

**FIBER OPTIC COMMUNICATIONS DESIGN FOR
FREEWAY MANAGEMENT CENTERS**

by

Brian P. Cronin

Professional Mentor

Walter H. Kraft, D. Eng. Sc., P.E.
Farradyne Systems Inc.

Prepared for

CVEN 689

Advanced Surface Transportation Systems

Course Instructor

Conrad L. Dudek, Ph.D., P.E.

Department of Civil Engineering
Texas A&M University
College Station, Texas

August 1994

SUMMARY

Mitigating congestion on America's freeways is one of the most important tasks of today's transportation engineers. States are trying to mitigate congestion by using traffic operations centers and incident management teams. Transportation engineers are monitoring traffic on the freeway by using detectors and video surveillance devices. These devices are very effective, but the data obtained are of no use unless the information can be sent miles away to an operations center where the data can be analyzed. One medium used for transmitting data is fiber optic cables. Fiber optic cables have the ability to transmit a large amount of information over one line, quickly and efficiently.

Fiber optic cables are more effective than other communications media. A communications system for freeway management will need to have enough capacity to handle video data, and also be able to transmit these data quickly. Fiber optic cable is currently the most cost-effective communications media that can meet the needs of a freeway management center.

The intent of this research was to study the use of fiber optic cable as a communications media for freeway traffic management centers. In particular, the location of the fiber lines with respect to the roadway, the ownership of the lines, and the installation method of the cable lines were investigated. This information would lead itself to recommendations for the most efficient and effective way to use fiber optics as a communications media for freeway traffic management centers.

Numerous states already have, or are planning a fiber optic communications system. The State of Minnesota has directly buried fiber lines on the limited access right-of-way for a number of years, and have had no problems. The State of Washington has an operational system in the Seattle area that uses fiber lines placed in conduits for protection. The State of Texas has fiber optic systems in both San Antonio and Fort Worth that utilize single mode fiber to handle the required capacity. The State of Missouri plans a privately owned fiber optic system.

Fiber optic communications systems are being used throughout North America, unfortunately every system is setup radically different than every other. Obviously some systems are more efficient than others. Consequently, the author has made recommendations for the most effective fiber optic communications system based on future needs:

1. Determine the main goal of your system and plan around that goal.
2. Utilize SONET OC-12 hubs with self healing loops to provide adequate redundancy and reliability to your system.
3. State owned fiber optic systems are preferred in order to provide more control of system growth.
4. Single mode fiber is the most cost-effective fiber type and should be used for both long haul and short haul links.

5. Fiber should be placed in conduit for ease of maintenance and protection from outside hazards.
6. Fiber lines should be placed in the right-of-way outside the shoulder edge as close to the fence line as possible to provide ease of construction and maintenance, while providing little hazard to the motorist.
7. Maintenance personnel should be trained to handle all maintenance tasks. Maintenance kits should be located throughout the system to facilitate timely repairs.

Fiber optic communications systems take a large commitment by the operating organization. Careful planning must be conducted throughout the project to maintain a reliable and cost-effective system.

The most important goal of this research was to identify the best location for fiber optic lines. As stated in the recommendations, fiber optic cable should be placed as close to the fence line of the public right-of-way as possible. This distance is usually in the range of 10 to 20 feet from the edge of the pavement. Fiber optic lines should be buried 30 inches in order to protect from freezing in colder climates.

TABLE OF CONTENTS

INTRODUCTION	B-1
Objectives	B-1
Scope	B-1
BACKGROUND	B-2
Communications Media	B-2
Fiber Optics	B-2
STUDY DESIGN	B-4
FIBER OPTIC COMMUNICATIONS SYSTEMS	B-6
Major Issues in Fiber Optic Communications Systems	B-6
<i>System Architecture</i>	B-6
<i>Public/Private Ownership</i>	B-9
<i>Fiber Type</i>	B-9
<i>Fiber Placement</i>	B-10
<i>Fiber Maintenance</i>	B-11
Fiber Optic Systems	B-11
<i>Existing Systems</i>	B-11
<i>Planned Systems</i>	B-13
SUMMARY OF FINDINGS	B-17
RECOMMENDATIONS	B-20
ACKNOWLEDGEMENTS	B-23
REFERENCES	B-24

INTRODUCTION

Mitigating congestion on America's freeways is one of the most important tasks of today's transportation engineer. States are trying to mitigate congestion by using traffic operations centers and incident management teams. Transportation engineers are monitoring traffic on the freeway by using detectors and video surveillance devices. These devices are very effective, but the data obtained are of no use unless the information can be sent miles away to an operations center where the data can be analyzed. One medium used for transmitting data is fiber optic cables. Fiber optic cables have the ability to transmit a large amount of information over one line, quickly and efficiently.

The use of fiber optic cable in the field of transportation engineering is relatively new. As a result, there is no set or proven best method for placing and operating fiber optic cable lines. An evaluation of the installation methods, the companies installing the cable, the owners of the cable, the cost of fiber optic cable installation, and the benefits associated with various system setups would be very beneficial.

Objectives

Numerous states are implementing or already have operational fiber optic communications systems. It is the objective of the research to review several fiber optic communications systems in North America and to determine what methods are being implemented and the relative benefits. From this analysis, recommendations will be made as to the best location for fiber optic cable lines for a freeway management communications system. Conclusions will be drawn as to the best procedures for installing a fiber optic cable communications system and what also should be avoided.

Scope

A literature review will be conducted with emphasis on the most recent articles relating to the state-of-the-practice. Only the use of fiber optic cable relating to the needs of the transportation engineer will be analyzed. Due to project time constraints this investigation will be limited to uses with freeway traffic management centers in North America only.

BACKGROUND

The mitigation of congestion on freeways is very important to transportation engineers. Traffic operations centers are being constructed for major freeway systems to monitor the daily traffic. Traffic is currently being monitored by detectors, surveillance cameras, and even motorists using cellular phones. These devices are very effective, but the data obtained are of no use unless the information can be sent miles away to an operations center for analysis. Data are transmitted over various kinds of media. Some of the most prevalent alternatives for traffic control systems are land line communication systems.

Communications Media

Various alternatives exist by which traffic control systems communications data can be transmitted. Both land line cable systems and wireless systems can be used. Land line alternatives include voice grade analog channels, coaxial cable, fiber optics, and leased lines. Some wireless communications alternatives are satellite, cellular radio, pocket radio, spread spectrum radio, terrestrial microwave links, and area radio networks. All alternatives have their advantages and disadvantages, but coaxial cable was the most widely used medium for communications in the past. Fiber optic cable is quickly becoming the most widely used communications medium.

Fiber optic cable has many advantages over other alternatives. One advantage is fiber optic cable lines are relatively immune to electrostatic and electromagnetic interference. Fiber optic cable operates in the light-wave region of the electromagnetic spectrum, and is therefore less susceptible to electrostatic and electromagnetic interference than copper cable, microwave relay, or satellite modes (1). Unlike coaxial cable, fiber optic cable is immune to electrical noise. Fiber optic cable has the lowest cost per unit of bandwidth of any transmission mode for high-volume, point-to-point routes (1). Bandwidth can be defined as the information-carrying capacity of an optical waveguide (2). Video is the driving force for communication capacity of a freeway traffic management communications system. Consequently, a large amount of bandwidth is necessary and is provided by fiber rather than other media like coaxial cable (3). Fiber allows for signals to be transmitted a longer distance without a repeater amplifier, resulting in more reliable operation than coaxial cable. Finally, fiber optic cable is relatively small and light weight making the installation process easier.

Fiber Optics

An optical fiber is a hair-thin strand (1/8 mm outside diameter) of glass, composed primarily of silicon. It consists of a glass core (diameter less than 1/100 mm) through which the light wave travels and a layer of cladding (silica glass with a different refractive index) that contains the light (1). Fiber optic communication uses the principles of refraction and reflection to transmit signals through a fiber (4). Refraction occurs when a light wave changes its direction upon contact with a boundary of two different materials. The critical angle of incidence occurs when a light wave does not enter the second material. Light waves will reflect when the angle of incidence is greater than the critical angle. The cladding provides a boundary that causes the light wave to reflect and propagate through the glass core. Figure 1 illustrates a typical fiber optic cable and the light propagation characteristics within the optical fiber (4).

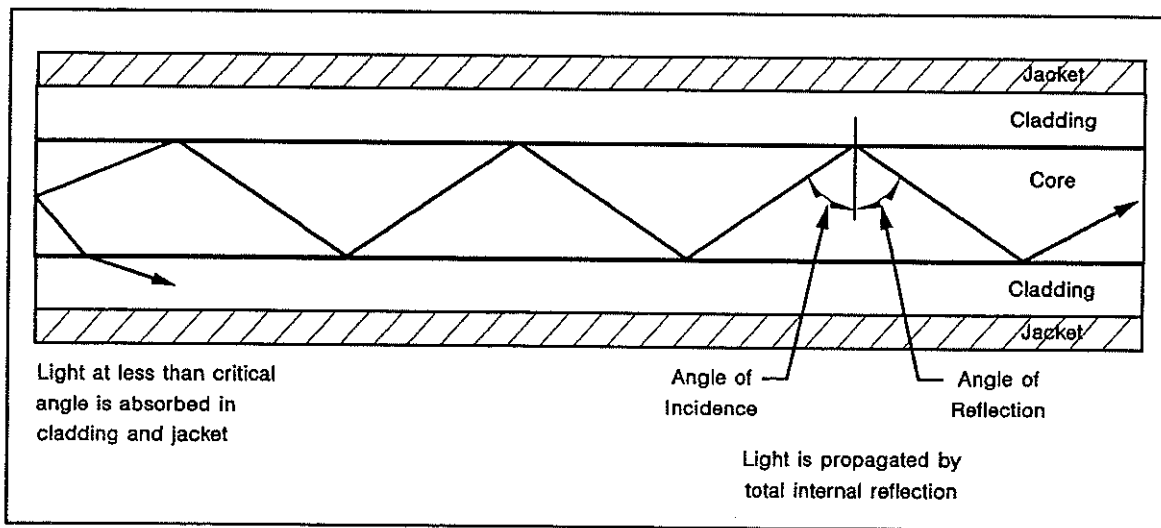


Figure 1. Light Propagation in Optical Fiber (4).

Fiber optic cable can be installed at long lengths without losing the signal. The length of the cable is limited by two parameters: attenuation and dispersion. Attenuation is the loss of light energy resulting from absorption, scattering, and bending. Dispersion, the spreading of light pulses, is based on the number of modes a fiber allows. The path that a light wave can follow while propagating through a fiber is represented by a mode. The larger the diameter of the fiber the more modes that are available. Unfortunately, the more modes a fiber has, the more dispersion occurs, thereby shortening the length a fiber can be and effectively transmit the signal.

Fiber optic cable has many applications in the transportation industry. Common applications of fiber optic communications systems to traffic control systems include

- Backbone and trunking communications systems
- Distribution communications systems
- Communication systems for small closed loop traffic signal systems(4).

Backbone and trunking communications systems are typically used over long distances when high data rate capabilities are needed. Distribution communications systems usually are used for lower data rate requirements. Communications systems for small closed loop traffic signal systems are not used with the freeway, but can be applied to the urban street network depending on the distance between controllers. These systems can support a wide variety of applications including: vehicle detection, traffic signal control, ramp meter control, lane control, changeable message sign control, closed circuit television, voice communications, highway advisory radio, and equipment status monitoring.

STUDY DESIGN

The intent of this research was to study the use of fiber optic cable as a communications media for freeway traffic management centers. In particular, the location of the fiber lines with respect to the roadway, the ownership of the lines, and the installation method of the cable lines were investigated. This information would lead itself to recommendations for the most efficient and cost-effective way to use fiber optics as a communications medium for freeway traffic management centers. The following agencies with existing and planned fiber optic systems were contacted:

Existing Systems

- Minnesota Department of Transportation
- Ontario Ministry of Transport
- Texas Department of Transportation
- Washington Department of Transportation

Planned Systems

- Arizona Department of Transportation
- California Department of Transportation
- Illinois Department of Transportation
- Maryland Department of Transportation
- Michigan Department of Transportation
- Missouri Department of Transportation
- New Jersey Department of Transportation
- Wisconsin Department of Transportation

A telephone survey was conducted with officials from the various states. A questionnaire was then faxed to the agencies for more detailed responses. The questionnaire was designed to provide general information on the use of fiber optic cable as a communications media for freeway traffic management centers, along with detailed information on the location and installation of fiber optic lines. The following questions were asked during the survey:

1. What were the most important issues surrounding the use of a fiber optics system over other communications systems?
2. Did you consider a public/private partnership regarding the ownership of the fiber optics lines?
3. Who funded the system setup and operations?
4. How was your system architecture set up? Is the system part of a backbone network or a distribution network?
5. Where is the fiber optic cable being placed with respect to the roadway?

6. How was your system installed? Did you use conduits? How long were your fiber optics cable runs?
7. Who installed your system?
8. How do you plan to maintain your system, and pay for the maintenance?
9. What was the cost per mile of the fiber optics cable itself, and the entire network including hubs, conduits, and construction costs?
10. Have you performed a benefit-cost analysis, and if so what were the results?
11. Did you use single mode or multimode fiber?
12. What type of splicing technique did you use?
13. How long has your system been in place?
14. What have been the pitfalls in the design, planning, and operation of your program?
15. If you were to install a new communications system would you use fiber optics, and would you do the same as you have done before?

Some of the agencies contacted do not have a fiber optic cable communications system in place and operating. As a result, the answers varied and some of the questions did not apply to some of the agencies. Along with the twelve public transportation agencies a few private industry companies were consulted. AT&T, Kimley-Horn, Farradyne Systems, Dunn Engineering, and Allied Signal were questioned on their role in developing fiber optic communications systems. Also general information about fiber optics and issues surrounding a fiber optic communications system were ascertained. A detailed summary of the key issues involved with a fiber optic communications system follows, along with a summary of the findings from the questionnaire, conclusions, and recommendations.

FIBER OPTIC COMMUNICATIONS SYSTEMS

Fiber optic communications systems for freeway management centers are currently being used in many locations in North America. Fiber optic cable is the communications medium of choice for many systems. Before installing a fiber optic based system, five major issues must be considered: system setup, public/private ownership, fiber type, fiber placement, and fiber optic line maintenance.

Major Issues in Fiber Optic Communications Systems

System Architecture

Freeway traffic management communications systems require various elements that are different from ordinary fiber optic cable installations. For instance, the level of redundancy and accuracy of the equipment is not as important as a telephone or cable television fiber network (3). Important considerations for the evaluation of a fiber optic network configuration are the redundancy in the key equipment and cable segments, expansion requirements, provisions for future technologies (such as ITS), performance, and environmental requirements. Most freeway traffic management communications systems are built as backbone networks with SONET, Synchronous Optical Network, hubs and either spokes or rings to connect outlying areas. SONET, is the international standard for optical cable. The SONET standards define transmission capacity, optical interconnects and internal formatted signals in terms of Optical Carrier type N (OC-n) where N specifies capacity in terms of electrical equivalents (4). Most systems are moving towards OC-12 signals so that the future needs of ITS can be handled. Redundancy is also necessary for the major trunk lines, but not for each traffic monitoring station and is normally provided by rings. Rings are easily created in most areas due to the existing freeway network that is in most cases in the form of rings. Redundancy is provided by rerouting a signal around the ring in the opposite direction. If spokes are used, redundancy can be provided by using two sets of fiber optic cable lines.

A fiber backbone is necessary because of the large quantity of data and video that must be transferred over long distances. A backbone leads itself to upcoming requirements of ITS. The performance of a backbone system is also much better than a smaller, distributive system that does not connect an entire network of freeways. A backbone will also allow for easier rerouting of data due to breaks in the system.

Other network topologies do exist. Figure 2 illustrates the various traffic control system communications network topologies. An unprotected ring could be used, but will have problems if a cable goes down because there is no redundancy and communication will be shut down on part of the system. A linear drop could be used in which nodes are placed in a line and data are dropped at certain nodes. Another popular network topology is the star formation that has a source node at the communication center and secondary nodes in the field that serve as hubs. A typical geometric configuration of a backbone fiber system field node and the field controllers that the node serves can be seen in Figure 3. The node operates as a linear drop from the node to the field controller. The field controller can be connected to the fiber optic backbone by coaxial or copper cable because coaxial or copper cable can serve the data rates necessary over the short length from node controller to junction (4).

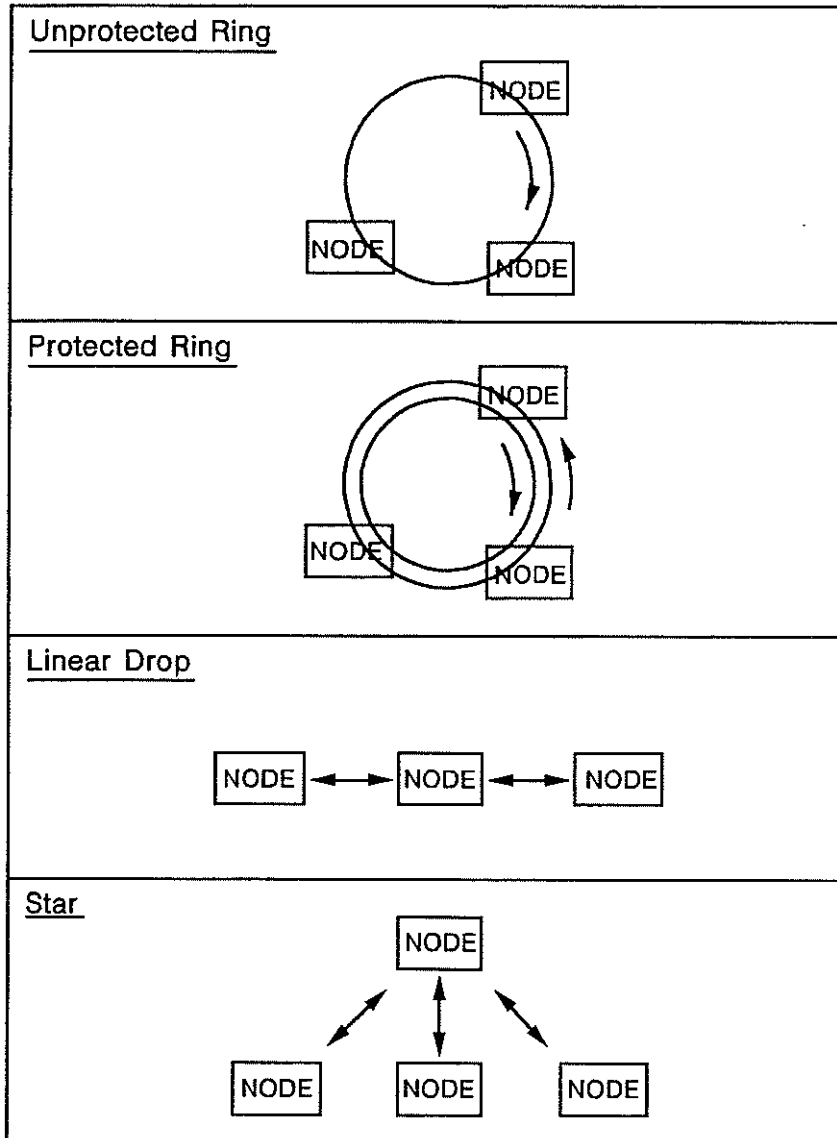


Figure 2. Traffic Control Communications Network Topologies (4).

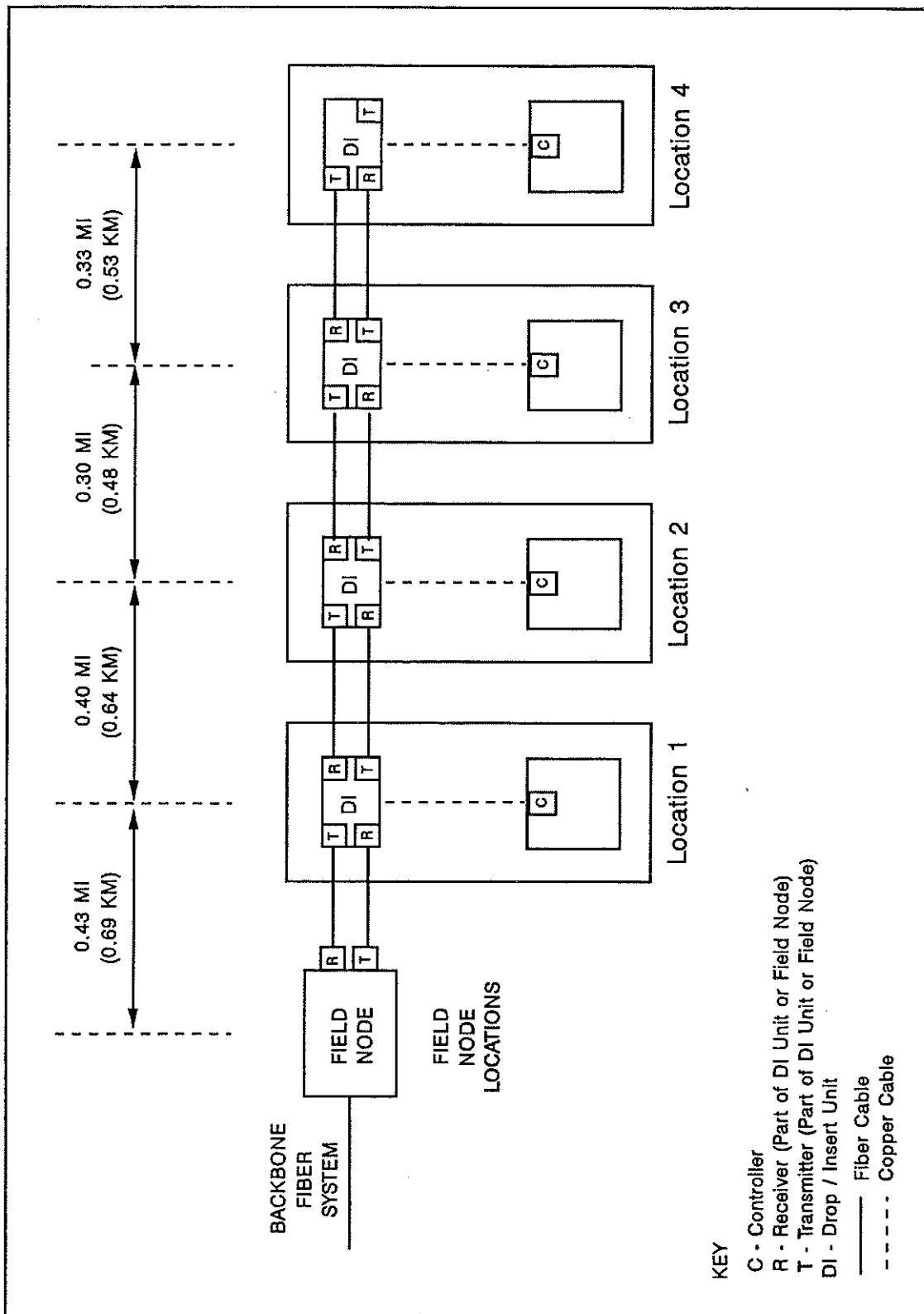


Figure 3. Geometric Configuration of a Node for a Freeway Communications System (4).

Public/Private Ownership

Fiber optic cable lines have been used for several years by telephone companies and other agencies. These companies are always looking for inexpensive locations to place their fiber optic lines. For this reason, the availability of public right-of-way at the edge of the freeway has always been intriguing to fiber optics providers.

In the past, individual states and the Federal Highway Administration have been unwilling to allow utility companies to use the interstate right-of-way (1). FHWA has stated many disadvantages to the use of interstate right-of-way by private industry. First, during installation and maintenance there will be negative affects on traffic flow and safety. FHWA also worries that during installation there could be damage done to the roadway. States could damage the fiber lines during routine maintenance of bridges and other structures. Finally, states worry that future widening of roadways could be limited by the placement of fiber optic lines (1).

On the other hand, utilities providers argue that the interstate is the quickest way between two points, thereby saving them money. States can make revenue by selling parts of the right-of-way to private companies, or by allowing companies to place their cables in the right-of-way states could receive fiber optic cable lines free in return for the right-of-way.

Freeway traffic management centers are using fiber optic cable lines as the medium for communication because of the amount of data that can be sent over one fiber line. If states use privately owned fiber lines, the states will run the risk that they will not be provided with adequate service. The states must prepare for the unknown bandwidth requirements that lay ahead. A plan must be set that will allow states to always have enough fibers so that adequate service can be provided to the motorist.

Public/Private joint ventures lead themselves directly into a trap over liability for faulty equipment. States will claim that the private company must maintain the lines at all times, and that the state will only be at fault when they cut the line during maintenance. Private industry must, however, make sure that the fiber lines are adequately delineated and marked so that highway maintenance personnel do not inadvertently cut a line. A hold-harmless clause in the contract between the state and the private company would solve the problem by holding the private industry at fault for everything except negligent acts by the state (1).

Fiber Type

Depending on the length of fiber necessary various modes of fiber can be used. Single mode fiber can carry a large amount of data over a very long distance. On the other hand, multimode fiber can carry less data and for only a short distance. In the past multimode fiber has been less expensive than single mode fibers. Currently, single mode fiber is cheaper and is the fiber of choice for most freeway management centers. Single mode fiber is strongly recommended for backbone networks (4). Multimode fiber is recommended for short to intermediate lengths where low to medium data rates are necessary. Single mode fiber is recommended for long haul systems with high data rates (5). Single mode fiber does have a problem in that it is hard to connectorize and splice due to the high degree of precision needed to align the small cores (5). As a result, single mode fiber is used mainly for long haul lines.

Recently, single mode fiber has become more cost-effective than multimode fiber for even the short haul sections, and is therefore recommended over multimode fiber for most situations (6).

Fiber Placement

Fiber optic cable lines can be placed in a variety of locations around the freeway. Three main locations are the median, the shoulder, and the fence line at the edge of the right-of-way. Each location has its advantages and disadvantages for placement of fiber optic cable lines. The location concepts within the interstate right-of-way for fiber optic cable lines are illustrated in Figure 4.

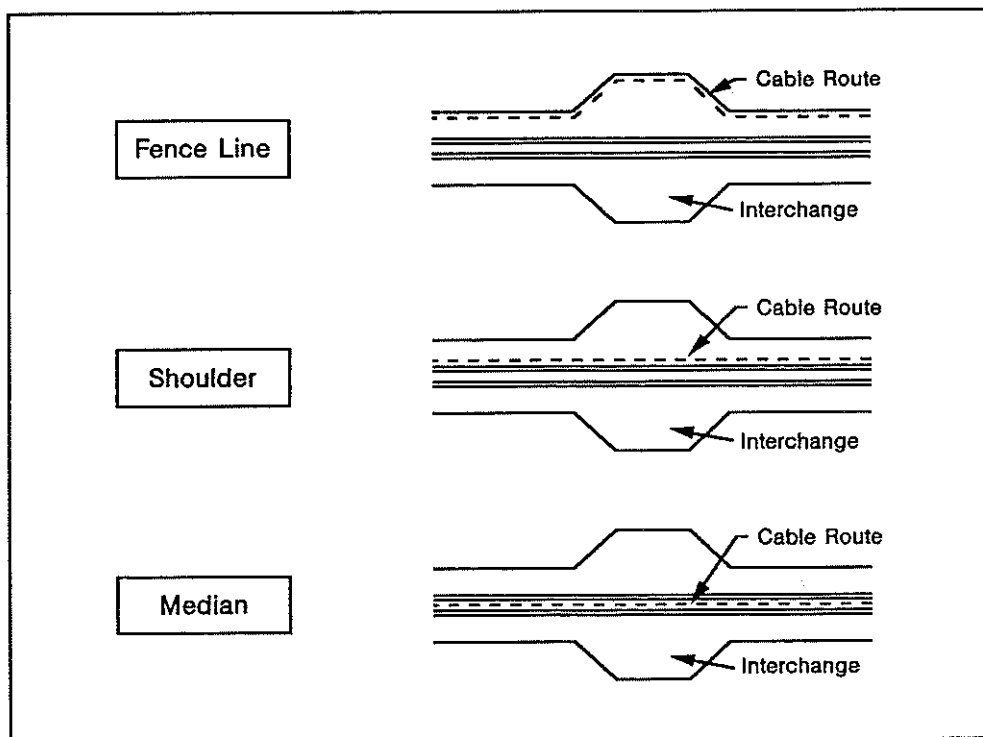


Figure 4. Location Concepts within Interstate Right-of-Way (2).

First, fiber optic cable lines can be placed in the median. The main advantage of this location is ease in which the fiber lines can be joined to the equipment used to monitor and advise motorists. Unfortunately, the median also provides the most dangerous conditions during installation and maintenance procedures (1). Work in the median usually will place maintenance personnel in the highest amount of danger. Drivers are also in danger of hitting maintenance vehicles and objects in the median. Finally, work in the median will usually entail the closure of at least one lane, which will definitely increase vehicle delay and annoy the motorist.

Fiber optic cable lines can also be placed in the shoulder. This location also provides ease of connection between the fiber and the traffic hardware, for at least one side of the roadway. Placing the fiber lines in the shoulder will also help protect the lines from damage during construction or maintenance. The cable will be in a consistent location so that maintenance will always know the location of the lines. A protective covering of concrete will also help maintenance personnel locate the fiber lines. Unfortunately, placing fiber lines in this location results in closure of lanes during installation and maintenance (1). Drivers and workers are also placed in potentially hazardous situations. Fiber lines might also need to be removed if future expansion of the roadway is necessary to create more lanes to meet the demand, resulting in a high cost retrofit or even new placement of the cable. Many freeways can no longer be expanded due to environmental concerns as a result of ISTEA, therefore placement in the shoulder is considered adequate as it would not affect the environment by damaging more land.

The edge of the interstate right-of-way line is the last reasonable location for fiber optic cable lines. This location is generally the cheapest if there is not rugged terrain that must be traversed (1). Drivers and workers are in the least amount of danger during installation and maintenance. Lane closures should also not occur. The major downfall is that the fiber lines are not close to the traffic hardware that is serving the motorist. This will require more cable to be used to connect the fiber trunk lines to the fiber service lines. Thereby increasing the cost of the fiber optic communications system.

As stated earlier, there are three main locations for placing fiber optic lines. For each location consideration must be taken as to placing the fibers into conduits, or to directly bury the fibers. Placing the fiber optic cable into conduits makes repairing fiber lines easier due to the ease of pulling out a faulty line from the conduit versus digging up a whole section of road, or right-of-way. Many fibers will be placed into separate condulets inside the main conduit providing ease of correcting only one faulty fiber, without placing the whole fiber system in that area off line. AT&T recommends that fibers be placed in conduits to protect from animals, ease of installation and maintenance, and protection from earth movement due to construction (7).

Fiber Maintenance

Maintenance of a fiber optic communications system must be planned for from the start of the project. If all goes well, very little maintenance should be needed. The problem is that if a fiber line is cut the system is in jeopardy. Motorists are depending on the system to reduce their delay on the freeway. If motorists see their tax money going into a system that does not work because the state can not maintain the system, the system is doomed.

To provide adequate maintenance of a fiber network a few maintenance kits must be provided throughout the network. These kits must provide all of the necessary equipment to make simple corrections to the system. Workers should be trained so that they can quickly identify the problem and apply the correct maintenance procedure.

Fiber Optic Systems

Fiber optic communications systems exist in at least four locations in North America, and at least eight more are being planned. The following section summarizes the existing and planned

systems, along with the transportation agencies' plans for the future. The system architecture, the type of fiber, and the location of the fiber optic lines used by the transportation agencies in their fiber optic communications system are the focus of the summaries.

Existing Systems

Minnesota Department of Transportation (8). The Minnesota Department of Transportation has been using a fiber optic communications system for approximately two years without any major problems. The system is state-owned and state-operated. A backbone style architecture was used. All data are transferred over single mode fibers, but some multimode fibers are used for short distances. The basic decision to use fiber was based on the capacity necessary to transmit data and video, system cost, and maintenance cost. Fiber optic cable is direct buried in the side slope of the roadway. Conduit was only used when necessary to cross the roadway, or a bridge.

Only a few problems have occurred throughout the two years of operation. Initially, the cost of fiber was quite high, but the price of fiber has steadily decreased as fiber is being used more frequently. Rodents have damaged the fiber optic pigtails, but armoring has since been placed on the cable to protect the fibers and the fiber pigtails from rodents. A fiber optic pigtail is used to separate a single fiber from the trunk line and interface it with field equipment. Finally, during the winter of 1994 a fiber optic pigtail was crushed, and was believed to be the result of freezing water.

Ontario Ministry of Transport (9). Highway 401 in Toronto was the first fully fiber optic communications freeway traffic management system. The system began operating in 1991. A 9.6-mile section of Highway 401 was equipped with single mode and multimode fiber. The system utilized a ring topology to insure redundancy in the system. The ring was completed by installing fiber optic lines on both sides of the freeway and connecting the sides by crossing the freeway mainlines. The fiber optic lines were placed close to the edge of the pavement and buried in conduits. Warning tape is used to alert maintenance crews of the presence of fiber optic cable lines.

The Ontario Ministry of Transport plans to expand the system in the near future. The fiber optic cable lines will be placed as close to the fence line of the right-of-way as possible in order to reduce the chance of a fiber optic cable cut during maintenance procedures. The only problem that the Ontario Ministry of Transport faced was the newness of the technology and hardware. Fiber optic technology and hardware for freeway traffic management systems has become common place and is no longer a problem for the Ontario Ministry of Transport.

Texas Department of Transportation (10, 11). The State of Texas currently has two cities with major fiber optic based communications systems for freeway management: San Antonio and Fort Worth. The San Antonio District of the Texas Department of Transportation has had a fiber backbone network with SONET hubs in place since March 1993. Single mode fibers were placed in conduits covered by concrete in the shoulder of the frontage roads. Manholes are evenly spaced to provide quick access to the fiber lines for maintenance. No major problems have occurred to date with the San Antonio system.

In Fort Worth, a 260 mile fiber optic backbone system is partly in place. A distributed processing architecture is being used that has three levels. Level one is equipment in the field. Level two is satellite computer buildings. Level three is a control center. Level one and two are served by multimode fibers, while level three is served by single mode fibers. Single mode fiber is being used in anticipation of future needs created by ITS. The distributed processing architecture provides an easy way to trouble-shoot maintenance. No major problems have occurred. The Fort Worth District of the Texas Department of Transportation believes that it is necessary to have a communications system capable of handling future unforeseen requirements by ITS. The Fort Worth District system is flexible and lends itself well to the implementation of ITS, since additional single mode fiber optic cable is already included in all main trunk lines.

Washington Department of Transportation (6). The Washington Department of Transportation has been using a fiber optic backbone communications system in the Seattle area since 1989. The backbone system now covers approximately 100 miles with SONET hubs every 10 to 14 miles. The SONET carrier is OC-12 with self healing and correcting rings in the system. The fiber lines are placed in the median or shoulder 24 to 36 inches deep using 4-inch conduits and 4 - 1-inch condulets inside. Currently, only two condulets are being used, and two are left for further expansion. Single and multimode fibers are used, but all new fiber will be single mode, because single mode fiber is now more cost-effective than multimode fiber.

Seattle has not experienced any major problems with the system. Keeping up with new technology, and planning for unknown bandwidth requirements have caused a few headaches. The only real problem is maintaining adequate spare parts and tools to perform maintenance tasks.

Planned Systems

Arizona Department of Transportation (12). The Arizona Department of Transportation will have a partially operational fiber backbone system in place in August 1995 in the Phoenix area. The Arizona Department of Transportation believed the number one requirement for a fiber optic communications system is redundancy. The Arizona Department of Transportation felt that the system should be operational 99.99% of the time. As a result, the 29-mile fiber optic communications system will have fiber lines on both sides of the freeway, so that at least one line would be operational at all times. For instance, if a fiber line is cut, the transmission will automatically be sent in the opposite direction.

The Phoenix system will have nodes every 5 miles that will be connected by single mode fiber. The nodes are attached to the field controllers by twisted pair wires for standard monitoring equipment. Multimode fiber will be used to connect the full motion video equipment to the nodes.

As stated earlier, fiber optic lines will be placed on both sides of the freeway. Fibers will be placed in conduits ten feet beyond the edge of the shoulder. The conduits will be concrete encased. By placing the conduits a uniform distance from the shoulder, and by encasing the conduits in concrete, it was believed that adequate protection against maintenance personnel accidentally cutting a line would be provided. Finally, extra conduits will be provided for expansion purposes.

California Department of Transportation (13). The California Department of Transportation is developing a fiber optic backbone system with SONET OC-12 rings and spokes for the Los Angeles area. This provides optimal coverage and redundancy. Private industry was considered, but not used due to maintenance considerations. Single mode and multimode fibers are being used. Most of the fiber lines are placed in the shoulder 4 feet from the edge of the travel lanes 9 inches deep with a concrete cover. Some of the fiber lines are placed 30 inches below the surface with warning tape for protection. Warning tape is placed along the conduit at certain intervals to warn maintenance crews about the presence of fiber optic cable lines.

The major problems that have occurred were during the trenching procedure in the shoulder. Trenches were required to be 6 inches wide, large enough to fit 4-inch conduits, that are actually 4 1/4 inches wide outside diameter and 1 inch of concrete. The trenching companies did not understand that the blade had a tendency to wear down and cut only 5-inch trenches. The companies proceeded to force conduits into the holes that were not large enough by stepping on the conduits. This produced conduits that were not stable, straight, or adequately protected. Consequently, the California Department of Transportation has required that trenches be constructed with an 8 inch trenching machine. The California Department of Transportation has also noted that single mode fiber is becoming more cost-effective and reliable.

Illinois Department of Transportation (14). The Illinois Department of Transportation has been placing duct work throughout the Chicago area since 1978. In the past traditional twisted pair wires and coaxial cable were used as the media for communications. With the addition of television cameras to the freeway traffic management program, additional bandwidth was required to handle the data requirements. As a result, the Illinois Department of Transportation is planning to use fiber optic cable trunk lines instead of coaxial cable trunk lines. The fiber system is planned for operation in the near future.

The Chicago area is unique with respect to the amount of protection provided for the fiber lines. The fiber lines will be placed in 4 inch conduits located in the foundation of the concrete median barriers. In Chicago, whenever a new sign post or guardrail was installed it was almost certain that a communications line would be cut. Protecting the fiber lines was one of the most important issues to the Illinois Department of Transportation. Placing the fiber lines in the foundation of the concrete median barriers provides more than adequate protection. Even when a median barrier is hit by a vehicle the fiber cables are not destroyed. To facilitate maintenance of faulty lines, junction boxes were placed every 1500 feet allowing for easy removal of fiber

lines. To date no junction box has been damaged by collision with an errant vehicle.

The Illinois Department of Transportation is also considering a public/private partnership. Most private companies have not been very interested in using the duct work that Illinois has provided. The private companies have used the railroad right-of-way successfully, and have not required the level of protection that the Illinois Department of Transportation is requiring. Other state agencies have been interested in sharing fiber optic lines. The transit authority might consider using subway tunnels to run fiber optic lines.

Maryland Department of Transportation (15). Maryland does not have the funds to place and/or maintain a fiber optic communications system. Maryland does however realize the need for a fiber based system as a result of new ITS technologies. As a result, the state plans a fully integrated backbone network using SONET hubs. Maryland can not afford to build their own fiber optic communications system. A public/private partnership is required in order to obtain a system. Maryland plans for single mode fiber to be directly buried in the ground off the edge of the pavement or in the median. Railroad right-of-way is also being considered, but is doubtful due to the high cost of obtaining the right-of-way, and the railroad companies' requirements for maintenance and surveillance of any system on their right-of-way. The Maryland Department of Transportation identified no major problems.

Michigan Department of Transportation (16). The State of Michigan Department of Transportation also does not have an operational fiber optic system in place. A public/private partnership is being considered. Michigan will require a backbone network of either fiber or other communications media. Michigan is currently looking at wireless possibilities for their communications system.

Missouri Department of Transportation (17). The State of Missouri plans a public/private owned backbone fiber optics communications system to be in place by 1995 in the St. Louis area. They believe that the interstate right-of-way leads itself to easy construction for a private fiber optics carrier. Single mode fiber lines will be direct buried into the earth 15 to 25 feet from the edge of the pavement. The Missouri Department of Transportation will receive a certain amount of fibers in return for the use of part of the interstate right-of-way. Maintenance will be provided by the private companies unless the State commits a negligent act.

The biggest problem that has occurred to date has been communicating with other state agencies. The fiber lines will eventually cover a large area in and around St. Louis. As a result, many state agencies are involved, but do not understand the need for fiber optics, and the advantages of using a private company to provide the cable.

New Jersey Department of Transportation (18). The I-80 Magic program in upstate New Jersey is being constructed by the State as a backbone system with SONET OC-12 self-healing loops. The system will be constructed of single mode fibers. The fiber lines will be buried 30 inches under the shoulder with a concrete cover for protection. Maintenance has been contracted out to private companies.

New Jersey has had two major problems in this project. First, a public/private partnership was considered, but the private company withdrew their services without warning the State. The second problem has been with the placement of the fiber optic lines. The shoulder has been the location of choice for a long time, but the depth at which the lines are to be placed has changed numerous times, delaying the start of construction. The depth has changed for both environmental and construction reasons.

Wisconsin Department of Transportation (19). The Wisconsin Department of Transportation is planning a 32-mile network of State owned fiber optic lines. The system will be a backbone system with SONET hubs utilizing single mode fibers. The Wisconsin Department of Transportation believes that maintenance costs will be too high if the fiber lines are placed in the shoulder. They plan to place the fiber lines 6 to 8 feet from the shoulder and approximately 30 inches deep. The fiber optic lines will be placed in conduits. Maintenance costs have been budgeted by the State.

As a result of the system not being constructed, no major problems have been identified. The only problems so far have resulted from lack of funding and construction costs and procedures. A public/private partnership is still being considered. The Wisconsin Department of Transportation is still evaluating other communications medium options including: spread spectrum radio, leased phone lines, leased fiber optic lines, and possibly microwave radio, but they are leaning towards State-owned fiber optic lines because of the reliability, versatility, bandwidth, and future expansion needs.

SUMMARY OF FINDINGS

For a freeway management center, fiber optic cable is definitely a viable communications option. Fiber optic cable has been used successfully in four locations (Minnesota, Ontario, Texas, and Washington), and is planned to be used in others (Arizona, California, Illinois, Maryland, Michigan, Missouri, New Jersey, and Wisconsin). Fiber optic cable is currently the most cost-effective medium for the volume of data and video that must be transmitted (6). Planning for the future is a definite goal of most states. Therefore, most states are providing extra fibers and using single mode fiber since more data can be sent over single mode fibers than multimode fibers.

Most states choose to own the fiber optic cable lines themselves. Although, a public/private partnership is intriguing to some states and cost-effective, states are considering the future and also possible liability concerns and have decided that owning the lines would be more realistic. States can put in extra lines, or the hardware that will support the addition of extra lines, while private companies most likely will not be willing to put in lines that may not be used. The states that are currently planning public/private partnerships are doing so because they cannot afford to install their own fiber optic cables.

The location of fiber optic lines varies for each location, Table 1. Transportation agencies are using the median, the shoulder, and the right-of-way beyond the edge of the pavement. Transportation agencies that plan to bury the fiber in the shoulder tend to have the most problems with construction of a fiber optic system. The systems have not been in place long enough to determine the extent of maintenance costs due to extracting a cable from the shoulder. Transportation agencies that are directly burying the cable plan to use warning tape to warn maintenance crews of the presence of fiber lines. This is a good idea, but the effectiveness is questioned. If a cable is damaged or faulty it will be difficult to repair the line. On the other hand if conduits are used, damaged or faulty, fibers can be pulled out of the conduit easily, and quickly replaced or repaired.

None of the states contacted have performed a benefit/cost analysis for the location of fiber optic lines. Placement decisions were based on protection, maintenance, and access. Some states performed benefit/cost analysis on fiber optics versus other communications media. Although none of the agencies contacted were able to provide accurate numbers, fiber has been proven to be the most cost-effective medium for the current communications requirements by the agencies contacted. Finally, the Washington Department of Transportation has determined that single mode fibers are now more cost-effective than multimode fibers.

Table 1. Summary of Location of Fiber Optic Lines.

Agency	Cable Location	Placement
Existing Systems		
Minnesota DOT	Off Edge of Pavement	Direct Buried
Ontario Ministry of Transport	Off Edge of Pavement (Both Sides)	Conduit
Texas DOT - San Antonio	Frontage Road	Conduits
Texas DOT - Fort Worth	(Not Available)	(Not Available)
Washington DOT	Median / Off Edge of Pavement	Conduits
Planned Systems		
Arizona DOT	Off Edge of Pavement	Conduits
California DOT	Shoulder	Conduits
Illinois DOT	Foundation of Concrete Median Barriers	Conduits
Maryland DOT	Off Edge of Pavement	(Not Available)
Michigan DOT	Off Edge of Pavement	(Not Available)
Missouri DOT	Off Edge of Pavement	Direct Buried
New Jersey DOT	Shoulder	Conduits
Wisconsin DOT	Off Edge of Pavement	Direct Buried

In summary, a fiber optic communications system has three main costs: SONET hubs, fiber optic cable, and conduit, if used. SONET hubs are very expensive and cost approximately \$50,000 to \$160,000 per hub. This value increases or decreases depending on whether the hub is above or below ground, and the amount of electronics in the hub. Single mode fiber optic cable now costs approximately \$2.00 per foot. Conduit costs approximately \$30 per foot installed. All costs were provided by the Washington Department of Transportation. The Washington Department of Transportation is planning a 280-mile system with 26 hubs. The cost of this project will be at least \$51.2 million (6). This is a very high price tag, and as a result many states are seeking public/private partnerships, and alternative system architectures. The Minnesota Department of Transportation quotes fiber cable costs for their system to be approximately \$4.00 per foot (8). The average cost per mile of their entire fiber optic system was \$55,000. California is planning a 7-mile section of their fiber optic communications system that will cost \$1.365 million (13). The system will use 24 single mode fibers per cable at a cost of \$1.71 per foot of cable in 1994 dollars (13). According to the FHWA Communications Handbook for Traffic Control Systems multimode 24 fiber cable costs \$2.65 per foot in 1992 dollars (4). When the 1992 dollar cost is translated to 1994 dollar costs including inflation single mode fiber can be found to be more cost-effective than multimode fiber.

RECOMMENDATIONS

Communications has found a stronghold in the transportation engineering field with the introduction of ITS. Freeway traffic management centers are being constructed throughout the United States and beyond. The heartbeat of any freeway traffic management center will be the communications system. Without a good communications system, a freeway traffic management center will be useless. Due to the need for high speed and high volume data transmission fiber optic cable is the medium of choice for these communications systems. Although other communications systems exist, fiber optic cable is the most cost-effective according to the transportation agencies interviewed.

Fiber optic cable communications systems are either operational or in the planning stage in at least twelve cities in North America. Fiber technology is relatively new to the transportation engineer leaving many questions to be answered about the appropriate use of fiber along the freeway. Of the twelve cities using fiber optic communications systems none of the systems are identical. Consequently, some of the systems operate far superior to other systems. As stated earlier, five major issues must be considered when installing a fiber optic communications system: system architecture, system ownership, fiber type, fiber placement, and fiber maintenance. After an extensive survey of the twelve fiber optic communications systems and a literature review, the following recommendations, developed by the author, for the best solutions to these issues are made.

Recommendation 1: Goal setting is essential.

All fiber optic communications systems will have different priorities. Systems can be oriented to be redundant, 100% reliable, low cost, or easily maintained. Meeting each goal requires a different kind of system. The author believes the most important requirement in any system is appropriately planning to meet current and future needs. As a result, goals must be set. Fiber should not be wasted, but it is cheaper to install a system that will meet future needs at the start than to retrofit an earlier design. The following recommendations take into account each one of the four goals previously listed and collectively provides a preferred option for a fiber optic communications system.

Recommendation 2: Utilize SONET OC-12 hubs with self healing loops.

System architecture must be one of the first issues tackled when developing a fiber system. After reviewing previously installed systems, the author believes that a fiber backbone with SONET OC-12 hubs and self healing loops would be the best architecture. Providing for future growth, flexibility, reliability, and redundancy is necessary when developing a fiber system. The SONET OC-12 hubs will be able to handle most any data volume requirement. The self healing loops will provide the necessary redundancy, allowing one cable break not to place the whole system in jeopardy.

Recommendation 3: State ownership of the fiber optic system is essential.

A public/private partnership should always be considered when developing a fiber optic communications system. A State that cannot afford to place and maintain their own fiber lines might be able to find a private fiber supplier that would be willing to place and maintain the fiber in return for the interstate right-of-way. CMAQ funds could also be used to pay for a fiber optic communications system. The State of New Jersey is using CMAQ funds to pay for the fiber optic communications system in their I-80 Magic Program. States must plan for the future. The state should determine their data volume needs and make sure that enough fibers are provided. Although public/private partnerships are good for States with inadequate funding, it is recommended that a state own their system. The author believes that State control of fiber optic lines will be beneficial. The State will be able to maintain the system without hassling with the private company over liability for the problem. States will also be able add fibers to the system whenever they want. If a private company owns the fiber lines they might not be willing to add fibers to the system without further compensation from the State. Finally, in a study conducted by the Washington Department of Transportation a State-owned system was cheaper in the long run than a privately-owned system (6). The capacity required by the Washington Department of Transportation will be 75 percent of a private companies' 1996 capacity (6).

Recommendation 4: Utilize single mode fiber.

When deciding on what type of fiber to use there are two choices: single mode fiber and multimode fiber. Freeway traffic management centers will require high data volume and high data rates for their communications system. The author believes the necessary fiber type is single mode since it is the most cost-effective and can handle the data requirements. Single mode fiber should be used for both short haul and long haul lines due to the capacity provided.

Recommendation 5: Fiber should be placed in conduits.

One of the major problems of having utility lines near the interstate is the frequency with which the lines are cut by maintenance. Fibers need to be placed in a protective casing in order to protect not only from maintenance personnel, but also from animals and other things that might cause a line to be cut. As a result, the author believes that fibers should be placed in conduits. Preferably a large conduit should hold numerous condulets of which at least one condulet should be left empty for future use. Conduits will provide minimal protection for fibers, but they will allow easy maintenance. Faulty fibers can easily be pulled out of a conduit for repair, where direct buried cables would have to be dug out of the ground before repairing. The author recommends that fiber lines should be protected by warning tape, and a gravel cover in order to provide a warning to maintenance personnel of the location of fiber lines. The author believes that concrete encasement of the conduit is not necessary, and could be detrimental. As concrete ages, concrete tends to expand and could break the conduit. Concrete does provide added protection against water seeping into the conduit. When water freezes in the conduit fiber optic cables will fracture because glass shatters when freezing. The important issue is to provide adequate drainage below the conduits. The author believes that a gravel cover would work well as long as a good drainage system is in place.

Recommendation 6: Fiber lines should be buried in the right-of-way as close to the fence line as possible.

Fiber lines can be placed in three major locations: the shoulder, the median, or on the right-of-way. The median provides the best location for access reasons, but will be a nightmare for construction and maintenance. Lanes will have to be closed in order to perform any maintenance. Maintenance personnel and motorists will be placed into hazardous conditions. The shoulder provides a little less danger to maintenance personnel and motorists, but the danger is still present. Both the California Department of Transportation and the New Jersey Department of Transportation are placing fiber lines in the shoulder and have had problems with the planning and construction of fiber lines in the shoulder. Although the fiber lines would be protected by a concrete cover, maintenance costs would be very high if a conduit or fiber line were found to be faulty. The author suggests the best location for a fiber optic line is in the right-of-way as close to the fence line as possible. This location will provide the easiest and least hazardous construction and maintenance. Trenches will have to be cut in dirt rather than concrete or asphalt shoulders allowing for lower construction costs. The Minnesota Department of Transportation has had fiber lines in the right-of-way for numerous years without any problems. The author suggests fiber lines be buried at least 30 inches below the surface and protected by a gravel cover and warning tape. A depth of 30 inches is necessary to prevent the fibers from freezing in cold weather. A depth greater than 30 inches is not recommended due to added construction costs.

Two considerations need to be evaluated on a location by location basis before placing the fiber optic lines directly adjacent to the fence line. First, areas with rugged terrain near the fence line should place fiber lines closer to the shoulder, but not in the shoulder. Freeways that will have sound walls placed in the future should also move the fiber lines in from the fence line. For both cases an attempt should be made to place the fiber lines a consistent distance from the roadway as possible. Consistency in placement will help maintenance personnel locate the fiber lines before any construction or maintenance is performed on the freeway right-of-way.

Bridge crossings add an extra dimension to the decision of placing fiber optic lines. Fiber lines can be placed in the bridge deck, below the bridge deck, or buried in the ground below the roadway or waterway being crossed. The author believes that fiber optic cable lines should cross just under the bridge deck. The fiber lines should be encased in conduit to protect from the environment.

Recommendation 7: Adequate maintenance must be provided.

Maintenance is a necessary part of any project. Maintenance needs to be budgeted for from the beginning. An operational fiber optic communications system that cannot be maintained is of no use, and soon will go belly up. The easiest way to maintain a fiber optic system is to train personnel how to fix a broken fiber. The next step is to maintain adequate spare parts and tools to fix a cut fiber. The best method is to have maintenance kits located throughout the network area that can be easily obtained and used to correct minor problems in the fiber optic communications system.

In conclusion, a fiber optic communications system is necessary for any freeway management system. The quality, capacity, and reliability that fiber provides places fiber above any other communications media. It should be noted that proper planning will provide for a fully operational fiber optic communications system that will meet the present and future requirements of ITS.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Walter H. Kraft for serving as mentor during the summer. The author greatly appreciates his guidance and support.

The author would also like to thank Dr. Conrad Dudek for establishing such a great program at Texas A&M University. The author wishes to thank Dr. Dudek for his guidance and support throughout the project.

The author wishes to thank Mr. Walter Dunn, Jr., Mr. Leslie Jacobson, Mr. Dave Roper, Mr. Gary Trietsch, and Mr. Thomas Werner for their guidance and support demonstrated throughout the Advanced Surface Transportation Systems Summer program.

Finally, the author wishes to thank the professionals that were surveyed during the project. The patience and time that they were willing to provide the author was definitely appreciated.

AT&T : Mr. Matt Liotine

California DOT: Ms. Teri Parola and Mr. Greg Damico

Illinois DOT: Mr. Joe McDermott

Kimley-Horn and Associates: Mr. Henry Wall

Maryland DOT: Mr. Charles Goepel

Michigan DOT: Dr. Robert Maki

Minnesota DOT: Mr. Glen Carlson

Missouri DOT: Mr. Dale Ricks

New Jersey DOT: Mr. Jack Hayes

Ontario Ministry of Transport: Phil Masters

Texas DOT: Mr. Pat McGowen and Mr. Reuben Bazan

Washington DOT: Mr. Les Jacobson and Mr. Michael Forbis

Wisconsin DOT: Mr. Ron Sonntag and Mr. Don Schell

REFERENCES

1. R.W. Hess, B.M. Mitchell. *Feasibility of Using Interstate Highway Right-of-Way to Obtain a More Survivable Fiber-Optics Network*. RAND Corporation, Santa Monica, CA, January, 1988.
2. *Feasibility of Allowing Fiber Optic Cable Along the Interstate System*. Joint Hearing before the Subcommittee on Economic Development and the Subcommittee on Surface Transportation of the Committee on Public Works and Transportation House of Representatives, Ninety-ninth Congress Second Session, U.S. Government Printing Office, Washington, 1987.
3. D.B. Tritter. "Fiber Optic Communication Systems for Freeway Traffic Management." Applications of Advanced Technologies in Transportation Engineering, ASCE, August, 1991, pp. 278-282.
4. R.L. Gordon, R.A. Reiss, W.M. Dunn, D.R. Morehead. *Communications Handbook for Traffic Control Systems*. FHWA-SA-93-052, Federal Highway Administration, Washington D.C., April 1993.
5. N.L. Christian, L.K. Passauer. *Fiber Optic Component Design, Fabrication, Testing, Operation, Reliability and Maintainability*. Noyes Data Corporation, Park Ridge, New Jersey, 1989.
6. Telephone interview with Mr. Les Jacobson and Mr. Michael Forbis of the Washington Department of Transportation, concerning Fiber Optic Cable use in Seattle, Washington.
7. Telephone interview with Mr. Matt Liotine of AT&T, concerning Fiber Optics.
8. Telephone interview with Mr. Glen Carlson of the Minnesota Department of Transportation, concerning Fiber Optic Cable use in Minnesota.
9. Telephone interview with Mr. Phil Master of the Ontario Ministry of Transport, concerning Fiber Optic Cable use in Ontario.
10. Telephone interview with Mr. Reuben Bazan of the Texas Transportation Department, concerning Fiber Optic Cable use in San Antonio, Texas.
11. Abed A. Abukar. *TMS to IVHS*. Texas Department of Transportation, Fort Worth District, Feb. 1994.
12. Telephone interview with Mr. Henry Wall of Kimley-Horn and Associates (Phoenix Office), concerning Fiber Optic Cable use in Phoenix, Arizona.

13. Telephone interview with Ms. Teri Parola and Mr. Greg Damico of the California Department of Transportation, concerning Fiber Optic Cable use in Los Angeles, California.
14. Telephone interview with Mr. Joe McDermott of the Illinois Department of Transportation, concerning the Fiber Optic Cable use in Chicago, Illinois.
15. Telephone interview with Mr. Charles Goepel of the Maryland Department of Transportation, concerning Fiber Optic Cable use in Maryland.
16. Telephone interview with Dr. Robert Macki of the Michigan Department of Transportation, concerning Fiber Optic Cable use in Michigan.
17. Telephone interview with Mr. Dale Ricks of the Missouri Department of Transportation, concerning Fiber Optic Cable use in Missouri.
18. Telephone interview with Mr. Jack Hayes of the New Jersey Department of Transportation, concerning Fiber Optic Cable use for the I-80 Magic project in New Jersey.
19. Telephone interview with Mr. Ron Sonntag of the Wisconsin Department of Transportation, concerning Fiber Optic Cable use in Wisconsin.
20. Edwards and Kelcey, Inc. *Route 80 - MAGIC Surveillance and Guidance System Plans*. Prepared for New Jersey Department of Transportation, June, 1993.

Brian P. Cronin received his B.S. degree in Civil Engineering in May 1993 from Virginia Polytechnic Institute & State University (Virginia Tech) and is currently pursuing his M.S. from Texas A&M University in Civil Engineering. During the summer of 1992 Mr. Cronin participated in the Undergraduate Transportation Engineering Fellows Program at Texas A&M University. Brian is currently employed with the Texas Transportation Institute as a Graduate Research Assistant. University activities he has been involved in include: Institute of Transportation Engineers, American Society of Civil Engineers, Chi-Epsilon, and the Virginia Tech Men's Varsity Swim Team and Waterpolo Club. Mr. Cronin's areas of interest are in traffic detection, congestion management, signal timing, and other traffic operations issues.

