulation extremes result in each source occupying a predetermined portion of the overall spectrum. The combined signals from many modulated subcarriers thus form a wideband composite signal. The composite frequency-multiplexed signal modulates a carrier frequency before transmission. After reception and demodulation of the carrier, the individual analog sources are recovered by assigned frequency slot bandpass filtering. Obviously, FDM equipment complexity increases as the number of individual analog signals increases. For data transmission systems serving thousands of analog sources, FDM becomes impractical.

A system that can scan each individual source on a time-shared basis is more practical for a large number of sources. In TDM, the information from each channel is transmitted in designated time intervals, using some type of pulse code modulation (PCM). In PCM systems, the analog signals to be transmitted are first converted to digital signals in an analog-to-digital (A-to-D) converter. Generally, the digital signal is a binary number representing the analog information. The number of binary digits (bits) used then determines the accuracy with which the analog signal can be represented. If n bits are used, then 2^n discrete levels (also called quantizing levels) are established. After the A-to-D converter samples the analog signal, it selects the binary number closest in value to the analog input value as representing that sample. Since each binary digit has only two possible levels (1 and 0), it may therefore be sent as a pulse. Various pulse coding schemes have been devised for representing the 1 and 0 levels by pulses. The simplest of these is NRZ (nonreturn to zero) where a high level is a 1 and a low level is a 0. In NRZ (c) (nonreturn to zero, change) and NRZ (m) (nonreturn to zero, mark), transitions from one level to another represent 1's or 0's. Other coding types include SP (split phase) and RZ (return to zero). SP uses a square-wave cycle to represent a 1 and an inverted square-wave cycle to represent a 0. RZ uses a square-wave cycle to represent a 1 and no transmission to represent a 0. Each PCM scheme has certain advantages and disadvantages.

The rate at which the original signal must be sampled to completely define the signal is established by the Nyquist Sampling Theorem. This theorem simply states that it is necessary to sample at a rate equal to 2F, where F is the highest frequency at which spectral energy of the original signal exists.

The advantage of multiplexing is that many signals or channels may be sent over one transmission link. Sequential time scanning of all channels to be transmitted is performed and the binary words (groups of bits) representing each channel are transmitted sequentially. Generally the entire sequence of all channels is called a frame. To reestablish timing at the receiving end (and to properly identify each binary word), frame synchronization words are also normally transmitted. Framing schemes may be devised to allow some channels to be scanned at higher rates than others. In addition to the frame synchronization word, some PCM systems transmit special coded pulse trains along with each data word to check for (and, in some systems, to correct) errors made in the transmission, detection, and data reconstruction process. Thus, the total number of bits required may be as much as twice the number of bits required for data alone. The bandwidth required for the multiplexed channel is therefore

$$f_b = 2\ n\ f_s$$

where f_b = bit rate or frequency

2^n = number of quantizing levels

f_s = analog channel sample rate

Components required for PCM-TDM include A-to-D converters, D-to-A converters, a PCM encoder and a decoder, synchronization circuits, a transmitter, a receiver, and the transmission medium.

APPENDIX C:

LONG-DISTANCE TRANSMISSION AND REPEATERS

Long-distance data transmission by fiber optics may be facilitated by using regenerative repeaters. Optical regenerative repeaters may be two or more transmitter-fiber optic-receiver systems connected in series. The optical receiver detects and decodes a low signal-to-noise ratio (SNR) signal and then generates a new pulse which drives the transmitter. Digital data transmission systems have an advantage over analog systems in that the noise is not accumulative. Digital system noise is limited to just the noise of a single transmitter-fiber optic-receiver link. Theoretically, therefore, any distance may be covered by adding more links. As the number of repeaters increases, so does the system cost. Minimizing the number of repeaters by optimizing the repeater spacings becomes imperative for maintaining cost effectiveness.

The maximum repeater spacing is a function of many different factors. Some are:

1. The selection of single or multimode, step- or graded-index fibers

2. The optical loss of the fiber and connectors

3. The optical power which can be coupled into the fiber

4. The spectral bandwidth (line width) of the optical power source

5. The spectral response of the optical receiver

6. The selected digital transmission code

7. Pulse shape at input of receiver

8. The threshold determination of the receiver.

In general, the maximum repeater spacing is obtained by maximizing the mean optical power coupled into the fiber.[11]

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[11] W. E. Heinlein, et al., "Repeater Spacing of Digital Communication Systems Using Optical Waveguide," *Proc. IEEE*, Vol 123, No. 6 (June 1976).

APPENDIX D:

SUMMARY OF FIBER OPTIC CABLE MECHANICAL STRENGTH TESTS SUMMARY

Information in this appendix has been derived from work done by the U.S. Naval Electronic Laboratory Center.[12] It is included to show the ability of optical fibers to withstand stresses and conditions likely to be encountered on construction sites.

Mechanical Strength Tests

Bending Radius

No MIL acceptance requirement exists for this cable property. Cable manufacturers generally state that the bending curvature should be limited to no less than five times the cable's outer jacket diameter. This criterion appears to be safe for cables having fiber diameters of less than about 3 mils. This acceptance condition was based upon not exceeding a 0.6-dB loss (13 percent fiber breakage level) per rotational turn. By comparison, cables with fiber diameters of about 2 mils can meet the above requirement with a minimum bend radius of about 0.25 in. (= about 3 times the cable outside diameter).

Tensile Strength

In lieu of a MIL requirement defining the acceptance of glass fibers under tensile loads, a test condition was developed for evaluating the tensile strength property of the cable (bundle only). With a 0.6-dB-loss (13 percent fiber breakage) acceptance level, tensile load-sustaining capabilities of about 25 to 30 lb were measured for cables with 1- and 2-square-mil bundle areas, respectively. This value corresponds to tensile stresses of about 25,000 psi of bundle area.

Terminal Strength (Tension and Torque)

The optical cables used in the tests performed acceptably, based upon comparable fiber breakage and transmission-line loss levels, after being subjected to the requirements of test conditions A and E of MIL-STD-202D, Method 211A, respectively, for tension and torque. The MIL-specified minimum acceptable terminal tensile load was 20 lb, with exposure duration of 5 to 10 seconds. No sustaining torque level was

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[12] R. L. Lebduska, *Fiber Optic Cable Test*, Report No. NELC TR-1869 (U.S. Naval Electronics Laboratory Center, 1973).

specified because of the small (1/16 in.) equivalent diameter for these cables. The results applied to cables using precision-epoxied terminals in their construction. Cables with crimp-type terminals were not able to meet the 8-lb tensile-strength condition required by MIL-T-7928F. From the tests conducted, it appears that the ability of the epoxy to sustain bonded integrity under tensile load generally provides a good match to the cable bundles' ability to sustain fiber continuity under comparable loads.

Twist

No MIL requirement exists to gage the cable twist property. Therefore, test conditions were devised to assess the optic cable's ability to sustain fiber continuity on the basis of rotations per unit of cable length. The test results indicated that twist levels not exceeding about three rotations per cable foot (cables of the CGW 5010 and 5011 types under normal ambient conditions) will not appreciably degrade the cable's performance.

Mandrel Strength

The requirements for cable mandrel strength compliance are stated in IL-C-3432D and Method 2011 of FED-STD-228. Cable integrity was not maintained under the specified mandrel diameter and tensile load condition (0.125 in. and 30 lb). The fiber optic cables exhibited mean fiber breakage levels of about 20 percent at tensile loads of 12 and 18 lb for the 5011 and 5010 CGW types, respectively. These mandrel strength limitations basically stemmed from the bending radius property of the glass fibers, which admittedly were inferior in bend to metallic fibers. The need for mandrel performance, however, in this small bend radius area does not appear to be great. Practical cable fabrication, installation, and routing techniques will obviate this requirement. By comparison, tests using mandrel diameters larger than the MIL-specified size showed that for 0.250-in. and 0.50-in.-diameter mandrels, essentially the full tensile load (25 and 50 lb) can be sustained by the 5010 and 5011 cable types, respectively.

Cyclic Flexibility

In lieu of a MIL requirement, this test consisted of cable degradation assessment at intervals of about 2000 cycles (at 90° bends) of cable flexure about a 1-in.-diameter mandrel. The flexure rate was controlled at 1 cycle per second. Cyclic exposure goals of 10,000 cycles were selected, and acceptance was based upon meeting the 13 percent fiber breakage (0.6-dB transmission loss) level after test exposure. The test results indicated that the flexural limitations found were jacket-dependent and did not reflect deficiencies or limitations within the bundle composition. Some improvement in jacketing particularly concerning flexibility at reduced temperatures) and use of terminal stress relief should provide cable acceptance to the above test condition.

Vibration

Procedure X of MIL-STD-810B defines the vibration requirement. The test condition was extended from 500 Hz to 2000 Hz to additionally satisfy a requirement for airborne transportability. The test cables were subjected to specification levels and durations with negligible evidence of cable degradation. Tests were also performed at vibration levels which exceeded the specification conditions by a large factor, again with little evidence of cable performance modification.

Mechanical Shock

The MIL shock requirement is defined by MIL-STD-202D, Method 213A. Both half-sine and sawtooth shocks approaching specification levels were applied to the test cables with negligible resulting performance modification. The vibration and shock tests were performed sequentially on the same cables, further supporting the conclusion that these conditions have negligible effect on cable integrity and performance. Also, complex cable harnesses were fabricated and subjected to these same test environments. They similarly exhibited negligible cable modification effects.

Abrasion

A simulation of the abrasion test requirement as defined in Method 2211 of Federal Test Method Standard 228 was used. The abrasive exposure was sufficiently intense to completely abrade the PVC jacket and expose the fiber bundle; however, the bundle was not contacted by the abrading element. No optical performance degradation of the cables tested was noted.

Environmental Tests

Life Test at Elevated Temperature

The test requirements of Method 108A of MIL-STD-202D were followed for this cable test. A dry-air (85°C) cable exposure for a duration of 250 hrs produced essentially no increase in fiber breakage level and/or cable transmission loss.

Thermal Cycle -- Short Duration

This test, in accordance with Method 102A of MIL-STD-202D, consisted of exposing the cable to five 1 1/2-hr temperature cycles ranging from -55°C to +105°C. Some increase in cable transmission loss but negligible fiber breakage resulted. The losses are attributed to terminal degradations primarily resulting from the high-temperature exposure. Epoxy fiber bonds and bundle/terminal bonds appeared to be affected by the temperature cycling. The measured cable losses were less than 1 dB for all cables subjected to these test exposures.

Thermal Cycle -- Extended Duration, Low Temperature

This thermal test exposure, specified by Method 502 of MIL-STD-810B and consisting of three cycles from ambient to -40°C for a test duration of 24 hrs minimum, produced negligible effects upon the test cable's properties and/or performance.

Thermal Cycle -- Extended Duration, High Temperature

As defined by Method 501, MIL-STD-810B, this test consisted of three cycles of hot "soaks" at 49°C (6 hrs) and at 68°C (4 hrs), for a total test duration of 36 hrs. Again, negligible test cable fiber breakage or increase in light transmission loss was noted after the test exposure.

Flammability

Exposure of the cable jacketry to an open propane flame cindered the jacket, with evolution of a gaseous product (presumably hydrogen chloride). The jacket extinguished quickly upon removal from the flame. The thermal shock incurred by the fiber bundle, however, was insufficient to produce fiber breakage or measured increase in transmission loss.

Humidity -- Steady State

This test consisted of a 240-hr test cable soak at 90 to 95 percent relative humidity and 100°F (38°C) chamber temperature, as specified by method 103B of MIL-STD-202D. No change in cable breakage level or cable attenuation was observed either during or following the humidity test.

Humidity — Cyclic

This test, in accordance with Method 106C of MIL-STD-202D, consisted of exposure to 10 cycles of temperature from 10°C to +65°C at humidities from 80 to 98 percent and a 15-minute vibration period per test cycle. The total 10-cycle test period duration was in excess of

240 hrs. The combined environmental exposure imposed by this test produced the greatest cable performance degradation observed for any environmental condition. Terminal faces were generally occluded after about five exposure cycles; fiber breakage level was difficult to assess but believed to be negligible. Cable attenuation increases varied from about 2 to 4 dB, as measured after a 10-cycle exposure period and cleaning of the terminals. The synergistic degrading effect of the combined environment was evident.

Salt Spray (Fog)

The salt-spray test consisted of a 48-hr exposure to an atomized 5 percent salt-water vapor at 35°C, as defined by Method 101C of MIL-STD-202D. Test results indicated that cable effects were confined to the terminal regions. Corrosion of brass and other more chemically reactive metallic terminals formed chemical compounds which migrated across the terminal faces and created adherent films. These films resisted cleansing and produced cable losses on the order of 1 dB after test exposure.

Chemical Tests

Salt Bath

Negligible cable property or performance degradation was noted after the 1-hr, 2-cycle salt solution/water immersion test as specified in Method 104A of MIL-STD-202D.

Oil Bath

Immersion of the cable into mineral oil at 100°C for 5 minutes produced no change in individual fiber continuity level. However, the thermal softening of the PVC jacket and the expansion of trapped air within the jacket interior occasionally ruptured the jacket wall as the air pocket was released. The 5-minute immersion was evidently too short an exposure to provide terminal-face epoxy bonding degradation as noted in the short-duration thermal cycling tests.

Acid Bath

This test, as specified by method 7011 of Federal Test Method Standard 228, provided for immersion of the cable for 46 hrs at 22°C in a 5 percent volume concentrated solution of sulfuric acid in water. Test results again showed that some cable transmission loss resulted at the terminal face. Stainless steel terminals were uncorroded, and no cable loss resulted. Brass terminals exhibited slight corrosion, and aluminum terminals were heavily pitted as a result of chemical action. Cable losses of 0.35 dB and 5.17 dB were measured for brass- and aluminum-terminated cables, respectively.

Alkali Bath

This test specified a 46-hr immersion in a 1 percent normal solution of sodium hydroxide in water at 22°C. Again, as typified by all the chemical tests, the cable losses recorded were related to chemical action between the metallic terminals and the chemical reagent. In this test, however, epoxy modification resulting from chemical action was also observed. Definite terminal face-etch phenomena, such as increased surface roughness, epoxy voids, and pit formation and topographic honeycomb effects were observed. The cable losses recorded were generally more independent of the terminal materials used, with losses ranging from 1 to 1.5 dB after the test exposure.

APPENDIX E:

OPTICAL FIBER CABLE INSTALLATION, MAINTENANCE, AND REPAIR

Fiber-optic cable may be installed in conduit or simply supported by cable hangers, since its tensile strength can be made sufficiently high by adding a load-bearing Kevlar strength member. A plastic jacket provides environmental protection and abrasion resistance. When fiber-optic cable is installed, it must not be bent at a radius less than the minimum specified by the manufacturer, or breakage will occur.

Optical fiber cable breaks can be repaired by butting the two cable ends together and bonding them with epoxy. Splicing kits are commercially available and consist of epoxy, cutting tools, resin, a cable clamp, and instructions. Splicing a fiber-optic cable will introduce a loss of 1 to 5 dB per splice, depending on fiber type.

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