MODULE 9. COMMUNICATIONS

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Figure 9-1. Fiber Optic Cable Installation in Fort Worth, TX.

9.1 INTRODUCTION

The communications subsystem is one of the most critical and expensive elements of a freeway management system. The function of the communications system is to link the devices in the field with the operating personnel in the control center. It is the backbone of the entire freeway management system because it allows the following types of information to be transferred from the field components and the control center: (1)

- Commands to the various field components.
- Data from the system detectors and sensors.
- Status checks of field equipment to detect malfunctions.

Typically, the communications system accounts for approximately 25 percent of the total capital costs associated with a freeway management system. Failure to plan, design, and properly maintain the communications system guarantees the entire freeway management system will have problems in achieving its operational goals and objectives. Poor planning and installation of the communication system can also result in high operating and maintenance costs. To avoid problems with the communications system, system planners, designers, and operators must be familiar with existing and emerging communication technologies and system architectures.

Three general types of communications systems are used in a freeway management system:

- A communications system allowing the transfer of surveillance data and control commands between field devices and the control center.
- A communications system allowing the computers within the control center to transfer data and displays between each other.
- A communications system allowing the operators in the control center to exchange data and information with other operators and field personnel outside the control center.

This module focuses on the first type of communications system (i.e., the communications system needed to transfer surveillance information and data, and control commands between the field devices and the control center). For information on the other types of communications systems, the reader is referred to Module 10.

MODULE OBJECTIVES

The objectives of this module are as follows:

- To outline the process that can be followed in planning and designing a new freeway management system or updating or modifying an existing freeway management system.
- To highlight the different types of communication technologies that are commonly used in a freeway management system.
- To provide insight into the issues associated with planning, designing, constructing, operating, and maintaining a communications system in a freeway management system.

MODULE SCOPE

The focus of this module is on the decision process for planning, designing, and selecting a communications system for a freeway management system. It is intended to help system designers and traffic engineers make informed decisions about communications systems. It is not intended to provide detailed information about the operation of different communications systems or technologies. For more detailed information about the different communications technologies, the reader should consult the *Communications Handbook for Traffic Control Devices* and the *Traffic Control Systems Handbook*.[1,2]

9.2 DECISION PROCESS

As with the planning and design of the other functional elements of a freeway management system, a systems engineering approach can also be applied to the planning, design, and use of a communications system for a freeway management system. An overview of the systems engineering approach is presented in **Module 2**. The information in this section highlights some important issues that need to be discussed, evaluated, and decided upon as part of the systems engineering process. The user is encouraged to consult other reference materials, such as the *Communications Handbook for Traffic Control Systems* for a detailed discussion of the technical aspects associated with planning and designing a communications system for traffic control applications. [(1)]

PROBLEM IDENTIFICATION

The first step in planning and designing a communications system for a freeway management system is to identify the physical, institutional, and other factors that might affect the design of the communications system. System designers and planners need to collect information on the following attributes and characteristics about each of the other elements and subsystems that will be supported by the communications system. The types of information that should be gathered include the following:

- The type of data that will be transmitted by each field device.
- The content and format of the data transmitted.
- How much processing of data will occur in the field devices and where this processing will occur.
- The total number of field devices and where they will be situated.
- The type and presence of existing communications technologies near the freeway management system.
- The relative importance of the information and how a loss of communication from each device would affect the overall operation of the system.

Table 9-1 summarizes some physical, institutional, and other issues that might affect the planning and design of the communications system for a freeway management system.

One question that must be addressed in planning and designing a communications system is the type of data that will be transmitted over the communications medium: voice, data, video, or a combination of all three. A communications medium is the pathway over which a signal is transmitted (i.e., twisted wire pair, coaxial cable, fiber, radio, etc.). "Voice" is the chosen term for audio signals, since the impetus for modern communications systems was the need to transmit vocal messages over the telephone. While some freeway management applications, such as Highway Advisory Radio, still depend on voice communications, data is the most general type of information transmitted in a communications system in a freeway management system. Digital data is the most common form of transmitted information in today's communications systems. With digital data, information is represented by a combination of bits, where a bit can assume one of only two states: "0" or "1." Digital data can be physically transmitted as voltage differences between pairs of wires, light intensities in an optical fiber, frequencies in a transmission line, or phases of a radio wave. Video is animated imagery and represents the most demanding form of data transmission.

The requirements for sending video signals differ significantly from data communications requirements. Systems with

Table 9-1. Resources and Constraints Considerations in Communication Systems. [3]

PHYSICAL FACTORS
- Number and location of field cabinets to be served, and location of control center
- Location and type of existing communication facilities
  - Cable
  - Conduit
  - Pole lines
- Nature of terrain to be trenched and backfilled (conduit installation)
  - Roadway
  - Sidewalk
  - Structure
  - Railroad
  - Soil
- Nature of terrain to be spanned (aerial installation)
  - Waterway
  - Railroad
  - Elevated roadways
- Location of utility equipment and underground structures that may interfere with installation
- Air-path propagation characteristics
  - Trees
  - Hills
  - Buildings
- Climactic conditions affecting communications
  - Temperature extremes
  - Moisture
  - Lightning
  - Ice storms
- Planned or current construction activities
  - New conduit installed
  - Existing conduit removed/relocated

INSTITUTIONAL ISSUES
- Rights-of-way
- Franchise agreements between utility companies and government
  - Right of the agency to use utility conduits and pole lines
  - Responsibility of clearing ducts and utility adjustments
- Franchise agreements with CATV for government use
- Telephone company tariffs and policies
- Other agreements (formal and informal)
- National and local codes (National Electrical Code)
- Federal Communications Commission (FCC) rules and regulations
- Restrictions on work procedures and traffic maintenance
- Rules regarding different types of conduit, overhead cabling, conduit installation, junction boxes, antenna structures, etc.

OTHER
- Personnel and skill levels for communications maintenance
- Other maintenance resources (budget, contract, etc.)
- Vandalism threat
- Presence of contractors in area with skill/experience in installation of communication networks

video components generally require a greater bandwidth, and if transmitted digitally, higher signal rates. Bandwidth is the range of signal frequencies that a communications medium (or channel) will carry without excessive loss of signal strength. The bandwidth requirements for video communications vary depending on the type of transmission mode. Generally, three modes are available for transmitting video images back to a control center:

- Full motion analog video.
- Freeze frame/slow scan.
- Compressed video.

Each of these techniques for transmitting videos images to a control center is discussed in more detail in the **Techniques and Technologies** section below.

Another critical piece of information that needs to be determined before a communications system can be designed is the type of data that will be transmitted. Examples of the type of data carried by the communications system for freeway management purposes include the following:

- Volume, speed, and occupancy from field detectors.
- Alphanumeric messages for DMS displays.
- Codes to select/implement stored messages or control strategies.
- Device status and malfunction reports.
- Weather/environmental sensor data.
- Video control.

Another issue that affects the design of the communications system is how much processing of the data will occur in the field. Generally, those systems where most of the processing occurs at a central location have greater communications needs than those in which the processing of the data is distributed between the field devices and the control center. Generally, those systems where most of the data processing occurs at a central location require shorter polling cycles (the time required to communicate with all the field devices on a communications line once). Those systems that distribute the data processing generally have long polling cycles and more robust field storage capabilities. The advantages and disadvantages of having longer polling cycles are listed in table 9-2.

The total number of field devices, and their location also influences the overall design of the communications system. Generally, the more devices that need to transfer data and information within a freeway management system, the greater the communications requirements. Also, the type of communications architecture can change dramatically if the devices are dispersed over a wide geographic region. For example, using a wireless communications architecture may be more economical where few field devices are widely dispersed throughout an area. If, on the other hand, all the devices are found in close proximity, a wire-type of architecture may be more suitable.

Another important factor and/or constraint that may influence the architecture design and medium selection is the presence of existing communications systems. Often, in-place, usable cable, conduit, and field equipment can be used in a new design. Since the conduit/cable is often the major cost in a system, a plan to use existing equipment can become the least expensive communications alternative.

Table 9-2. Advantages and Disadvantages of Longer Polling Periods. [1]

Advantages	Disadvantages
• Usually results in lower data rate requirement for each field unit to perform the same functions. • Enables more field units to be serviced by a communication channel of given bandwidth or data rate. • Enables higher resolution surveillance data to be communicated. • Avoids use of data overflow schemes.	• Requires more extensive processing of data for the field devices. • Requires large field data base. • Delays transmission of data.

The relative importance of the information (and the impact the loss of the information has on the operation of the system) can have a significant impact on the type of transmission medium and architecture used in a system. Through policy, some jurisdictions may place certain constraints on the types of communications media or architectures possible. Examples of these constraints include the following: [1]

- Rejection of radio-based technologies.
- Preference for owned communications media over leased media.
- Avoidance of communication designs containing points of single failure that disrupt communication to many devices.

Maintenance of the system is also an important issue that needs to be considered in the initial planning and design of a communications system. The increasing sophistication of many newer communications media may require a level of maintenance experience and capability beyond what many local agencies may be willing to supply. Maintenance issues that need to be considered during the initial planning and design phases include the following:

- Who will maintain the communications (i.e., in-house forces, contract forces, or a combination of both)?
- How will maintenance of the communications system be funded?
- Can a simpler technology that can be maintained using in-house forces be used and still provide the same functionality as a more sophisticated technology?
- What kind of leased-line service can be used to reduce the need for in-house maintenance forces?

IDENTIFICATION OF PARTNERS AND CONSENSUS BUILDING

A final issue is what other organizations/ agencies will want, or if they would be willing to share resources in constructing and maintaining a communications system. Traditionally, transportation agencies have wanted to own and operate their own communications systems for traffic management purposes; however, the cost of installing and maintaining these systems can be substantial. As a result, many agencies are looking for methods to share the cost of installing, operating, and maintaining their communications systems. Some agencies are discovering that leasing their communication needs is the most cost-effective method. System planners and designers should attempt to identify other organizations and agencies that also need to install communications systems as potential cost sharing partners. However, along with sharing resources among agencies and organizations comes the need for building coalitions and consensus on the design of the system. Potential agencies and organizations that should be considered in the initial planning and design of a communications system include the following: (3)

- Other TMCs in the area.
- Media.
- Emergency service providers.
- Private communications providers.

The maintenance responsibilities of these agencies should also be defined during the initial planning and design of the system.

ESTABLISH SYSTEM GOALS AND OBJECTIVES

The next step is to establish goals and objectives for the system. The goals and objectives of a communications system are influenced by the goals and objectives of the other functions and systems included in the freeway management system. For example, an objective of an incident management subsystem might be to detect all incidents within two minutes of their occurrence. The goal of the communications system should be to make sure the control center has all the data it needs to detect incidents on the freeway two minutes after they occur. In this example, a communications media and architecture that results in a five-minute polling cycle of all the field detectors does not allow the incident management system to achieve its stated objective.

Agencies should develop both technical and nontechnical goals and objectives for evaluating the performance of communication alternatives. Technical goals and objectives relate to criteria that establish the effectiveness and efficiency of the communications system. Examples of nontechnical goals and objectives include the following: (3)

- The ability to provide and/or the potential for providing intra- and inter-agency data sharing.
- The potential for expanding the communication system to permit future growth and adding functions to the freeway management system.
- How much redundancy or reliability is built into the system.
- The life-span of the system (i.e., whether the system is permanent or temporary), and the potential for installing the system in phases.

ESTABLISH PERFORMANCE CRITERIA

Establishing performance criteria and measures of effectiveness is extremely important in the initial planning stages of a communications system. The criteria can be used not only to evaluate different design alternatives, but also to measure the reliability and expandability of the system. Agencies need to decide up front what represents a “good” level of operation for the communications system.

Most agencies use system reliability as the primary measure of performance for their communications system. System reliability is measured in two ways:

- Transmission errors.
- System uptime.

Transmission errors are primarily caused by noise in the communications system. Noise is any unwanted signal or disturbance of a signal that interferes with or distorts the original communication signal. Noise causes the receiver to produce incorrect outputs and errors in the bit stream that transmits the information. Noise can be caused by many factors including the following: (1)

- Temperature extremes.
- Natural radio or other electronic signals (such as lightning or cosmic/solar bursts).
- Human-made electrical signals (such as motors, car ignitions, power lines, etc.).
- Signals from another communication channel (i.e., crosstalk).

Transmission errors are measured in Bit Error Rate (BER). BER is the ratio of incorrectly transmitted bits to correctly transmitted bits. Values of about 10^{-6} or better for end-to-end communications represent an acceptable BER for most computer and traffic control communications systems. (1)

Most systems have processes to detect errors in communication signals. Table 9-3 describes the error detection techniques commonly used in traffic control systems. When an error in a message is detected, most systems either ignore the message until the next polling cycle, or request that the device retransmit the message. In either case, transmission errors reduce the effective throughput of the communications channel.

System uptime is also another common measure of performance of a communications system. System uptime represents the portion of the normal operating time of the system during which a link or the entire communications system is functioning properly. System uptime can be used to identify problem locations that might need special communication considerations (e.g., a link susceptible to outages due to construction activities or environmental conditions).

It should be noted that bandwidth is NOT a measure of system performance. Bandwidth is the range of signal frequencies that a medium or channel will respond to, or carry without excessive attenuation. (1) It is a measure of the characteristics of a system and does not tell anything about the performance of the system.

FUNCTIONAL REQUIREMENTS

The purpose of a communications system is to transfer information and data from one freeway management function to another with no loss in accuracy. Therefore, the functional requirements of the communications system need to describe how it can help the other elements of the system achieve their goals and objectives. For example, a functional requirement of a communications system might be to ensure that the volume, occupancy, and speed data are transported to the incident detection algorithm every 20 seconds. Likewise, if an objective of an incident management system is to ensure that appropriate aid is dispatched to an incident scene in response to any detected incident, a functional requirement of the communications system might be to have video images transmitted

Table 9-3. Commonly Used Error Detection Techniques. (1)

Techniques	Description
Parity (also known as vertical parity)	An additional bit is added to each data byte or character. The sum of the 1s in the byte and the additional bit must be an odd or even number as specified. This technique detects an odd number of bit errors in the byte.
Longitudinal Redundancy Check	An additional byte is provided after an entire message or portion of a message (block). A bit in the new byte is computed from the corresponding bit in each data byte in a way similar to the parity check. An odd number of bit errors is again detected. When used in conjunction with parity this is a powerful technique.
Checksum	An additional byte or character is added at the end of the message or block. An algorithm is used which computes the checksum byte as a function of the message bytes. The receiving station performs a similar computation and determines whether the checksum byte is consistent with the received data.
Cyclic Redundancy Code (CRC)	An additional two or more bytes are added to the message or block. Algorithms are used to compute these bytes which provide protection, particularly against bursts of errors.
Repeat Transmission	The entire message is repeated. At the receiving station the messages are compared and an error is detected if they are not identical.

directly to emergency service providers and police dispatchers.

The communications functional requirements need to be developed for every element in the system. The information that should be specified in the functional requirements for a communications system includes the following:

- The type of data required by each element in the system (i.e., voice, data, video, or a combination of all three of these).
- The need for one-way versus two-way communication between the element and the control center.
- The type of messages being transmitted (i.e., traffic flow data, text messages, video images, device commands, etc.).
- The frequency at which information is being transmitted or required (i.e., continuously, once every second, once every 20 seconds, once every minute, etc.).
- The desired level of control (e.g., monitoring traffic conditions vs. full operational control through field devices).
- The importance of the information (i.e., critical, important, non-critical).

DEFINE FUNCTIONAL RELATIONSHIPS, DATA REQUIREMENTS, AND INFORMATION FLOWS

Once the functional requirements of the communications system have been identified, the functional relationships, data requirements, and information flows also need to be identified. Generally, these relationships and requirements can be grouped in two categories: logical and physical.

Logical

The logical relationships and requirements of a communications system defines what information flows from one element to the next in the system. Generally, they can be represented by a series of data flow diagrams and process specifications that illustrate what type of information is used by each element in the freeway management system. Identifying the logical requirements and relationships requires that all the functional requirements of the system be broken down into smaller and smaller subfunctions until each process in the system can be specified. Process specifications describe the following in detail:

- The type of information needed to execute a process.
- How the information is processed or manipulated.
- What information or action is produced by the process.

The data flows is constructed by combining the data flows of the various elements (e.g., the incident management subsystem, the ramp control subsystem, the information dissemination subsystem, etc.) that are being installed in the freeway management system. The data and information flowing out of the elements are what needs to be transported by the communications system. Figure 9-2 illustrates, at a high level, a logical architecture for a typical freeway management system.

Once the logical relationships have been mapped out, the transmission mode (i.e., the direction of flow over a communications channel) can readily be determined. The following are the transmission modes commonly used in communications systems:

- Simplex.
- Half Duplex.
- Full Duplex.

Table 9-4 summarizes the characteristics and applications of each of these transmission modes. Most systems use either a half duplex or a full duplex transmission mode so that the status of the field devices can be checked and transmission errors corrected.

Physical

Once the logical relationships of the communications system has been identified, the physical design can be established. The physical design highlights how information flows from one element of the system to the next. It forms the basis for selecting the transmission media used to connect the different elements in the system. Factors affecting the selection of the physical architecture include the following:

- The number and location of the field devices.
- Distance between field devices and control center.

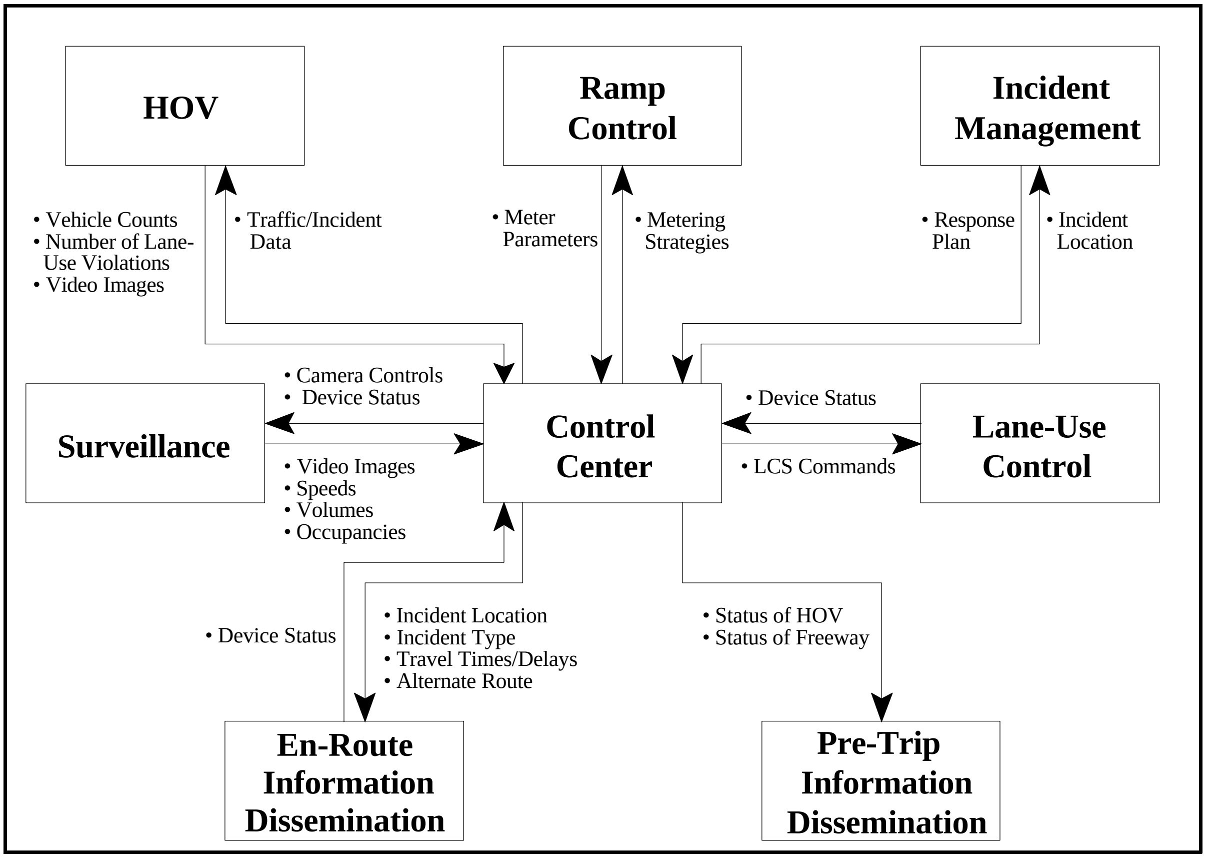

Figure 9-2. High Level Logical Architecture for a Communications System.

- Type and frequency of data being transmitted.
- Availability of right-of-way for placing communication media.
- Proximity of existing communications systems, including private communications systems.
- Presence of geologic or manufactured features that might prevent wireline connections.

The type and importance of the data have an impact on the design of the system and the type of error correction technique used. For example, with a centralized system using once-per-second communications, a single undetected error in detector data represents only one second's worth of sampling time. To discard this information would not be critical, since new information will be provided during the next polling cycle. If, on the other hand, the error occurred in a command to operate a dynamic message sign or other traffic control device, it might cause an unsafe condition on the freeway, or reduce credibility of the system. A distributed system having longer periods between updates (typically one minute for detector data, and possibly hours for controller information) requires more elaborate error correction techniques to avoid losing information caused by communication errors.

The physical architecture of most communications systems used in traffic management applications fall into the following five major categories: (1)

Table 9-4. Characteristics of Transmission Modes. (1)

Mode	Data Flow Direction	Characteristics	Comments
Simplex	Data flow in one direction only.	• Does not provide verification that data were received and acted upon. • Does not provide answer-back, status reporting, or validity checking.	• Commercial radio and television are examples. • Traffic control systems which provide no return information to a master controller or traffic operations center use this mode.
Half Duplex (HDX)	Data flow in either direction, but only in one direction at a time.	• Requires modem at each end of the line. • Requires control capability to assure proper operation. • Uses latency time or turnaround time (the time period required to turn the line around) for the process in which the direction of data transmission is reversed, which can be time consuming.	• In a copper wire transmission medium, HDX requires two wires but may be used with four wires (four wires provide improved interference characteristics).
Full Duplex (FDX)	Data flow possible in both directions at the same time.	• Acts like two simplex channels in opposite directions. • Permits independent, two-way, simultaneous data transmission • May raise cost of channel. • Reduces the one-way capacity if frequency multiplexing is used on a single channel.	• In a copper wire transmission system, some FDX modems require four wires while others require only two wires. In the latter case, the modem divides the channel into two subchannels to achieve simultaneous bidirectional service.

- Central.
- Distributed.
- Trunked.
- Backbone.
- Multimedia.

Characteristics of these communications architectures are summarized in table 9-5.

Central

A *Central* communications architecture is one that possesses only one level of communication before the signal reaches the field controller. In other words, all of the field devices link directly to the control center. Because data flows directly from the field devices to the control center, it is not processed along the way. As a result, only one data rate exists between the field controller and the control center. Because the field devices and the control center are linked directly, central communications architectures require only one

Table 9-5. Common Applications of Communications Architectures. [1]

Traffic System Communications Architecture	Common Application	Examples
Central	Communication requirements limited to a small number of field controller and video channels at each field location.	• Traffic signal systems controlled by computer at traffic operations center. • Small or medium sized freeway surveillance systems with limited video.
Distributed	Traffic control system computations performed at locations other than traffic operations center and field controllers.	• Closed loop traffic signal control systems.
Trunking	Achieves economies by concentrating data onto high speed channels for long runs to traffic operations center.	• Large freeway surveillance systems with long runs to traffic operation center.
Multimedia Channel	Geometrics and/or economics render single medium impractical.	• Signal systems and freeway surveillance systems with no right-of-way connection to traffic operations center requiring leased media to access control center. • Change from land line to wireless medium to cross a physical obstacle.
Backbone and Distribution System	Very heavy communication requirements (usually including video) that make the use of high speed channels economical for the longer transmission links.	• Large area-wide freeway surveillance systems and corridors.

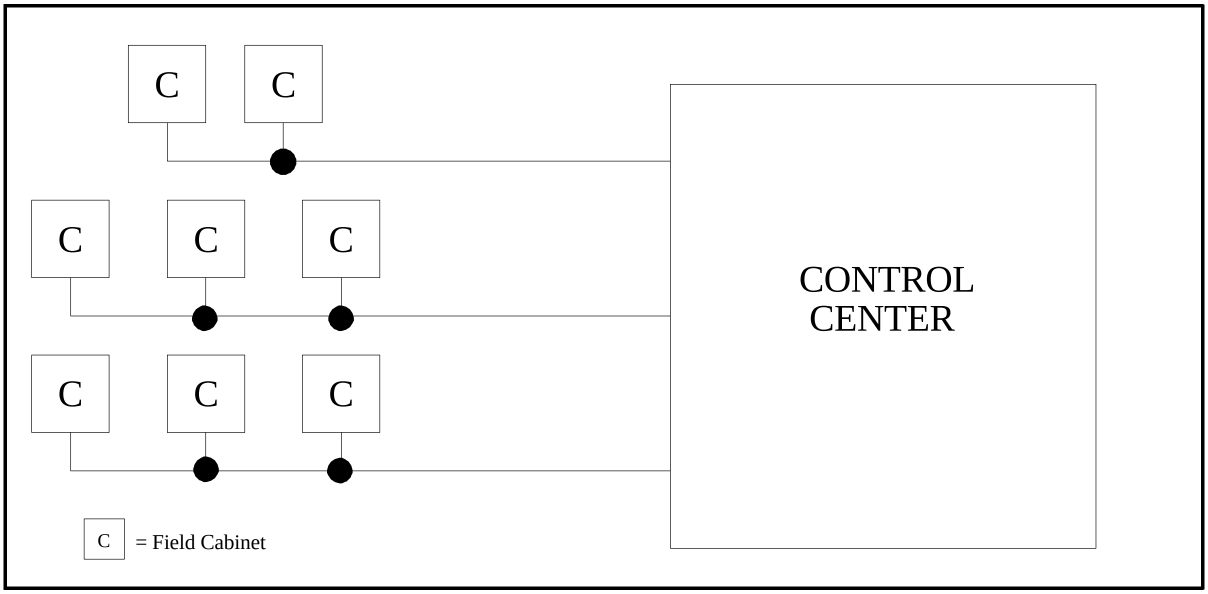

Figure 9-3. Illustration of a Central Communications Architecture. [1]

communication protocol. The primary advantage of this type of communications architecture is that a direct link is provided between each individual field device and the control center; therefore, if a link fails, communications are cut only to that one device. Figure 9-3 illustrates the concept of a central communications architecture.

Distributed

A *Distributed* architecture is generally used as follows:

- Where multiple levels of computations occur between the field devices and the control center.
- Where changes in the data rate occur between the field devices and the control center.

This type of architecture commonly uses field master controllers to collect data from many of the local control units, processes the data, and then transmits the processed information back to the control center (see figure 9-4).

Trunking

A special type of distributed architecture is a *Trunking* architecture. A communications system is trunked if the following holds true: [1]

- The communications system collects information from, and distributes it to several field controllers.
- At some field location, the data rate or bandwidth of the communication channel increases to require fewer channels for communicating with the control center.

Figure 9-5 shows an example of a trunked type of communications architecture.

Backbone

Another form of distributed communications architecture using multiple data rates is a *Backbone* type of architecture. This type of architecture is characterized by a high data rate backbone connected to a series of field communications hubs or nodes. Equipment at each hub transforms these high data rate

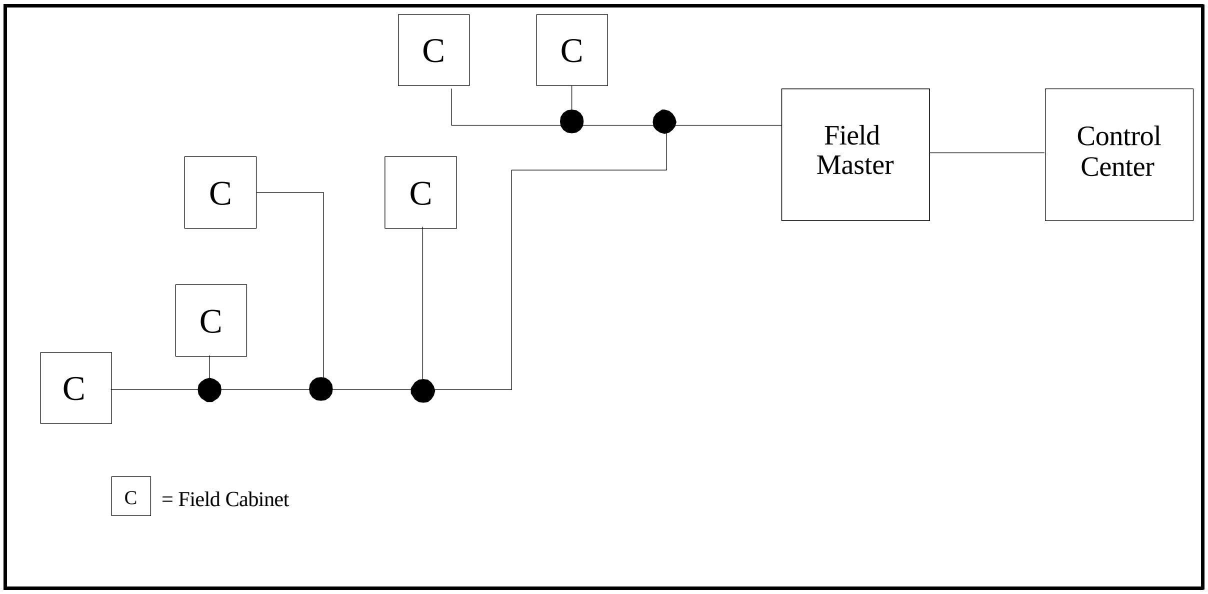

Figure 9-4. Illustration of a Distributed Communications Architecture. (1)

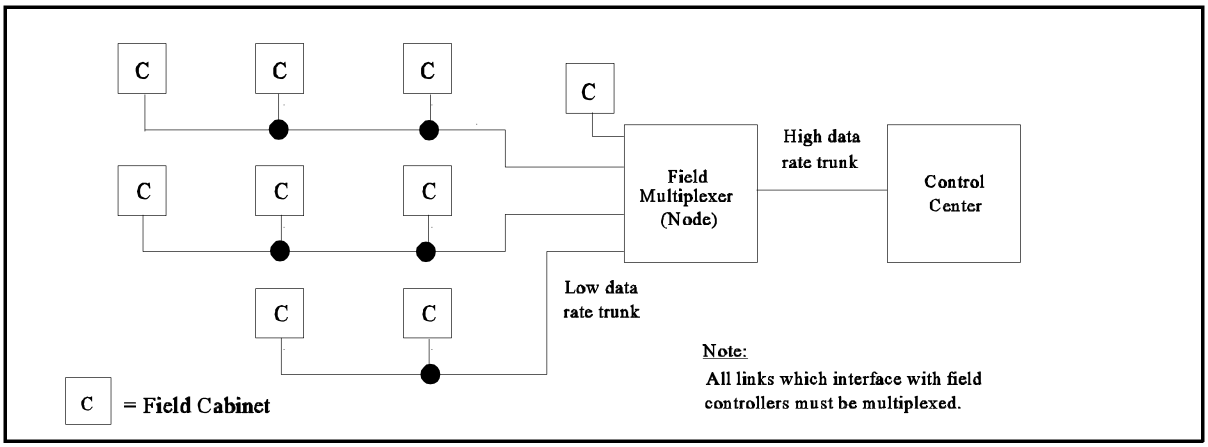

Figure 9-5. Illustration of a Trunked Communications Architecture (1)

channels into many separate low data rate distribution channels. Figure 9-6 shows an illustration of a backbone type of architecture.

Although it can be used with other high bandwidth communication media, the backbone type of architecture is commonly used with fiber optic networks. The four common types of topologies (i.e., network configurations) used with backbone architectures for fiber optic systems include the following:

- Unprotected Ring — Each node (i.e., a communications hub or field device) is connected to two others by unidirectional transmission links, creating a “closed” loop.

- Protected Ring — Two rings are used instead of one, thereby providing two unidirectional transmission paths that may run in opposition directions. Redundant opposite direction paths allow each node to communicate with every other node, even if the communication media is cut.

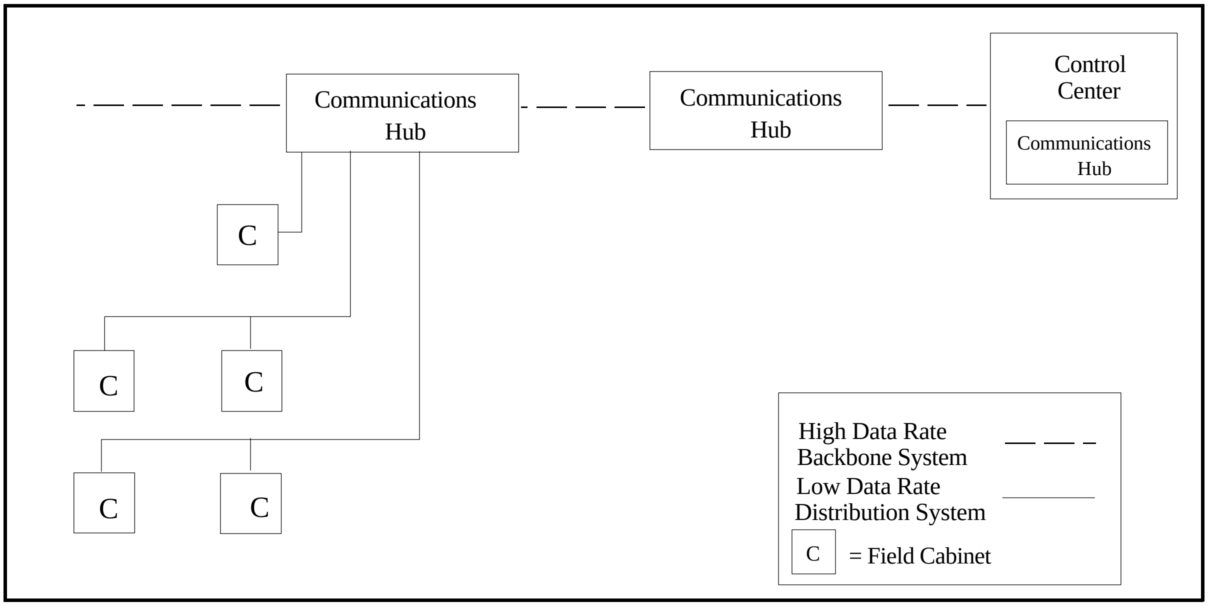

Figure 9-6. Illustration of a Backbone Communications Architecture. [1]

- Linear Drop — Nodes are connected in a string or chain, with transmission data being "dropped" at a designated node.

- Star — Communication links emanate from a source node (e.g., traffic control center) to multiple secondary nodes (e.g., a communication hub or field device).

Figure 9-7 illustrates each of these backbone architecture topologies.

Multimedia

Although not a communications architecture per se, planners and designers need to be aware of the impact changing communication media has on the architectural design of the communications system. A *multimedia* communication channel occurs where more than one medium is used to transmit data and commands to and from the control center and the field devices without altering the data rate and transmission protocol. This type of communication channel is generally used to breach natural or manufactured impediments (i.e., mountains, valleys, etc.) to provide wireline type of communication. Figure 9-8 illustrates the general concept of a multimedia communication link.

IDENTIFY AND SCREEN TECHNOLOGIES

After the functional requirements and system architecture have been established for a communications system, the next step is to identify and screen alternative communications technologies. The *Communications Handbook for Traffic Control Systems* describes a process for identifying, screening, and selecting the communications technologies in a freeway management system.[1] The steps in this process include the following:

- Identify generic or typical links consistently used through the communications architecture. Figure 9-9 illustrates some generic links that occur

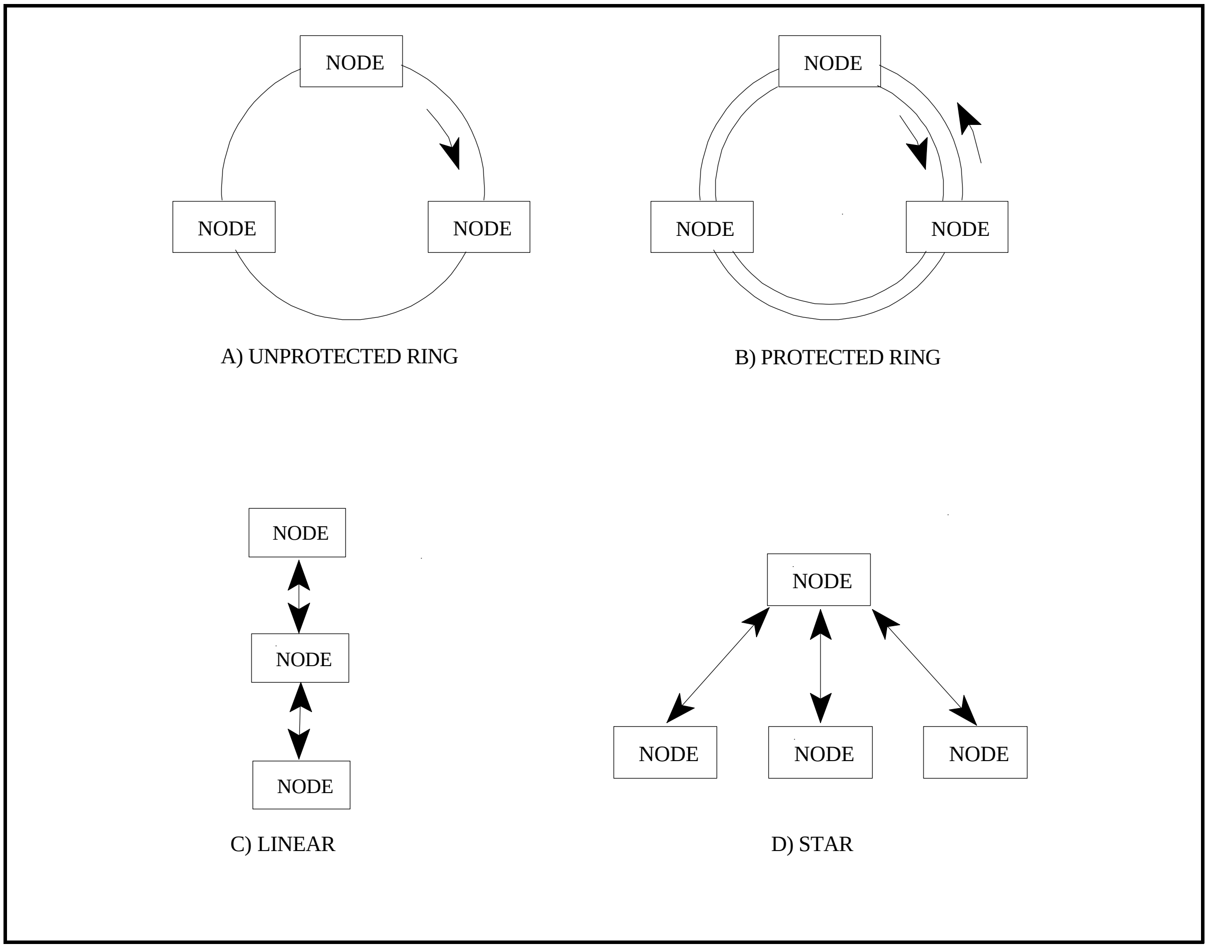

Figure 9-7. Traffic Control Communications Network Topologies. (1)

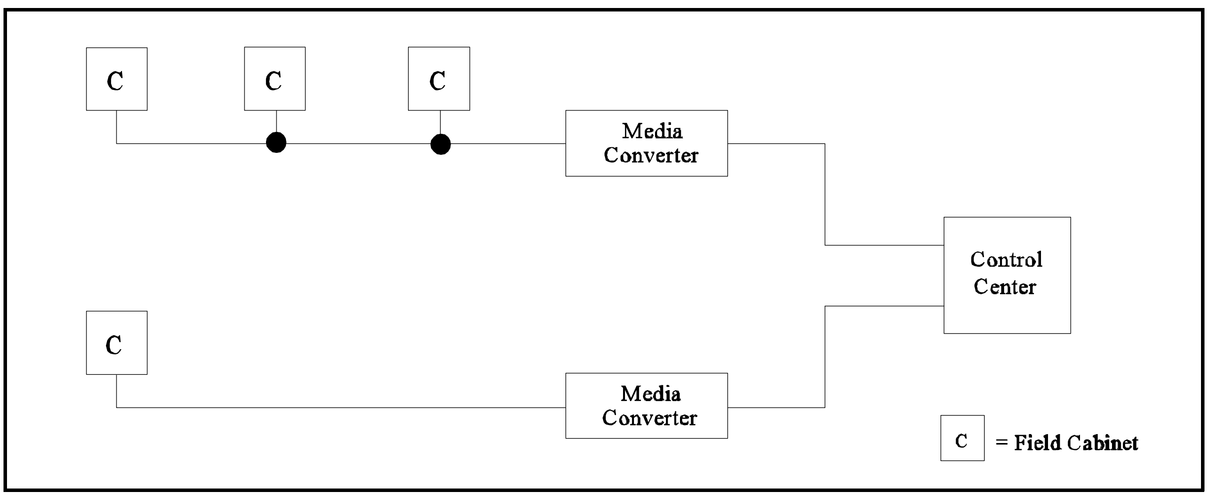

Figure 9-8. Illustration of a Multimedia Communications Channel. (1)

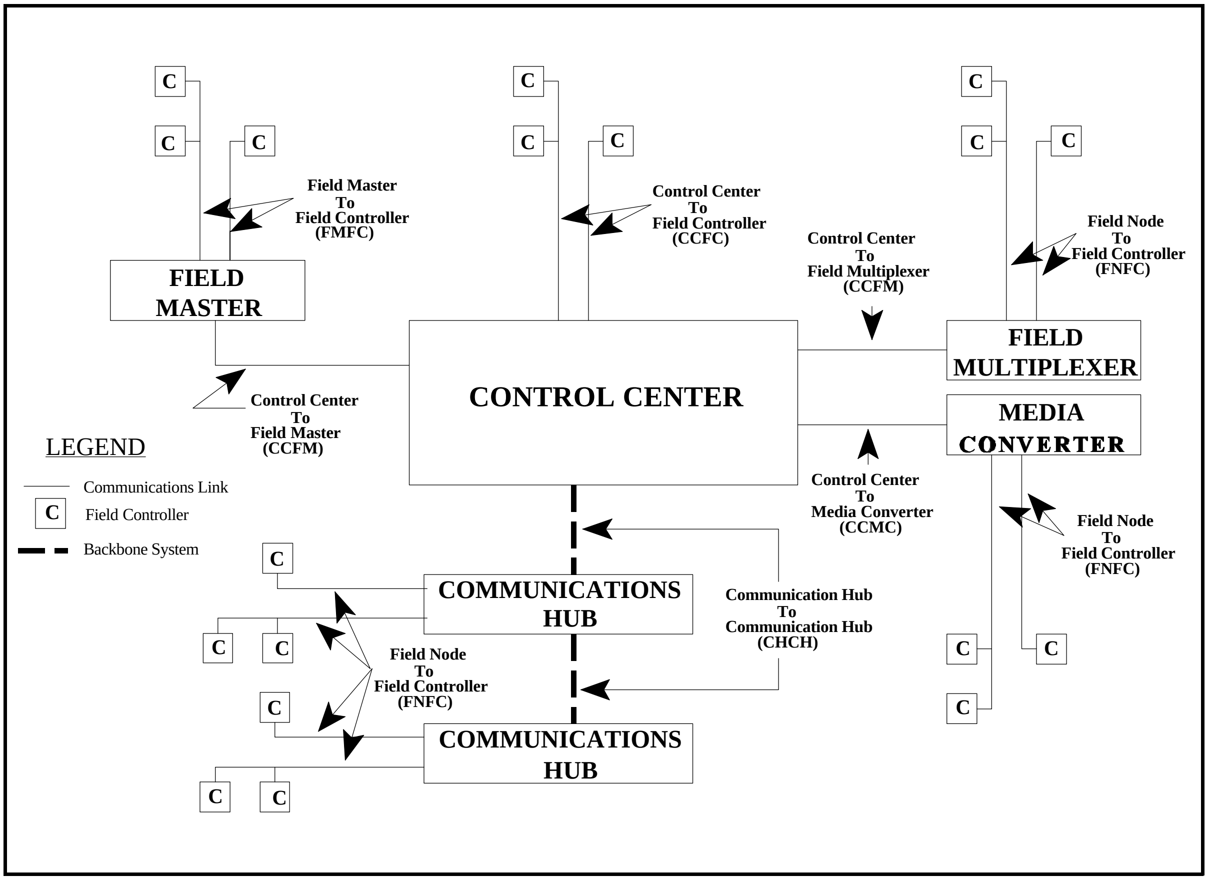

Figure 9-9. Illustration of Generic Communication Links. (1)

in communications systems, while table 9-6 summarizes the characteristics of these links.

- Using tables 9-7 and 9-8, identify candidate media for each generic communications link.
- Conduct a preliminary screening of the media to eliminate any that are impractical or unavailable in an area. The preliminary screening should also eliminate those media and technologies that are not compatible with institutional goals and policies.
- Estimate the data rate requirements for the communications channel serving each field device.
- Eliminate those media and technologies that cannot meet the data rate requirements of the field devices.
- Assess the potential for satisfying the communications requirements via leased communications systems.
- Assess the remaining technologies to decide the following:
  - Whether or not they satisfy the functional requirements of the system.
  - The interface requirements of the field controllers and other field equipment in relation to the communications media.

Table 9-6. Attributes of Generic Links in a Communications System. (1)

Type of Generic Communication Link	Attributes
Control Center to Field Controller (CCFC)	The type of connection between a control center and field controller where no computation or change in data rate occurs.
Control Center to Field Master (CCFM)	The type of connection between a control center and a field master that provides supervisory control to a group of local controllers. The master controller generally does not provide direct control over the site, but rather processes data and adds information and/or control commands.
Field Master to Field Controller (FMFC)	The type of connection between a field master and local field controller. The local field controller provides direct control and collects information from the specific devices at a site. The master controller processes data from a group of field controllers.
Control Center to Field Multiplexer (CCFX)	The field multiplexer site provides higher data rates to the control center link than does the field controller. While the data rates differ, the multiplexer performs no processing related to traffic system functional requirements.
Control Center to Media Converter (CCMC)	The type of communication that occurs between a control center and a device that converts the communication channel to a different type of media (e.g., from twisted pair to fiber optic).
Communication Hub to Communication Hub (CHCH)	This type of connection occurs between two communication hubs. This type of connection typically represents a high data rate backbone link.
Field Node to Field Controller (FNFC)	The field controller connects to a field node for either of the following purposes: • To provide a higher order of multiplexing by means of trunking or backbone systems between the control center and field node (CCFX, CHCH) by means of a field multiplexer. • To use a medium more suitable for communication to the control center while retaining essentially the same communication channel capacity (CCMC). The field node in this case consists essentially of back-to-back modems to service each medium.

Table 9-7. Relationship of Communication Technology to Generic Communication Link for Data Transmission. (1)

Communication Technology	Generic Communication Link						
	CCFC	**CCFM**	**FMFC**	**CCFX***	**FNFC**	**CCMC**	**CHCH****
Twisted wire pair voice grade channels	✓	✓	✓	✓	✓	✓	
Leased voice grade channels	✓	✓	✓			✓	
Switched voice grade channels		✓					
Fiber optics channels	✓	✓	✓	✓	✓	✓	✓
CATV channels	✓					✓	
Leased digital channels	✓			✓		✓	
Area Radio Networks (owned)	✓	✓	✓		✓	✓	
Terrestrial Microwave	✓	✓	✓	✓	✓	✓	✓
Spread spectrum radio	✓		✓		✓		

* Trunking Link **Backbone Link

CCFC = Control Center to Field Controller
CCFM = Control Center to Field Master
FMFC= Field Master to Field Controller
CCFX = Control Center to Field Multiplexer
CCMC = Control Center to Media Converter
CHCH = Communication Hub to Communication Hub
FNFC = Field

- The types of controls needed to provide adequate environmental protection.

- Examine the feasibility of providing a backbone or trunking architecture for the field devices.
- Isolate those links where geometric or physical situations require a change in the communications media.
- Identify multiplexing strategies for each communications media.
- Develop life-cycle cost estimates for the alternative communications technologies for each system link. Cost estimates should include not only capital cost but also operating and maintenance costs.
- Using the estimate of the link costs, estimate the total communications systems costs.
- Assess the impact of the non-cost related factors on the total system costs. Examples of the non-cost related factors include the following:

Table 9-8. Relationship of Communication Technology to Generic Communication Link for Video Transmission. (1)

Communication Technology	Generic Communication Link				
	CCFC	CCFX*	FNFC	CCMC	CHCH**
Twisted wire pair voice grade channels					
Leased voice grade channels					
Switched voice grade channels					
Fiber optics channels	✓	✓	✓	✓	✓
CATV channels	✓	✓	✓	✓	✓
Leased digital channels	✓	✓	✓	✓	
Area Radio Networks (owned)					
Terrestrial Microwave	✓	✓	✓	✓	✓
Spread spectrum radio	✓		✓		

* Trunking Link ** Backbone Link

CCFC = Control Center to Field Controller
CCFM = Control Center to Field Master
FMFC= Field Master to Field Controller
CCFX = Control Center to Field Multiplexer
CCMC = Control Center to Media Converter
CHCH = Communication Hub to Communication Hub
FNFC = Field

– The risk of the leased communication costs escalating in the future.

– The differences in service reliability between owned lines, leased services, and radio communications.

– The ease of maintaining each communication alternative.

- Select the “best” communications system alternative.

- Review assumptions and iterate the process if necessary.

The *Communications Handbook for Traffic Control Systems* or similar references should be consulted for a detailed explanation of the analyses involved in each step, and example applications of the evaluation process.(1)

IMPLEMENTATION

National ITS Standards

In the past, some agencies have experienced problems maintaining and expanding their systems because they used communications equipment that did not conform to standard equipment interfaces and protocols. One method of ensuring maintainability and expandability is to specify communications equipment and system designs that use common standards. System planners and designers must recognize the importance of standards during the design process. The designer must prepare specifications in sufficient detail to ensure the desired level of standardization of field equipment functions and communication interfaces and protocols. Standards are available for the following elements in a communications system: [(1)]

- Serial data interfaces.
- Modems.
- Voiceband channels.
- Digital signals.
- Fiber optics.
- Integrated services digital networks.
- Compressed video.
- Local area networks.

The reader should consult the *Communications Handbook for Traffic Control Systems* for more details about the specific standards that relate to these elements.[(1)]

The advantages and disadvantages of incorporating standards into the design of a communications system are summarized in table 9-9.

Beginning in 1995, a group composed of infrastructure operators, manufacturers, system integrators, and representatives from the FHWA began developing a national communications standard. Communications standards were needed to ensure interoperability and interconnectivity of traffic control and ITS devices such as variable message sign control, camera control, vehicle classification, and general purpose data collection and device control.[(4)] This standard is known as the National Transportation Communications for ITS Protocol (NTCIP). It is designed to provide a communications interface that allows hardware and software products from different manufacturers to be connected in a traffic management system. The potential benefits of adopting the NTCIP standards for use in designing freeway management systems include the following: [(5)]

- Reduction in warehousing requirements and costs.
- Reduction in training needs for personnel.
- Improvement of staffing effectiveness if same personnel are used predominately for repairs and operations of unique equipment.
- Reduction in product costs of some devices if a more competitive procurement environment yields cost reductions.
- Mitigation of procurement issues associated with system expansion and spares.
- Reduction in downtime.
- Enhancement of interjurisdicational coordination and integration.
- Shared use of the communications network, providing the opportunity to share the costs of communications with other agencies (or at least avoid the cost of dedicated parallel communications systems).

For more information about NTCIP, the reader should consult the **Lessons Learned** section at the end of this module.

In addition, the National Architecture effort also spurred development of standards for other freeway applications, such as the following:

Table 9-9. Advantages and Disadvantages of Using Communications Standards. [1]

Advantages	Disadvantages
• Ensures the availability and compatibility of equipment spares for repairs and future expansion. • Allows system to be expanded to locations not contiguous to the existing system and accessible by land line. • Ensures the compatibility of test equipment. • Supported by a wide body of literature describing the functions of ports and modems designed to common communications standards.	• Some existing system architectures are incompatible with accepted standards. • May result in higher system costs since equipment with less than optimum data rate may be required to conform to standards. • May require higher level of maintenance personnel.

- Transit Communications Interface Protocols (TCIP).
- Dedicated Short Range Communication (DSRC).
- Location Referencing.
- ITS Data Bus.
- FM ATIS Broadcasting.
- Navigation Messages.
- MayDay Reporting.
- Navigation Human Interfaces.
- ATIS Message Set

The technical edition of the *ITS Deployment Guidance for Freeway Management Systems* lists possible standards for the following different applications within Freeway management systems:

- GIS Applications
- DMS Applications
- CCTV Applications
- ETTM Applications
- ATIS Applications
- Center-to-Center Communications
- Center-to-Roadside Communications
- Roadside-to-Vehicle Communications
- Vehicle-to-Vehicle and In-Vehicle Communication
- Center-to-Remote Access Communication
- Center-to-Vehicle Communication

If circumstances dictate the use of nonstandard equipment, agencies should procure sufficient spare devices for use well into the future. Agencies should also consider acquiring an inventory of specialized parts (e.g., custom integrated circuitry) that may become difficult to purchase in the future. [1]

Installation

The use of proper installation techniques and procedures is critical to installing a successful and functioning communications system. Failures and unreliable performance in a communications system commonly occur because proper installation procedures were not followed. Examples of improper installation techniques associated with wireline communications systems that can affect overall performance include the following: [1]

- Improperly installing fiber optic cable and coaxial cable connections.
- Exceeding the maximum pulling tension on the cable.
- Using a tighter radius than recommended by the manufacturer when bending a cable.
- Improperly splicing cables.

Installation and construction inspection personnel should receive appropriate related training before starting installation.

Three basic methods of installing cable are commonly used to connect devices in a freeway management system:

- Cable in Conduit.
- Direct Burial.
- Aerial Mounting.

Table 9-10 summarizes the advantages and disadvantages of each of these installation options.

9.3 TECHNIQUES AND TECHNOLOGIES

This section discusses the transmission media that are commonly used in communications systems for traffic management applications. This section also discusses some options available for transmitting video images to a control center. This section is intended only to highlight several major characteristics and issues associated with these media. For more detailed information on any of these media, the reader should consult the *Communications Handbook for Traffic Control Systems* or similar references.[1]

Communication media can be divided into the following two categories:

- Land-Line.
- Wireless.

The media contained in each of these categories are discussed below.

LAND-LINES

Land-lines (i.e., wire cable), whether leased or owned, are by far the most prevalent form of traffic control system communication media.[1] The three primary land-line transmission media commonly used in freeway management systems include the following:

- Twisted Wire Pair.
- Coaxial Cable.
- Fiber Optic.

Table 9-11 provides an overview of the land-line communication technologies that will be

Table 9-10. Advantages and Disadvantages of Installation Methods for Land-Line Communications Media.

Installation Method	Advantages	Disadvantages
Cable in Conduit	• Most secure because cable is placed in conduit that is buried approximately 1 m underground. • Requires the least maintenance if adequately protected by markouts and tight permitting process. • Access to cable provided through junction boxes.	• Frequent junction boxes required, especially when bending cable. • Can be damaged by excavation or installation of sign posts, guard rail posts, etc. • Relatively more expensive than other installation methods.
Direct Burial	• Cable, which is protected by extra insulating jacket, is buried directly in the ground. • Eliminates need for conduit and junction boxes. • Easier to install than conduit and aerial methods. • Suitable for use where roadside development is limited.	• Greater susceptibility to damage by excavation. • More difficult to maintain and repair. • Requires good control of excavations through permitting process.
Aerial Mounting	• Cable hung from existing utility poles in or near right-of-way. • Least expensive installation method (often ¼ the cost of installing cable in conduit or direct burial). • Not susceptible to damage by excavation. • Relatively easy to repair.	• Normally requires yearly rental fee on utility poles. • May also be assessed fee for relocating existing utilities on poles. • Because sun can deteriorate cable, it must be replaced approximately every 15 years. • Susceptible to damage from tree limbs, etc. during wind storms.

discussed and some of their notable features. Each of these media is discussed below.

Twisted-Wire Pairs

Twisted-wire pairs are the most prevalent type of communications media used in traffic control applications. A twisted-pair cable consists of sets of two wires wrapped around each other. The twisting of each pair reduces interference from external sources because the pairs of conductors carrying the signal are always immediately next to each other in the cable. Therefore, the induced signal from the interfering source will affect each conductor of the pair similarly. Figure 9-10 provides an illustration of one conductor in a twisted-wire pair cable.

Since the receiver is measuring only the difference in voltage between the conductors, the fact that both conductors have the same induced voltage will not be noticed. The design of the cable also reduces crosstalk between lines, because the same current is flowing in opposite directions in each conductor (see figure 9-11). Therefore, the electric field radiates from the two conductors in opposite directions (radially around each wire). This results in the two fields canceling each other out. (1)

Table 9-11. Summary of Land-Line Technologies and Their Features. (2,6)

Features	Twisted-Wire Pairs	Coaxial Cable	Fiber Optics
Transmission Media	Copper Wires	Center conductor is copper clad aluminum Outer conductor uses aluminum	Glass or plastic fibers
Transmission Range	14 to 24 km (8.7 to 14.9 miles) with repeaters	Commercial subscriber network repeaters at 0.5 km (0.31 mi); 1 km (0.62 mi) or more on dedicated systems; maximum of approximately 60 repeaters	Rarely a limitation when drop/insert units used at communications hubs or drop points
Principal Multiplexing/ Modulation Technique Used	Time Division Multiplex (FSK)	Frequency Division Multiplexing to divide channel bandwidths; Time Division Multiplexing to communicate data	Time Division Multiplex (FSK)
Carrier Frequency Band	300 to 3000 Hz	5 MHz to 350 MHz	850 to 1,550 nanometers
Bandwidth/Channel Bandwidth	Will exceed 2.7 Hz for most systems	6 MHz/channel	Various
Data Rates per Channel	1,200 to 3,100 bps Higher rates possible with different modulation techniques	Up to 7.5 Mbps based on channel subdivision	Up to 2.4 Gbs
Government Regulation of Channel or Service	None	May require licensing from local and state authorities, FCC provides legislation	None
Types of Information Supported	Data, voice, slow scan TV	Data, voice, video	Data, voice, analog TV, Codec
Owned or Leased	Owned	Either	Owned

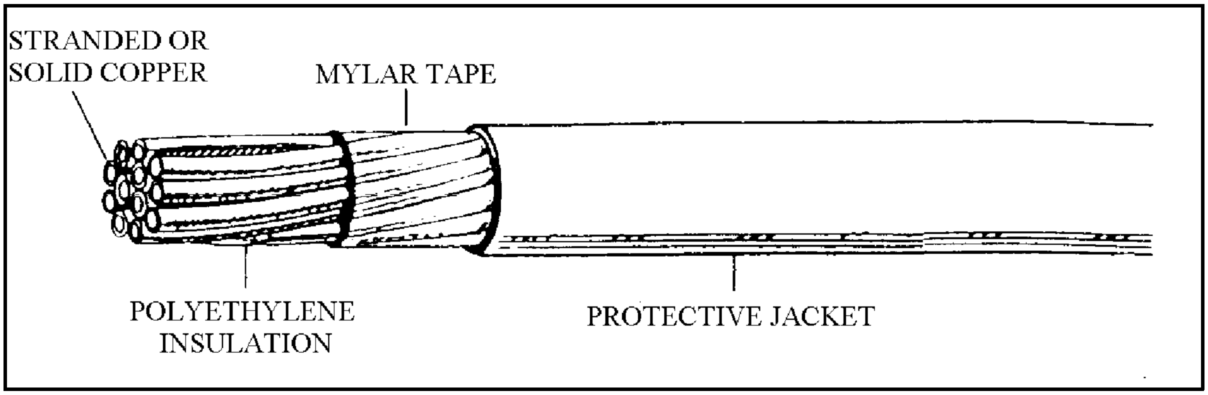

Figure 9-10. Illustration of a Twisted-Wire Pair Cable.

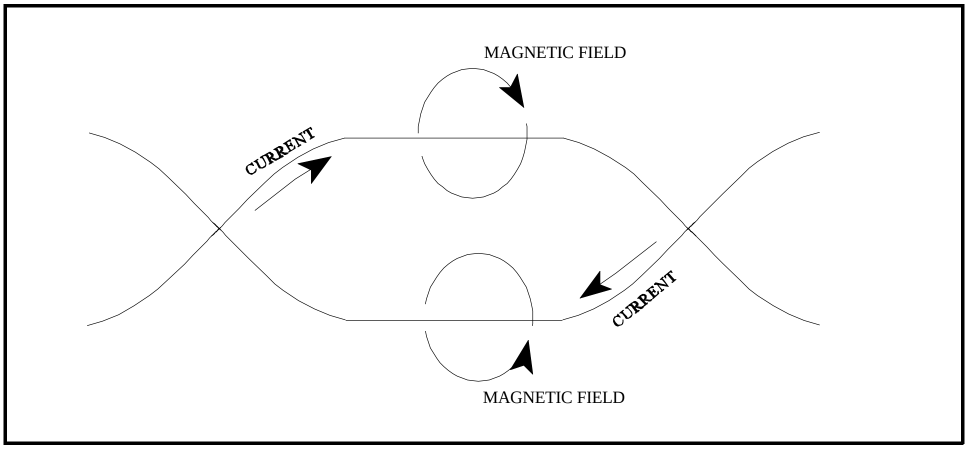

Figure 9-11. Crosstalk Reduction by a Twisted-Wire Pair. [(1)]

Most twisted-wire pair cabling used in traffic control systems is usually of the voice-grade type. This means the usual bandwidth (the range of signal frequencies a medium or channel will respond to, or carry without excessive loss in signal strength) ranges from 300 Hz to 3000 Hz, the audible frequency range of the human voice. Twisted-wire pair cabling is commonly used in voice telephone communications. A voice-grade cable will accommodate a data transmission rate of 1,200 bits per second (bps), which is adequate for transferring small amounts of data (i.e., loop detector data). When higher data transmission rates are required (for trunking applications), the twisted-pair cable must be conditioned by adding electronic equipment, such as loading coils, to improve the transmission characteristics of the line.

Twisted-wire pair technology consists of two insulated copper wires wrapped around each other and used to convey signals. Twisted wire is manufactured in standard numbers of pairs (6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, and 1200) in wire gauges 19, 22, 24, and 26 American Wire Gauge (AWG). [(2)] The maximum number of twisted pairs of wires manufactured in a single cable is 2600. [(7)]

The advantages and disadvantages of twisted-wire technology are summarized in table 9-12.

Twisted-wire pair technology is an inexpensive communications medium whose acquisition cost is lower than that of both coaxial and fiber-optic technologies; however, long term operating costs are dependent on installation considerations and are higher when life-cycle costs are considered. [(6)] The extent of such costs will vary greatly with the different installation and maintenance procedures required to support the installation method used and the terrain covered. For example, aerial installations can be damaged or links severed by sources ranging from falling trees to storm related damage. By comparison, buried cable affords protection from those threats, but may be subject to construction-related severance and will reflect higher installation costs. [(1)]

Twisted-wire pairs can be stranded together to form color coded binder groups that can then be wrapped around a common axis to increase the number of conductors in a given cable. The amount of twist in a given binder group is used to control how much crosstalk occurs.[(1)] A cable consisting of multiple

Table 9-12. Advantages and Disadvantages of Twisted-Wire Pairs. [1,6,7]

Advantages	Disadvantages
• Represents a low cost form of transmission. • Easy to splice. • Requires no special interface equipment. • Electrical characteristics are very favorable to basic analog transmission.	• Data cable splicing is not recommended. • There is a bandwidth limitation in that twisted-wire pair tends to attenuate high-frequency electrical signals, thereby limiting the ability to transmit digital information at high data rates. • Bandwidth limitation prevents transmission of live television images, though recent developments permit transmission of slow-scan television. (Prototype equipment is available for transmission of full-motion television over twisted-pair copper wire.) • Low security.

twisted-wire pairs can transmit several channels of data. In a full-duplex network, every two pairs can provide one channel.

The electrical characteristics of twisted-pair copper strongly support basic analog transmissions; however, its capability to transmit digital information at high data rates is limited by attenuation of high-frequency electrical signals.[7] The attenuation of high-frequency signals increases with increased cable length and decreased diameter. [1]
Noise can be a source of problems with some twisted-pair cable communications systems. Most modems used with twisted-pair systems, however, can filter out signals, many sources of noise below 750 Hz, but in noisy high frequency environments, other types of communications media may be more appropriate. Sources of potential noise in a twisted-pair communications system include lightning, high voltage power lines, and large electric motors. [1,6]

The use of equipment from multiple vendors can increase the difficulty in separating a given signal and transmission noise. [6] Noise may also rise if the twisting of the wire pair does not completely cancel the induced electrical fields. Moisture in twisted-pair cable networks can also lead to increased crosstalk and cable noise by introducing signal reflections (cable splices are the primary source of moisture entry). [1]

Several features of twisted wire pair communications should be considered during the design process. Fundamental concepts that should be considered by system designers include the items summarized in table 9-13. Besides those items listed in table 9-13, other items that should be considered during the design and installation processes including the following: [1,2]

- Maximum allowable transmitter power.

- Signal level expected at the receiver.

- Limitations on the number of drops on a multipoint line.
- Wire gauge.
- Environmental effects, such as moisture entry, noise, and transients.
- Aspects involving the number of repeaters, special functions of the system, and testing.
- Susceptibility to inadvertent electrical surges resulting from maintenance activities (consideration should be given to the provision of transient protection for sensitive electrical devices connected to the cable).
- Installation should not exceed the maximum pulling strength of the cable. Installation specifications should require either hand-pulling or tension monitoring using a strain gauge.
- Consideration of the use of existing facilities should take into account the limitations of the system, potential to expand, and physical plant responsibilities.

Finally, it should be noted that this transmission medium offers little security. It may be easily tapped and the electromagnetic field it radiates can be read by sensitive electronic devices. [6]

Coaxial Cable

Coaxial cable technology can transmit either data or video via several communications channels. [2] Its name is derived from its characteristic shape, essentially a set of two concentric circles. As shown in figure 9-12, the cable consists of an unbalanced pair made up of an inner conductor within an outer conductor held in a concentric configuration by a dielectric material that separates the two conductors. [7] Physical structure characteristics typical of coaxial cable include the following: [1]

- A center conductor composed of copper clad aluminum.
- An outer conductor composed of aluminum as a braided metal fabric, corrugated semi-rigid metal, or a rigid metal tube.
- A dielectric composed of solid polyethylene or polyvinyl chloride, foam, Spirafil, or inert gas (when gas is used, the center conductor is kept in place by spacers or disks).
- An outer jacket composed of low density, high molecular weight polyethylene.
- Optional armor for use in direct burial in gopher areas.
- Cables that vary greatly in size and construction. Typical traffic control applications commonly use a 19.05 mm semi-rigid coax for trunk lines, with smaller diameters used for connections between the trunk and field drops.

Table 9-14 summarizes the major advantages and disadvantages of coaxial communication technology.

A coaxial cable system uses frequency-division multiplexing (FDM) and time-division multiplexing (TDM) to fit all traffic control signals on a single conductor. FDM is used to subdivide the cable bandwidth into appropriate channels for data, video, and voice transmission, and TDM is then used to communicate the data.[1]

Table 9-13. Design and Installation Considerations Relating to Twisted-Wire Pairs. [1,2]

Consideration	Design Factors/Options
Number of wire pairs required for startup and expansion	• Total number of field drops • Maximum number of drops allowed on each channel • Network configuration
Cable routing and installation techniques	• Field drop locations • Existing communication facilities • Cable termination requirements • Cost
Installation methods	• Underground, in conduit • Underground, by direct burial • Aerial, using existing/new utility poles • Support of cable or conduit by bridges, overpasses, and other structures • Need for submarine cable
Cable size	• Minimum bending radii • Cable weight
Cable size affect on conduit design	• Available conduit and pole spacing • Size of manholes and junction boxes • Required bend of conduit at entry to cabinet/junction box • Aerial cable weight
Attenuation levels	• Signal frequency • Conductor size • Cable length • Number of splices and connections
Susceptibility to electrical transients from natural phenomena such as lightning	• Storm frequency • Terrain • Type of cable
Moisture prevention	• All splices on telephone terminal blocks should be inside weatherproof cabinets, or in waterproof splice enclosures for aerial installations • Installation must be performed such that the cable does not drag on the pavement or rub against jagged conduit ends causing cuts or abrasions • Be aware of cable jacketing imperfections • Seal cable ends during pulling operations to prevent moisture entry
Thorough testing after installation including at least:	• End-to-end continuity for each pair • The insulation resistance for each conductor (to ground and to the paired-conductor) • Attenuation

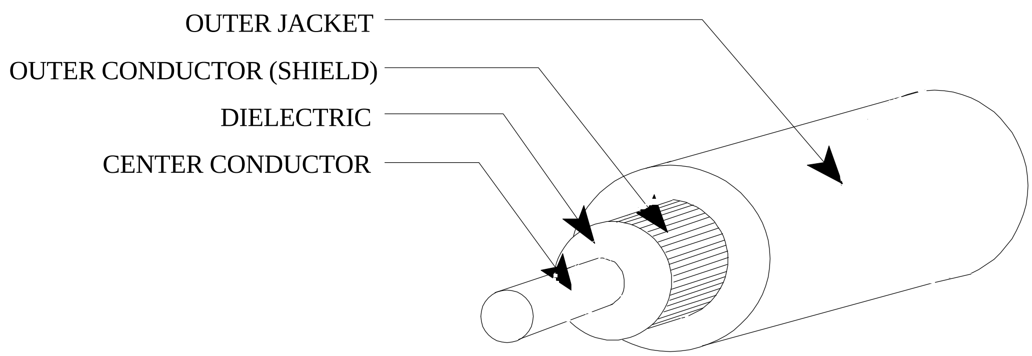

Figure 9-12. Illustration of Coaxial Cable Design.

Table 9-14. Advantages and Disadvantages of Coaxial Cable. [1,6,7]

Advantages	Disadvantages
• Because of its physical structure, coaxial cable is more immune to electromagnetic interference and has a much higher bandwidth than twisted-pair cable. • Minimal signal losses. • Low signal leakage. • Higher bandwidth allows for transmission of video signals (cable television using coaxial cable can transmit as many as 75 independent video signals) and for the transmission of digital data at very high rates. • Bandwidth of coaxial cable permits theoretical transmission rates as high as 700 million bits per second (Mb/s). These rates are more favorable than typical twisted-pair rates that are limited to less than 24 Mb/s for short distances.	• Splice connections are susceptible to noise and transient problems. • Cannot be spliced together by manual strip and twist method. Inherent nature of cable, and the importance of conductor alignment, make the coaxial cable much more difficult to splice. • Lower communication reliability than fiber optic. • Higher maintenance and adjustment effort required compared to fiber optic. • Low security. • Cannot be conventionally “tapped.” Requires termination.

The typical coaxial communications system can be used for two-way communications by dividing the frequency spectrum into two parts. The upstream channels (generally inside the control center) use one range of frequencies to transmit data, while the downstream channels transmit in the opposite direction (from the field to the operations center). Filters and amplifiers are used at the repeater locations to carry the signals simultaneously in both directions. [2]

The coaxial network branches out from the operations center via a series of splitters, directional couplers, taps, and repeaters. Splitters are used to divide and combine signals within the tree-like network depending on their destination. Directional couplers are used to combine signals onto cables by direction. Taps are then used to divert signals to and from the trunk line at field drops. Repeater amplifiers are supplied to boost the signal along the system based on transmission frequencies, cable size, number of connectors, and design tolerances of the system. [1]

Coaxial cable's physical structure is less affected by electromagnetic interference than twisted wire pairs. [7] Repeater amplifiers have low noise levels and can deliver strong signals over a wide range of output levels; however, coaxial cable does experience moderate signal attenuation losses. Coaxial systems amplify the signal at each repeater, instead of regenerating it. As a result, background noise is also amplified at each repeater. This phenomenon limits the number of repeaters that can be placed in series to approximately 60 (this limit has not been reported to have affected traffic control systems using this technology). [1]

The attenuation in a given coaxial cable varies as a function of frequency, temperature, and cable size. Attenuation levels roughly double each time the bandpass frequency quadruples. Temperature variations can also degrade performance. For example, every 10-degree increase in temperature above 68 degrees results in approximately a 1 percent increase on attenuation.[6] Amplifiers are designed to compensate for the effects of temperature, though technicians must occasionally retune them. Unfortunately, the modems that are commercially supplied for coaxial systems often have temperature settings that fall below NEMA specifications. Use of these modems can result in interference with adjacent channels and the disruption of system communications if their temperature limits are exceeded. [1]

While only one cable may be required in a coaxial system, the design of a coaxial network is more complex than that of a twisted pair network. The higher frequencies and lower tolerances associated with noise and interference among coaxial cables translate to both higher skill level and test equipment requirements to support a coaxial network. [1] As indicated in describing the previously cited potential modem problems, it is essential that the designer have a thorough understanding of the equipment required by these systems.

Similar to twisted wire pairs, coaxial cable may be installed underground in a conduit, by direct burial, or overhead on utility poles. Generally, coaxial network connections can be spliced using press-fit connectors that clamp over the ends of the wires and are then screwed together. Many alternative connector and splicing arrangements can be employed for inserting tabs at midpoints in the cable and for ending cable runs. Given these factors, a design must consider the following: [1]

- The placement of amplifiers, couplers, splitters, and pilot generators.

- Provision of power for the amplifiers (repeaters).

- Compensation for temperature extremes and rate of change.

- Minimization of electromagnetic interference (EMI) and radio-frequency interference (RFI).

- Allocation of frequencies to the channels.

Contingent on the method of installation, the installer must ensure the following: [1]

- All conduit has gentle bends between pull boxes. (Severe bending of the conduit may cause the outer conductor to collapse and/or the inner conductor to permanently shift.)

- The maximum pulling tension specified by the manufacturer is not exceeded.

- All splices and connections are made in waterproof cabinets to reduce exposure to moisture and noise ingress.

During the installation process, care should be taken to ensure good quality control. Adequate construction supervision and thorough testing of the entire installed network are needed to maintain good quality control. Testing should consist of an end-to-end examination conducted under various weather conditions that exemplify operations at different temperatures.

Fiber Optic

Fiber optic communication provides a high volume, cost-effective means of transmitting either data or video via several communications channels with immunity to electrical interference. [1] Its name is derived from the medium's use of an optical fiber to transmit light by means of internal reflection off the surrounding surface cladding. Essentially, light impulses are coded and transmitted into a glass fiber structure. The fiber itself confines and guides the beam of light between origin and destination points. Upon reaching its destination, the light signal is detected, converted to electrical pulses, and decoded to an appropriate output. [7] The advantages and disadvantages of fiber optic communications media are summarized in table 9-15.

Fiber optic technologies are more expensive to acquire than comparable metallic transmission media; however, fiber optic cable has a reduced life-cycle cost when compared with copper transmission media, and is increasingly being used to replace coaxial cable systems. [7] Because of the high cost of fiber optic systems as compared with copper transmission, they are typically used for trunking applications in which large amounts of information must be transmitted over long distances or for high-speed local area networks that are to be distributed over a campus area. [2]

Fiber optic communications rely on light to act as a signal carrier within an optical fiber composed of a core region, cladding, and a coating. To transmit video, voice, and other data, the information is converted to a coded pulse of light, and introduced into the optical fiber, and is transmitted by internal reflection of the light wave within the fiber. Depending on the entry angle of the light into the fiber, the light will travel different distances. [2] Light waves that enter the core at an angle greater than the critical angle reflect and propagate within the core. Those light waves that enter at less than the critical angle refract into the cladding and attenuate. [1] As the light travels through the fiber, its bandwidth changes due to the spreading of the light pulses. As the pulses spread, they overlap and may interfere with

Table 9-15. Advantages and Disadvantages of Fiber Optic Communications.[1,7]

Advantages	Disadvantages
• A pair of light tubes can support many more circuits than a metallic path. • Immunicty from electromagnetic interference (EMI) and radio-frequency interference (RFI). • High integrity for data transmission. • Emits no radiation and it is difficult to tap a fiber tuve without detection of the resulting signal loss, thus represents a highly secure means of communication. • Use of small cable diameters and low-weight cable. • Small bending size, small bending radius, and light weight. • Safety in hazardous environments. • Extremely flexible - can be installed to support a low-capacity (low-bit-rate) system and, as the system's requirements expand, can use broadband capabilities of optical fibers and convert to a high-capacity (high-bit-rate) system simply by changing the terminal electronics.	• Designing a fiber optic network tends to require substantial engineering effort due to complexity of networks, light distribution characteristics and medium, and other factors. • Splicing tends to require elaborate equipment and expertise.

each other. [2] This dispersion effect limits the transmission speed and, if the pulse spreads so that the last portions of one pulse arrive after the first portions of the following pulse, may diminish the signal to a point that the receiver can no longer distinguish individual pulses.[1]

Several supplementary equipment items are needed with fiber optic communications systems. These items include modems, multiplexors, and repeaters. Fiber optic modems transmit data over a dedicated pair of fibers (e.g., between a controller and a traffic operations center) by converting an electrical signal to an optic signal and vice versa. This technology allows for full duplex communications over one or two fibers. Conversely, multiplexors transmit voice, data, and/or video over a fiber backbone network. [1]

Multiplexors combine many low- to medium-speed digital data channels into high-speed channels. In fiber optic systems, two types of multiplexors are used: electrical and optical. As implied by the name, electrical multiplexors combine signals electronically, and result in a combined electrical signal that drives the fiber optic transmitter. Single fiber optic channels can be used to carry multiple signals, using wavelength-division multiplexing. This technique is useful for long distance backbone and trunk lines, but is not cost-effective for local distribution uses. [1]

After entering a fiber, a pulse is carried by the optical fibers to the receiving station, where it is either received or regenerated. At the final receiving station, the light pulses are converted to electric signals, decoded, and converted to the original form of information. To correct pulse dispersion, fiber optic repeaters convert the optical signal back to its original form and then back to an optical signal.[1]

In systems with multiple drops placed in series, common practice uses drop/insert units, which perform the following functions:[1]

- Interception of the optical signal.
- Conversion of the signal to an electrical form for use by the device.
- Injection of a response if necessary.
- Modulation of the electrical signal back to an optical signal.
- Retransmission of the optical signal.

In a daisy-chain multiple drop configuration, the failure of any drop/insert unit results in the loss of all the remaining units beyond that point. This situation can be avoided by using units that contain a passive transfer feature. [1] The passive transfer feature uses a separate battery back-up for each unit which provides continued communication to the downstream units in case of an electrical power failure in the controller. [2]

Fiber optics can also be used to transmit video signals in one of three manners: [2]

- Baseband — transmits unmodulated video signals.
- Modulated — extends the transmission range, using amplitude modulation or frequency modulation.
- Multiplexed — enables transmission of several video signals on the same fiber.

Because of its dielectric nature, fiber optic communication medium is unaffected by electrical signals. As a result, many problems such as radiative interference, ground loops, and lightning-induced damage (when fiber optics have been installed in a cable without metal) can be avoided with fiber optic technology. This property makes fiber optics an ideal communication medium in a noisy electrical environment.

Fiber optics is, however, affected by dispersion and attenuation. The negative impacts of these two factors increase with the number of modes, and limit the length of a given fiber optic link. To limit the effects of dispersion, graded-index fiber can be used. Graded-index multimode fiber design limits the dispersion created by multiple modes by permitting light waves traveling different length paths to travel at similar axial speeds. Attenuation is caused by the following factors: [1]

- Absorption — where propagating light interacts with impurities in the silica glass.
- Scattering — where geometric imperfections in the fiber cause light to be redirected out of the fiber.
- Microbends — which may occur during fiber or cable manufacture.
- Macrobends — which can result from improper installation practice (e.g., exceeding the minimum bending radius).

The extent of the effects of dispersion and attenuation vary depending on the baud rate transmitted. Typical multimode fibers have a bandwidth of 400 MHz-km at a wavelength of 1300 nm. Such a fiber can sustain a baud rate of 400 MHz over a distance of 1 km (0.6 mi) but only 100 MHz over a distance of 4 km (2.5 mi). Traffic control systems that use multimode fiber at the low baud rates typical of distribution channels for small signal control systems will typically be limited by attenuation considerations. (1)

As with the other land-line transmission media, fiber optic cables may be installed underground in a conduit, by direct burial, or overhead on utility poles. Recent traffic control system designs have specified conduit installation of the fiber cables. (1) The proper design of a fiber optic communication system requires a knowledge of the transmission characteristics of the optical sources, fibers, and other devices (such as connectors, couplers, and splices, etc.). Transmission criteria that affect the choice of fiber type used in a system include the following: (7)

- Signal attenuation.
- Information transmission capacity (bandwidth).
- Source coupling.
- Interconnection efficiency.

Interconnection efficiency is usually measured by signal attenuation, the loss of signal strength within the fiber, plus the loss of signal strength in the splices and connectors. (7)

Fiber optics can be installed using single or multimode technology. Single mode fiber boasts higher capacities than multimode fiber and is preferred for long-distance communications. (7) As a result, single mode fiber is recommended over multimode fiber for any communications link that serves as, or could evolve into, part of a backbone network; (1) however, multimode fiber optic systems are sufficient for most transportation related applications. (7)

Splices or connectors are commonly interconnection devices used to install fiber optic systems. To reduce attenuation, interconnection must result in a highly accurate alignment of the fibers so that light can be successfully transmitted between them. Two tools exist for interconnection purposes: splices and connectors. Splices are used to join lengths of fibers together permanently, while connectors are temporary devices that can be disconnected and reconnected as needed. Designs must compensate for the losses introduced by splices and connectors used for interconnection purposes. They also need to provide a closure system that offers environmental protection and mechanical support. (1)

Field splicing of fiber optics is grouped into two methods: fusion and mechanical. Fusion splicing yields lower losses but also requires more time to complete. (2) For temporary connections of individual fibers in controlled environments, connectors and distribution systems are used together. Inexpensive interconnection cables (patch panels) can be used to end the distribution cable. Within these cabinets, small fiber counts of 12 to 48 fibers can be spliced, ended, and stored. Larger distribution frame shelves can be used to end as many as 144 fibers at major hubs. For traffic applications, fibers can be pulled into a breakout box and cable assembly with factory-installed jumper cables on one end and distribution cables on the other. Up to 24 fibers can then be connected from the equipment cabinet to a pull box. (1)

WIRELESS

Several forms of wireless communications technologies commonly used in freeway management systems include the following:

- Areawide radio networks.
- Terrestrial microwave links.
- Spread spectrum radio.
- Cellular radio.
- Packet radio.
- Satellite transmission.

Table 9-16 summarizes the characteristics and features of the wireless communications technology used in freeway management systems. The first three of these communication media are generally owned by the public agency while the last three can generally be leased from commercial providers.

In general, owned communication technologies offer several advantages and disadvantages as compared with commercially leased wireless communication technologies, as summarized in table 9-17.

Area Radio Network

Area radio networks derive their name from their ability to broadcast signals to an area as opposed to a specific location. (2) Table 9-18 summarizes the advantages and disadvantages of area radio networks applied to traffic control systems. (1)

Area Radio Networks operate in the 150 MHz to 960 MHz bands; the 450 to 470 MHz and 928 to 960 MHz bands are the most commonly used. (4) Bandwidth channels in the 25 KHz range are often used for data transfer and can support a signal rate of 9.6K bits/second; however, they will not support video transmission. (1) Depending on antenna location, the signals generally radiate uniformly in all directions and rely on the scattering and reflection properties of the signal to propagate throughout the area. During propagation, signals may "bend" slightly over changes in the ground surface, reflect off buildings or other obstacles, or penetrate into buildings.(1) Because of potential signal degradation, repeaters are sometimes used. (2)

In most applications, radio transmitters use the same transmit and receive channels. Voice communications use receivers all tuned to the same broadcast channel, and users respond only to the messages directed to them. This feature represents a potential limitation in data transfer applications and requires that protocols be established to permit multiple transfers of data on one communication channel. The protocols available vary and include both polling techniques (each data source receives exclusive use of the transmitted channel for a short period) and multiple access contention techniques (compensation is provided for collisions caused by simultaneous transmissions). (1)

While the scattering and reflection of radio signals allow the signal to propagate into built up areas, they also reduce the signal strength. Terrain barriers and weather factors can also interfere with the performance of area radio networks.

Operation of area radio networks requires an FCC license. The design of radio communication systems is complex and often requires special expertise. It is recommended that, if a preliminary study shows the usefulness of a radio network, an engineer with the necessary background be retained to evaluate system needs further.

Table 9-16. Wireless Communication Technologies and Their Associated Properties.

Technology	Principal Multiplexing/ Modulation Technique Used	Carrier Frequency Band	Bandwidth/ Channel Bandwidth	Data Rates per Channel	Transmission Range or Repeater Spacing	Government Regulation of Channel or Service	Types of Information Supported	Owned or Service	Constraints on Use
Area Radio Network	Time Division Multiplex, Modulation technique varies	15-174 MHz 405-430 MHz 450-470 MHz 928-960 MHz	25 KHz channels	9.6 Kbps	Several kilometers	FCC licensing of channels for each network	Data	Owned	Channel availability, line of sight in 900 MHz band, multipath sensitivity, geometries
Microwave	Time Division Multiplex, Modulation technique varies	928 MHz to 40 GHz	Various	Up to 7.5 Mbps depending on channel allocation	Varies, may extend several kilometers	FCC licensing of channels except for channels in 31 GHz band for each installation	Data, voice, analog TV, Codec	Owned	Channel availability, line of sight availability, multipath sensitivity, geometries, weather
Spread Spectrum Ratio	Time Division Multiplex, Modulation technique varies	902 to 928 MHz	Various	200 Kbps (typical)	0.8 km (0.5 mi) to several km	No license in the 902-928 MHz band for the network	Data, Codec	Owned	Line of sight, geometries, protocol compatibility
Cellular Radio	Because of narrow channel width, usually only simple polling or other multiple access techniques	825-845 MHz for mobiles, 870-890 MHz for base stations, 20 MHz in reserve	30 KHz per channel	1.2 to 14.4 kbits/sec, depending on modem type used	3.2 - 16 km (2-10 mi) per sector or “cell”	FCC has divided U.S. into 734 service areas, two cellular operators licensed/area	Voice, data	Service	Transmission cost, data transfer limitations
Packet Radio	Multiple access protocol	800 and 900 MHz bands	12.5 and 25 KHz channel widths	4.8 to 8 kbits/sec; 19.2 kbits/sec in major cites	16 - 32 km (10-20 mi) per base station		Data	Service	Service limited to major cities, time delay in delivery
Satellite Transmission	Frequency Shift Keying, Minimum Shift Keying, Phase Shift Keying	C Band (4-6 GHz) Ku Band (2-4 GHz)	Various	Various, depending on system complexity	Essentially unlimited, based on coverage area	FCC allocates frequencies for fixed satellite communication	Data	Service	Availability in some geographic areas, cost

Table 9-17. Advantages and Disadvantages of Owned Radio Communications. [1]

Advantages	Disadvantages
• No need for physical medium since signal propagates through the atmosphere. • No cost of major land-line installations and maintenance. • Used to span natural barriers or provide communications link between points where rights-of-way are not available. • Flexible implementation. • Commercial off-the-shelf equipment available. • Used in a number of traffic control systems.	• Relatively complex design (compared to land-line communication systems) since the local operating environment (e.g., terrain, potential sources of interference, available frequencies, etc.) must be investigated and taken into account for the design process. (However, a variety of theoretical models can be used to predict radio wave propagation for a given set of conditions.) • Limited choices of operating frequencies based on regulatory issues. • Path line of sight constraints (e.g., in the microwave region of 900 MHz and above, line of sight to the receiving antenna(s) generally required). Propagation relationships govern the actual obstacle and adjacent structure clearance required. • Fading considerations. • Turnaround time considerations. • Limited bandwidth. • Requires external antennas and cable. • May require repeaters. • Specialized maintenance.

System designers should consider the following items when installing an area wide radio network: [1]

- Maximum distance to be covered.
- Antenna requirements, including line-of-sight requirements.
- Transmitter power requirements.
- Operating frequency characteristics.
- Receiver sensitivity.
- Line losses at the antenna.
- Required polling intervals.
- Radio transmission considerations such as bending, clearance of obstacles, propagation over bodies of water; and the effects of weather.

Table 9-18. Advantages and Disadvantages of Area Radio Networks. [1]

Advantages	Disadvantages
• Can operate traffic controllers or other traffic control devices. • Can provide voice communications to highway maintenance vehicles. • Can propagate into built up areas and buildings. • Can support 9600 baud data rate. • Can prove cost effective depending on application.	• Terrain may limit range. • Limited channel availability in metropolitan areas. • Requires antenna at each controller site. • Turnaround time excessive for some applications. • Service reliability may limit use of some applications.

Microwave

Microwave systems convey point-to-point messages at very high frequencies that allow for reuse at small distances. [7] The advantages and disadvantages of terrestrial microwave links are summarized in table 9-19.

Microwave systems are expensive due to the infrastructure costs required to interconnect communications. [6] These infrastructure requirements are directly attributable to the operating frequency in use. Higher frequencies require smaller antennas that in turn have fewer extensive infrastructure needs; however, the larger antennas typically required by 2 GHz and 6 GHz systems cost more to purchase, are more difficult to install, and require stronger support structures due to their higher wind loads. [1]

In terrestrial microwave technology, microwave signals are radiated through the atmosphere along a line-of-sight path between highly directional microwave frequency transmitting and receiving antennas. Use of microwave radio allows transmission in both directions simultaneously. [1]

To convey signals, microwave systems use both analog and digital transmission techniques. The analog systems typically use frequency modulation techniques to manipulate the available bandwidth into channels for multiple voice, data and/or video communications. Conversely, digital microwave systems require the use of other modulation techniques including Amplitude Key Shifting, Frequency Shift Keying, and Phase Shift Keying. [1] These techniques do not afford secure transmissions. [7]

Microwave-based “line-of-sight” systems rely on radio waves that travel in paths approximating a straight line. Because of this routing technique, microwave communications are limited by both the effects of the curvature of the earth and the local topography. Interference problems can be overcome to some extent through modification of antenna heights and relative positions. How much compensation can be applied to sources of interference depends on the nature of the interference. For example, as the length of microwave paths increases, the effects of fading also increase due to factors such as atmospheric conditions, ground reflections, and water reflections along the propagation path.

Table 9-19. Advantages and Disadvantages of Terrestrial Microwave Links. (1)

Advantages	Disadvantages
• Useful as a point-to-point trunk. • Can transmit data and a limited number of full motion video channels. • Can control groups of traffic control devices. • Can use both analog and digital transmission.	• Require line of sight path. • In most cases, require FCC license. • Channel availability limited. • May have little choice in operating frequency. • Possible interference due to rain, snow, and atmospheric conditions. • May require antenna tower. • Available bandwidth usually limited.

Rainfall, heavy fog, and other atmospheric factors can reduce the power of the signal below a usable level. This type of fading affects a wide band of frequencies and may last several hours. (7)

Other types of interference vary by season. For example, multipath fading occurs when there is no wind to break up the atmospheric layers. Such conditions are typical of early mornings and nights during the summer season. This type of fading is typically experienced over a limited frequency range and recurs frequently, but lasts only a few seconds. It can be reduced by either “frequency diversity” or “space diversity” techniques, depending on the severity of the problem. (7)

Several aspects of microwave communications should be considered during the design process. The fundamental concepts include the items summarized in table 9-20.

Spread Spectrum Radio

Spread spectrum radio systems operate by transmitting a signal bandwidth over a wide range of the frequency spectrum. To receive such a broadband transmission, the signal is compressed to the original frequency range at the receiver. The major advantages and disadvantages of spread spectrum radio are summarized in table 9-21.

The infrastructure equipment necessary to operate an unlicensed spread spectrum communication system is readily available. Local area traffic control uses will require equipment levels very similar to land-line systems. In contrast, vehicle-to-vehicle communications have no infrastructure requirements. Because of the low-power requirements and general availability of required system components, this communications medium is considered a low-cost technology. (6)

Spread spectrum radio relies on low-power transmitters to provide short-range communications by spreading a signal’s transmission spectrum, an application of code division multiplexing. Such systems operate by transmitting a signal bandwidth over a wide range of frequencies and then compressing the signal to the original frequency at the receiver. Each network in an area is operated using a different code,

Table 9-20. Microwave Communication System Design and Installation Considerations. (2,3)

Consideration	Design Factors/Options
System selection factors	• Spectral efficiency requirements. • Performance requirements. • Equipment complexity economics.
Transmission beam is narrowly focused	• Requires precise location of the transmitting and receiving devices. • Antenna towers must be rigid enough to withstand high winds without excessive antenna deflection.
Frequency availability	• FCC allocates a portion of the radio frequency bands of the electromagnetic spectrum for government and public service use. • Most civil government and industrial microwave radio systems operate in the 6, 11, 18, and 23 GHz bands. • Some bands require site licensing, others do not. • Bands above 6 GHz are the easiest to obtain and least costly, but are subject to power fading capabilities.
Repeater spacing	• Geography of a given radio route. • Terminal equipment technology. • Can use point-to-point communications in a daisy chain fashion; path availability and network geometry must be carefully considered. • Transmitter power permitted by the FCC. • Typical repeater spacings in the 6 GHz spectrum are 32 to 40 km (20 to 25 mi), and 1.6 to 4.8 km (1 to 3 mi) in the 23 GHz spectrum; longer spacings are possible when the effects of fading are expected to be minimal.

thereby permitting different networks in the same area to use the same frequency band. [6]

Pseudorandom noise direct sequences (PN) and frequency hopping techniques (FH) are used to provide the necessary expansion of the signal. [6] The PN spreading technique relies on a wide baseband signal to modulate the original baseband signal while the wideband signal's amplitude is continually changed between two states. In contrast, the FH technique uses very short transmissions carried on different frequencies ranging in number from a few hundred to the thousands. [1]

Spread spectrum technology was originally developed by the military to resist enemy radio interception and jamming during World War II. Spread spectrum broadcast techniques allow receivers to decode spread spectrum signals even if background noise levels exceed the signal level and they can resist the effects of multipath interference.

Table 9-21. Advantages and Disadvantages of Spread Spectrum Radio. [1]

Advantages	Disadvantages
• Very flexible installation. • Does not require cable installation and maintenance. • Does not require FCC channel use approval in 902-928 MHz band. • Works extremely well in a high-noise environment. • Currently in use for many industrial process control applications. • Uses low transmitter power. • Can be used in a mixed system of wired or radio interconnected controllers. • No land-line interconnect required. • Relatively low equipment cost. • Potential for broad range of traffic control system applications.	• New technology for traffic control and surveillance applications. • Uncertain range 0.48 to 9.7 km (0.3 to 6 mi); function of area topography. • Higher bandwidth than radio fixed frequency transceivers. • Requires external antenna and cable. • Requires more sophisticated equipment and specialized technicians. • Unprotected channel space.

This technology is considered to have a security advantage over similar wireless transmission techniques; intentional interference with spread spectrum communications is extremely difficult unless the transmission technique is known. [6]

Severe electrical storms have the potential to cause sporadic interference, but the effects are generally short-term. [6] Line-of-sight obstructions can affect transmissions, though obstacles in the 902-928 MHz band generally can be avoided through bending. Though spread spectrum radio itself is noise resistant, it can cause significant interference with other communications systems using the same broadcast frequencies. [1]

Spread spectrum radio currently permits digital communications between equipment in the 200 to 300 Kbps range. This allows uses including communications between a field master and local controllers in closed loop systems, communications between field points and field controllers, and transmission of low-end compressed video. [1] Vehicle-to-vehicle communications can also be supported with this technology. [6]

Fundamental design and installation considerations that should be kept in mind when using Spread Spectrum Radio communications have been summarized in table 9-22.

Cellular Radio

Cellular radio is a new data transmission medium that has grown rapidly since its introduction in 1983. The Federal Communications Commission has designated 666 channels in the 800 MHz band for cellular service purposes. Cellular communication systems are small radio sectors, or “cells” that provide

Table 9-22. Spread Spectrum Radio Design and Installation Considerations. [1,6]

Consideration	Design Factors/Options
System selection and implementation factors	• Maximum peak output power. • Maximum effective radiated power. • Maximum antenna height. • Minimum processing gain. • Favor line-of-sight alignments.
Frequency availability	• Must ensure compliance with FCC regulations. • Potential interference with/from other licensed services.
Operating range	• Varies by application but typically ranges from 0.8 km (0.5 mi) to several kilometers. • Generally used for short-range communications with multiple users. • Repeaters may be required.
Potential for expansion	• Number of users in code division multiplexing systems can be increased by increasing the code length. • Limitations to number of users based on noise levels at receiver. • In FH systems, increasing bandwidth will increase system capacity.

communications coverage in a series of small, slightly overlapping areas. [7] The cells are sized to reflect the density of users in a given area, and typically cover between 0.8 and 8 km (0.5 to 5 mi) each. [6] An antenna is placed in each cell so that, within a given system of cells, antennas relay signals through the system via a series of communications with their closest counterparts. The frequencies used for transmission in one set of cells can be reused in another set of cells by keeping the two signals far enough apart to avoid interference. [7]

With mobile cellular units, the mobile unit establishes a communications link with the closest antenna, and commences communications through that link. The cellular service provider then monitors the strength of the signal link via a mobile telephone switching office (MTSO). The original link antenna will typically be used until the signal power diminishes due to increasing distance and/or interference between the mobile unit and the antenna.

Once the MTSO determines that the signal power has diminished to an established level, the link will shift to the next closest antenna, if that level can better support the link. The communications link then transfers to the antenna closest to the mobile unit. This process of transferring and switching frequency assignments typically requires only milliseconds to complete and often remains undetected during voice communications. [7] In some instances, this transfer process may result in a "click" that users can hear. In other instances, the system may drop a call if no other antennas are available to support the link.

The advantages and disadvantages of cellular radio are summarized in table 9-23.

The cost for cellular "airtime" varies widely, depending on the provider's service plan and the area of concern. Additional variability in operating costs arises in transmitting data by cellular means and is dependent on the type of modem used. (1) Cellular service can be expensive, depending on usage. Basic service charges apply no matter whether a cellular telephone user originates a call or receives an incoming call. The specification of additional service features beyond the basic operating programs will result in additional fees being assessed.

The costs associated with the use of cellular technology for communications between permanent installations is much higher than those of other communications media. However, it should be noted that cellular radio technology can significantly improve the efficiency of personnel who spend substantial periods traveling in vehicles, and it can be the most cost-effective alternative for temporary communication purposes. (7)

Early cellular communications were handled through analog technology. Currently, conversion programs are underway to transfer operations to digital operating systems to achieve enhanced system quality and capacity. Additional details are offered in reference 8.

In general, noise and interference levels associated with cellular communications typically increase as the distance between the communications source and the nearest receiving tower increase. One major shortfall of cellular technology rests in the fact that it was not originally designed to support data transfer. The switching process historically has caused interruptions that require retransmission of the entire message. Problems with data transmission become especially apparent when operating in the overlap area between two cells. Within this area of overlap, cellular communications may begin "hopping" between the frequencies of the two cells, potentially resulting in data link severance. (8) Consequently, cellular providers often suggest that cellular users do not transmit data via cellular networks while they are in motion. (6) Voice communications are less affected by this form of interference; the audible effects often remain unnoticed. Noise and interference can be reduced through selection of appropriate modems and the use of digital transmission technology. An in-depth analysis of the cellular technologies available is contained in reference 8.

Cellular technology is not currently appropriate for continuous communication service, due to the service costs involved; however, applications that require communications at infrequent intervals or to some remote locations may prove ideal for cellular use. Areas that do not have owned land-line service, those where provision of land-line service is cost prohibitive, and locations of temporary installations may be candidates for communications systems that use cellular technology. (1) Potential traffic control applications include the following: (6)

- Communications with hazardous-materials teams.
- Control of remote equipment.
- Communications with traffic signal/ ramp meter repair crews.

Table 9-23. Advantages and Disadvantages of Cellular Radio. (1)

Advantages	Disadvantages
• May prove cost effective for infrequent communications. • Eliminates need to connect to a telephone company service point or provide owned land-line. • Effective for controlling portable variable message signs. • May prove effective for temporary installations. • Network covers 93% of U.S. population.	• "Airtime" cost excessive for continuous communication service. • Actual data throughput reduced due to protocol overhead. • Remote areas may not have service.

- Communications with motorist call boxes.
- Transmission of dispatch data.
- Control of portable variable message signs/highway advisory radio units.
- Communications with management and other staff members.

During the design and installation process, consideration should be given to the following attributes associated with cellular telephone technologies:

- Local service concerns such as coverage and cost.
- Available data transmission options.
- Compatibility with other equipment (especially important for data transfer).
- Security implications of this communications medium.

A recent report noted that some features of cellular technology as used in portable CMS and HAR applications can be exploited. To prevent the exploitation of portable cellular units, call-back diagnostic features that require the cellular phone on field units to be continuously transmitting should not be used. Continuous monitoring of the telephone bill for each unit (often automatically done by cellular phone companies) is strongly recommended. Further details are offered in reference 9.

Packet Radio

Packet radio services were designed for the transmission of data via wireless means. The distinction between packet radio and the evolving cellular packet data technology is becoming increasingly blurred, except that packet radio does not support voice communications. Table 9-24 summarizes the advantages and disadvantages of packet radio service.

Packet radio operates in the 800 and 900 MHz bands and relies on a system of base stations placed between user terminals to

Table 9-24. Advantages and Disadvantages of Packet Radio Service. [1]

Advantages	Disadvantages
• Designed for data transmission. • Cost effective for short messages. • Can eliminate need for leased or owned land-line. • At least two major providers.	• Not cost effective for continuous communications. • Not cost effective for lengthy file transfers. • Service currently limited to major cities. • Time delay in delivering packet.

convey communications from origin to destination. Radio base stations are positioned on towers or other large structures so that they provide coverage areas of 16 to 32 km (10 to 20 mi). The base stations are connected to backbone communications networks through which they can direct packets of information over one or more frequency pairs. [1]

This technology permits remote terminals to use the same frequency pair for transmitting and receiving data. Multiple access protocol algorithms are employed to reduce the probability of collisions between transmissions from remote terminals. [1]

Packet radio technology is expensive and is not cost effective for file transfers or continuous communication purposes. Specific costs will depend on the service provider and will likely include an initial subscription fee, monthly service fees, and modem and terminal charges. [1]

Noise and interference levels will vary depending on the access protocol used and the provider's quality of service. The packet radio system itself monitors noise and/or interference problems. For example, the ALOHA algorithm transmits data and then waits for the destination base station to confirm that it has received the signal. If the transmission is not acknowledged, the signal transmission is repeated and confirmation is again sought. [1]

The destination of communications can also affect performance issues. Some packet radio service providers offer service adequate for mobile purposes, while their service inside buildings has been characterized as inferior. [8]

The best source of design and installation considerations can be found in project specifications and information available through local packet radio providers. At a minimum, the following factors should be considered in evaluating the feasibility of using packet radio in a freeway management application: [1]

- Number of channels available.
- Channel width.
- Radio frequency protocol.
- Coverage area.
- Raw data transfer rates.
- Modem and terminal requirements.

Satellite Transmission

Satellite communications make use of space-based equipment to relay signals transmitted from earth. Unlike other means of communication, because of the relay equipment's location in space, satellite transmission technology is less dependent on the relative location of transmitters and receivers. [7] Table 9-25 summarizes the basic advantages and disadvantages of satellite communications.

The cost of making frequent satellite transmissions is generally considered excessive in comparison with that of other technologies. As with the other technologies examined, advances in the satellite industry will continue to enhance the economics of communications via satellite transmission. [1]

Satellites in orbit are used to convey signals between earth stations. To transmit a signal, an earth station first receives the data from its source (such as a telephone network) and converts it to a form suitable for radio-frequency transmission. The signal is then amplified to power levels of between one watt and several kilowatts, and is sent to an antenna where it is directed toward the satellite. After being received by the satellite, this signal is then shifted to a down-link frequency band, amplified, and reradiated toward earth. Antennas at various earth stations within the intended coverage area can then receive the transmission from the satellite and, after converting the signal to a usable form, transfer it to other communication media for distribution. [7]

Table 9-25. Advantages and Disadvantages of Satellite Communications. [1,7]

Advantages	Disadvantages
• Cost of circuits independent of their length. • Cost effective for long-haul circuits. • Downlink signals can be received over a wide area. • Cost effective for point-to-multipoint distribution applications (e.g., cable TV). • Uplink signals can originate over a wide area. • Flexibility for "quick setup" or mobile applications. • Provides option to links that cannot be achieved by earth-based communication media.	• Not proven cost effective for local communications. • Limited number of service providers. • Channel leasing costs subject to increases. • Most transportation agencies have no need for the frequent long distance transmission capabilities of satellite technology.

Satellites receive signals transmitted from earth (up-link) on frequencies in one band and then retransmit them back to earth (down-link) on frequencies in a different band. Currently, the C band (5.925-6.425 GHz uplink and 3.7004.200 GHz downlink), and the Ku band (14.0-14.5 GHz uplink and 11.7-12.2 GHz downlink) are designated for use by the FCC. (1)

Satellite access is dominated by two types of networks: preassigned access and demand assigned access. Preassigned access networks, which are best suited to heavy volume trunk service, assign fixed subsets of telephone channels to various destination points. This type of hierarchy is desirable if large subsets are used and load variations among destinations are small. In contrast, demand assigned access is more appropriate for use in communication systems where the demand volumes are lower. This approach makes uses of a pooled collection of channels assigned and used on an as needed basis. (7)

Satellite systems are generally considered to support all-weather operations; however, very severe weather may affect earth-based equipment and interfere with operations. Potential interference problems also exist between some mobile satellite systems and use of the Global Positioning System, and should be investigated for a given application. (6)

Long-haul trucking companies are currently using mobile satellite technology for dispatching purposes. Using inexpensive transmission and reception equipment, messages can be relayed between individual trucks and their dispatching centers, and the truck's location can be monitored. Such technology can also be used for dispatching transportation maintenance crews and emergency equipment from freeway management centers. Unfortunately, these technologies are still being refined and their usefulness in metropolitan areas has been limited due to interference from buildings, trees, and power lines. (7)

Several aspects of satellite communications should be considered during the design process. Table 9-26 illustrates some fundamental concepts that should be considered.

9.4 LESSONS LEARNED

DESIGN PRINCIPLES

Four fundamental principles that should be followed in the design of a communications system for freeway management applications include the following:

1. **Design for "Understandability" —** The communications system should be designed so that its functions, specifications, and processes are easily understood by those who will be responsible for operating and maintaining the system. The underlying principle for achieving understandability is to "Keep It Simple." Simpler designs are easier to operate and maintain. Another general rule-of-thumb is to stay in the mainstream of communications design and not pioneer anything unless it is clearly on the horizon for common communications carriers.

2. **Design for Redundancy —** Many operational problems experienced by existing freeway management systems are caused by communication failures. Designing a communications system where individual field devices or communication hubs can be reached even when a link has been disrupted can help maintain system performance and credibility. Redundancy can be provided

Table 9-26. Satellite Communication System Design and Installation Considerations. [1,7]

Consideration	Design Factors/Options
System selection and implementation factors including data rate and type of satellite	• Long distance communications more cost effective than short distance • High data rates demand strong signal levels at satellite. Requires either: - Low earth orbits; - Higher antenna gain at satellite; or - Higher radiated power transmission level from earth. • Low earth orbits require more satellites to cover a given area continuously • Geosynchronous satellites have lower data transmission rates • Geosynchronous orbits have potential access problems due to local geography • Short transmissions efficiency can be enhanced by using data networks that are better suited than standard gateway connections
Operating frequency	• Availability of desired frequencies • Frequency characteristics vary with propagation effects and equipment performance • FCC regulations govern
Potential for expansion	• Can be achieved by adding satellites • Feeder link traffic limited by FCC transmitter power restrictions

in a system by using dual ring and self-healing types of system architectures. Examples of functional specifications that can improve the reliability of the communication system include the following:

- Provide a redundant communication backbone.
- Limit the number of controllers on one communication channel.
- Provide adequate power margins to account for component degradation without adversely affecting the performance of the system.
- Provide adequate environmental controls (i.e., ventilation, heating, humidity control, pest control, etc.) in field cabinets.
- Provide adequate lightning protection.
- Provide adequate power surge protection.

3. **Design for Maintainability** — An agency can take several steps during the initial planning and design of a communication system that will enhance an agency's ability to maintain the system, including the following:

   - Critically assess the agency's capability to provide timely maintenance of communication equipment and lines. Either a less complex technology or leased communication channels may be preferred if adequate support cannot be provided.
   - Establish a maintenance plan well ahead of the installation of the system. In preparing construction bidding documents for installing the system, specify the type and level of

training that will be provided to the personnel responsible for maintaining the communications system. The training should be specified to occur during the installation of the system.

- Ensure that adequate documentation on the design and operations of the communication system is provided. The documentation should include all communication line connection and controller and field device channel communication assignments.

- Obtain the appropriate quantity and type of communication testing equipment.

- Establish a mechanism to coordinate the use of the right-of-way by utility companies so that construction and maintenance activities do not present a threat to the communication cable and conduit.

4. **Design for Expandability** — Ability to expand the system to meet future growth is a critical feature that can only be incorporated at the initial design phase. Several items that system planners and designers can use to ensure expandability include the following:

   - Use standard design, equipment, and protocols (such as NTCIP).

   - Provide spare communications channel capacity.

OWNED VERSUS LEASED COMMUNICATIONS

Using a leased communications network is an alternative to owning the infrastructure of a communications system. Several forms of leased communications systems are commonly used in freeway management systems, including services available through Local Exchange Carriers (LEC's), cable TV providers, and metropolitan area network providers. [(1)] Leased telephone services fall into three categories: terminal equipment, switching equipment, and transmission facilities. These categories encompass such leased services as office communications service, analog and digital point-to-point services, foreign exchange service, wide area network service, broadband video transmission service, switched digital data service, and channel bank termination service within central offices. [(7)] Several aspects of leased operations should be considered when evaluating their potential use.

Usually, the transmission characteristics and performance of telephone company channels are equivalent to those of a twisted-pair cable network. Because the lessor is paying for a dedicated communications system, they do not have to be concerned with the engineering aspects of the facility. For example, the distance of the transmission line, amplification needs, and other issues should all meet preestablished specifications and tolerances, thereby releasing the lessor of responsibility to maintain the required infrastructure. [(7)] Table 9-27 compares user-owned and leased wire-pair cable. These findings can be easily extrapolated to other means of communication.

The use of leased telephone company channels is most appropriate in areas where a high volume of voice or data communication is required between separate facilities. They may be used in areas where it is not cost-effective to locate other forms of communication technologies (due to physical or political constraints), or in temporary applications. [(7)]

Leased services may also encompass the use of coaxial cable communication systems through cooperation with community

Table 9-27. Comparison of User-Owned and Leased Wire-pair Cable.

Feature	User-Owned	Leased
Capital Cost	High - especially when installed underground in new conduit.	Reasonable - involves connection from access points to cabinets and from central facility to manhole(s) or other cable access.
Ongoing (Maintenance) Cost	Reasonable - owner has full maintenance responsibility.	High - lease costs almost always tied to general service rate increases. Agency must maintain connection described above.
Response to Maintenance Requirements	May be better or worse than leased line service depending on jurisdiction's capability.	In some cases can be specified.
Maintenance Responsibility	Always borne by the owner.	Sometimes difficult to determine whether problems are the responsibility of the lessor or lessee.
Control of Communication Network	Excellent - owner is user and can fully control.	Less control - communication traffic requirements and limitations on leased channel may impede use.
Design of Communication Network	Completely flexible since designer/owner starts from scratch.	Constrained by telephone company cable network. In most cases it is generally compatible with signal system requirements.
System Expansion	Cost determined by location of expansion.	Accessibility to expansion site usually available.
Reliability	Excellent - with proper maintenance procedures.	Good to poor - depends upon lease contract terms and level of owner's maintenance function.

antenna television (CATV) providers. Franchise agreements sometimes require CATV suppliers to provide such services. [2] Several features of CATV result in both advantages and disadvantages, as summarized in table 9-28.

After deciding on the requirements of the leased system, various configurations can be explored to evaluate system cost. Typical cost evaluations will include providers' fees and charges, costs associated with constructing any connections between the provider's termination point and the lessor's equipment, and any special hardware costs

Table 9-28. Advantages and Disadvantages of CATV.

Advantages	Disadvantages
• Single 6 MHz channel adequate for data transmission. • Network already in place. • Design efforts and initial installation cost much lower than a dedicated coax system. • Franchise agreement may provide for government use of CATV cable and bandwidth at reduced rates or free, reducing recurring costs. • Second separate coax institutional network (I-net) may exist for the express purpose of providing bi-directional services to commercial subscribers. • I-nets generally provide good levels of service to subscribers.	• Most CATV networks designed and installed with emphasis on downstream transmission of video signals to cable subscribers. • Video channels take up most available bandwidth. • Bandwidth available to traffic control may be very narrow, ranging from a single 6 MHz channel to 4 or 5 channels. • Single 6 MHz channel does not support full motion video transmission in addition to data communications. • Frequencies of available channels often least desirable in susceptibility to noise and interference. • Quality of video signal required for CATV considerably less than required for data. • CATV subscribers sometimes concentrated in residential areas. • Service to CBD and industrial areas sparse or nonexistent. • Area of coverage and network layout may not coincide with control equipment locations. • Traffic control system may have to compete with other public I-net users for more desirable channels.

required for interfacing with the provider's equipment. (1)

To illustrate the items that must be evaluated, consider leased telephone lines. These lines typically have a low initial installation cost as compared to an owned network of similar size, especially if underground installation is required. However, the monthly lease cost may be much higher than the recurring costs of an owned network. Furthermore, because telephone company rates and charges are established by tariff and are subject to approval by State regulatory agencies, future costs cannot be guaranteed by the telephone company.

The leasing tariffs and the method by which they are calculated vary from State to State. Some tariffs are based on the "drop-to-central office mileage" (the distance from one drop [traffic signal controllers, a ramp meter, etc.] to the telephone company central office). Other tariffs use "drop-to-central office fixed," in which a fixed charge per drop is assessed, whatever the distance. Additional charges are usually assessed when communications between central offices are required in the path from field to central equipment. These charges may be the most significant element of the total cost. Alternatives to leasing communication lines for great distances through multiple central offices should be explored. (3)

The transmission technique in use depends on the communication medium that is being leased. Local telephone companies (often called local exchange carriers, or LECs) offer both voice grade service and digital private line data services. Such systems support communications between control centers and field devices or maintenance shops through synchronous transmission speeds of 2.4, 4.8, 9.6, or 56 Kbps. LECs also provide coded video transmission capabilities via higher capacity digital transmission channels such as T1. (2) Most digital transmission facilities provided by telephone companies are based on the use of digitized voice channels. These providers typically do not use the same conversion process as modems to transform voice information to digital transmissions. Reference 2 provides additional details concerning this subject. Other communications vendors offer leased transmission techniques including high capacity DS1 and DS3 circuits, voice grade, digital data service, and fractional T1 circuits. (2)

In certain circumstances, leasing fiber optic networks should also be considered. Leasing of fiber optic technology would be most appropriate for traffic control applications that require high-capacity links.(2)

Interference encountered in leased systems varies depending on the communications medium used and the service provider. Specifications should be made in the lease contract about how much noise and interference are permissible.

The limit of the potential traffic control applications for leased technologies is dependent on the technology that is being used. Leased twisted-pair telephone lines are frequently used for traffic surveillance and control system applications such as the interconnection between a central computer and remote field equipment (e.g., traffic signal controllers, variable-message signs, freeway ramp meters, traffic counting equipment, etc.). (7) Other potential applications information can be found listed under each of the technology sections presented in this module.

Leased communications require agreement on a contract between the lessor and the service provider. The development and use of a leased communication system require close cooperation with the service provider at all levels of personnel including engineering, sales, and data transmission representatives. (7) At a minimum, the concerns summarized in table 9-29 should be addressed.

NTCIP

The National Transportation Communications for ITS Protocol (NTCIP) is a standard communication protocol for transmitting data and messages between electronic devices used in ITS, freeway management systems, and arterial traffic control systems. It uses the OSI (Open

Table 9-29. Leased Communications Service Design and Installation Considerations.

Consideration	Design Factors/Options
Desired system features	• Data characteristics including desired transfer rates and bandwidth required. • Acceptable level of noise and interference. • Operational aspects of the system (e.g., once-per-second/dial-up communications, full/half duplex, etc.). • Number of field drops and their locations (e.g., controller/ ramp meter cabinets).
Characteristics of the leased channels and equipment restrictions	• Type and number of channels to be provided (insure both up and downstream channels are provided for CATV applications). • Data transfer rates. • Transmission characteristics and quality. • Frequency allocations. • Any system limitations.
Availability of service	• Time required to initiate service. • Facilities the provider will use to supply service to field locations. • Future expansion capability. • Location of the nearest access point to the provider’s transmission line from each of the lessor’s field locations.
Understanding of contract requirements	• Rules regarding leased circuit terminations at the central facility, including any equipment which the jurisdiction must furnish. • Division of work between the provider and user in connecting to field locations (i.e., is complete service connection provided or will lessor need to make connections to the provider’s equipment). • Respective maintenance responsibilities of the provider and the jurisdiction. • Maintenance response priorities. • Testing criteria and requirements prior to acceptance. • Rates and charges; both one-time charges and monthly fees. • Pending rate increase requests, if any, and an estimate of expected increases in leasing rates. • Expiration/renewal terms.

Systems Interconnection) Reference Model for providing communications links between devices. [10,11] The OSI Reference Model is based on a concept developed by the International Standards Organization (ISO). The model is called the ISO OSI Reference Model because it deals with connecting systems that are “open” for communications with other systems. The OSI model consists of seven hierarchical layers. Each layer performs a related subset of the functions required to talk with another system. Each layer relies on the next lower layer to perform other functions and to conceal the details of those functions. It in turn provides "services" to the next higher layer. These layers are defined in such a manner so that changes in one layer do not require changes in the other layer. Table 9-30 identifies each layer and gives a brief description of the functions associated with each layer.

NTCIP is a common set of codes, procedures, and relative timing relationships (i.e., communications protocols) that follow the OSI model to allow different types of field devices to communicate with one another without the need of a physical conversion box or reliance on a single vendor to supply all the equipment in the system. [11,12] Rather than defining a unique format for each combination of data items that need to be communicated, the NTCIP defines a structure that uses a modular approach for delivering generalized messages. By defining a series of message pieces that can be collected into groups of data items, system software designers can create virtually any useful message structure without requiring new programming in the field device. NTCIP promotes two important features that could not previously be provided in traffic control systems:

- *Interoperability* — the ability to connect devices of different types to the same communications medium.
- *Interchangeability*—the ability to exchange devices of the same type, but from different vendors, without any lossof functionality or modification to the rest of the system.

To date, four profiles have been developed for different traffic management applications.[10,12] A profile defines the standard communication protocols that are appropriate for the different types of traffic management applications. The Class A profile allows messages to be routed from one device to the next. The Class B profile allows devices to talk with one another over a low speed, low capacity communications system where routing is not required. Class B can be used where legacy communications exist, typically twisted-pair copper wire. The Class C profile supports file transfer and sequencing and routing, while the Class E profile provides routing, sequencing and file transfer capabilities over a point-to-point communications link.

Table 9-31 shows the specifications applicable in each layer of the OSI for the different classes. Additional NTCIP profiles will be developed to satisfy various system architectures and communications media as the need arises.

Besides defining how communications between devices will occur, the NTCIP also defines what information is contained in a data stream (i.e., object definitions). The NTCIP uses a hierarchical method of addressing where data elements are stored in a database, similar to that used widely on the Internet. [12] The hierarchical method allows data to be grouped into logically related data elements. Each of these logical groupings can be expanded over time as new elements are added to the group, without running out of addresses in the group or limiting other groups to fewer addresses. Currently, object definitions have been developed for traffic signals, but object definitions for other traffic management elements (i.e., variable message signs, CCTV camera controls, ramp meters, vehicle detection/count stations, highway advisory radio, etc.) are under development.[13]

More information about NTCIP can be obtained through the Internet at http://www-atms.volpe.dot.gov/ntcip/.

Table 9-30. Layers of Open Systems Interconnection Reference Model. [10]

OSI Layer	Description
Layer 7: Application	Defines procedures for file transfers, access methods, and management of messages.
Layer 6: Presentation	Defines the syntax and semantics of transmitted information. It provides services such as encryption, text compression, and reformatting.
Layer 5: Session	Defines the procedure for different communications equipment to establish dialogues. Provides the control structure for communication between applications. It establishes, manages, and terminates connections (sessions) between cooperating applications.
Layer 4: Transport	Defines the organization of data passing to and from the lower layers. Involves breaking longer messages into packets for transmission.
Layer 3: Network	Defines how packets of data are routed from source to destination. Provides upper layers with independence from the data transmission and switching technologies used to connect systems. It is responsible for establishing, maintaining, and terminating connections.
Layer 2: Data Link	Defines methods for ensuring data integrity such as error correction. It sends blocks of data (frames) with the necessary synchronization, error control, and flow control.
Layer 1: Physical	Defines the mechanical, electrical, and procedural characteristics used to establish, maintain, and deactivate the physical link.

SHARED RESOURCE PROJECTS

The need for increased communications capabilities has led many agencies to consider shared resource projects. Shared resource projects refer to those projects where the private sector would use public highway rights-of-way, previously viewed as entirely within the public domain, to install telecommunications hardware (principally fiber-optic lines, but also including cellular towers). In return, the private sector would “compensate” the public sector, either through barter or cash. In barter or in-kind arrangements, private parties install the communications system. In return for providing telecommunications capacity and/or services to the public agency, they receive access to the right-of-way for installing their own capacity. In cash arrangements, private parties install the telecommunications system, receiving access to the right-of-way in return for monetary compensation to the public agency. Hybrids of the barter and cash alternatives can also be created in which in-kind (communications capacity) and monetary compensations are combined as consideration for private access to right-of-way for private sector use. [14]

At the outset, potential shared resource partners must address the threshold legal and

Table 9-31. Specified Protocols for NTCIP Profile Classes. [10]

OSI Layer	Profiles			
	Class A	**Class B**	**Class C**	**Class E**
Application	STMF	STMF	Telnet FTP SNMP	Telnet FTP SNMP
Presentation	Null	Null	Null	Null
Session	Null	Null	Null	Null
Transport	UDP	Null	TCP	TCP
Network	IP	Null	IP	IP
Data Link	PMPP	PMPP	PMPP	PPP
Physical	EIA 232E FSK	EIA 232E FSK	EIA 232E FSK	EIA 232E FSK

STMF = Simple Transportation Management Framework
SNMP = Simple Network Management Protocol
FTP = File Transfer Protocol
UDP = User Datagram Protocol
TCP = Transmission Control Protocol
IP = Internet Protocol
PP = Point-to-Point Protocol
PMPP = Point-to-Multipoint Protocol
EIA 232E = standard modem interface
FSK = Frequency shift keying

political issues that, if unresolved, can preclude shared resource arrangements. Some of these issues are summarized in table 9-32. In some situations, new statutes or regulations will be required to permit private sector access to right-of-way or to conduits in the right-of-way. In other cases, careful contractual arrangements can ensure effective private sector longitudinal access without violating legal or regulatory constraints; for example, using leasing rather than easements to convey rights. [14]

Most other issues can be addressed without resorting to legislative or regulatory changes. For example, the issue of bond tax exemption can probably be addressed through attention to the ways that bond issues are structured and bond proceeds are used. In some cases, the number of options available is limited by regulation, resulting in little (or even no) choice but to pursue legislative changes (e.g., where cash compensation is precluded by statute). Even under these circumstances, shared resource projects can be effective without legislative initiatives so long as the potential partners are willing to accept an option that is within currently accepted boundaries. [14]

Often, the choice made among ways of addressing these issues is based on preferences and an evaluation of the pros and cons of each option. The choices between exclusivity and multiple partners, allocation of infrastructure relocation and liability for repairs, and selection of barter over cash compensation are often based on preference rather than necessity. [14]

Table 9-32. Issues Associated with Shared Resource Project Development. (14)

THRESHOLD LEGAL AND POLITICAL ISSUES	
Public sector authority to receive and/or earmark compensation	The public sector may be precluded from receiving cash payments, but may still be free to engage in barter arrangements, particularly if they are structured as procurements. In general, state departments of transportation (DOTs) have less flexibility; municipalities and authorities such as turnpike and transit agencies have greater flexibility in dealing with cash flows.
Authority to use public right-of-way for telecommunications	Shared resource arrangements may be precluded if state law mandates free access for utilities or if pubic agencies are not allowed to discriminate among utilities (e.g., permit access for telecommunications but disallow access for gas and sewerage).
Authority to participate in public-private partnerships	Because shared resource arrangements are a form of public-private partnering, legal authority to enter into such agreements is a basic requirement. In some cases, "implied authority" is not considered sufficient and specific legislation or "express authority" must be passed.
Political opposition from private sector competitors	Shared resource arrangements may trigger political opposition, though not necessarily prohibition, from private sector companies resisting the establishment of bypass networks that they perceive as competing with the services they offer. Opposition may be slight when the bypass system is limited to transportation needs, but it is likely to be stronger if the system supplies a greater range of public sector communications needs.
Inter-agency and political coordination	In addition to investing effort in coordination among agencies in the same political jurisdiction, the lead pubic agency may also have to orchestrate agreements between geographically proximate political jurisdictions to ensure continuity for fiber for their private partner(s).
Lack of private sector interest in shared resources	At its core, shared resource arrangements depend on private sector interest in expanding telecommunications infrastructure. Reluctance to enter into partnerships with pubic agencies for access to right-of-way may stem from insufficient market demand for increased communications capacity, cost factors such as more stringent installation specifications along roadway right-of-way, and administration or managerial burden of compliance.
FINANCIAL ISSUES	
Valuation of public resources	Before entering into shared resource agreements, the public sector needs to have some idea of the value of the assets it brings to the partnership; that is, continuous or sporadic access to its right-of-way for placement of private (communications) infrastructure.
Tax implications of shared resource projects	Partnerships between public and private entities may pose unique tax issues, particularly bond eligibility for tax-exempt status when proceeds may benefit profit-making private organizations.
Valuation of private resources	Valuation of the private resources provided in barter arrangements helps the public sector determine whether it is receiving a fair market "price" for its resource.
Public sector support costs	Although shared resource arrangements provide cash revenue or telecommunications infrastructure without public sector cash outlays, such compensation is not without cost since the pubic sector must use agency labor hours for administration, coordination, and oversight.
PROJECT STRUCTURE ISSUES	
Exclusivity	Shared resource arrangements may limit access to pubic right-of-way to a single private sector partner in any specific segment, that is, grant exclusivity. From the public sector point of view, exclusive arrangements have both advantages (administrative ease) and disadvantages (potential constraints of competition among service providers, lower total compensation received by the public sector).
Form of real property right	Shared resource arrangements can be structured in any of several legal formats (easement, lease, franchise, license) with variations in the property rights conveyed. Moreover, the property right may involve access to the right-of-way itself for privately owned infrastructure, or be limited to access to (or use of) publicly owned infrastructure.
Type of compensation	Compensation to the public sector may be in the form of goods (in-kind), cash, or combinations of both. Moreover, in-kind compensation can include not only basic fiber-optic cable but also equipment to "light"* fiber, maintenance, and even operation and upgrading.
Geographic scope	Projects can be extensive in scope, covering long segments of roadway, or more focused on specific areas. The option that is best in any individual context depends on other factors, such as considerations of administrative burden, service interests of potential bidders, and private willingness to install infrastructure in an area larger than their primary area of interest.

*"Light" fiber refers to fiber optics supported by equipment for transmission and receipt of communications signals; "dark" fiber refers to physical fibers devoid of supporting telecommunications equipment.

Table 9-32. Issues Associated with Shared Resource Project Development (Cont'd). [14]

CONTRACT ISSUES	
Relocation	Allocation of responsibility for infrastructure relocation in case of roadway improvements affects private partner willingness to pay for right-of-way insofar as it carries a financial responsibility as well.
Liability	Similarly, allocation of legal liability among partners affects the financial risks assumed by each one. Liability includes responsibility for system repair, consequential damages (economic repercussions), and tort actions.
Procurement issues	Shared resource arrangements face many of the same issues as other procurements regarding selection and screening of private vendors or partners.
System modification	Shared resource arrangements may or may not include explicit provisions for system modification; that is, technological upgrading to keep abreast of technical improvements and expansion of capacity to meet subsequent needs.
Intellectual property	Intellectual property involves intangible components (e.g., software programs) of the operating system that might not be available to the public sector partner when the partnership is dissolved after the lease period unless specifically addressed in the contract.
Social-political issues	Social-political issues involve equity among political jurisdictions or population segments within the right-of-way owner's domain. More specifically, two issues may affect how shared resource arrangements are structured: most-favored community issues — comparable compensation for all communities engaging in shared resource arrangements, and geographic and social equity — equitable access to and benefit from shared resource arrangements.

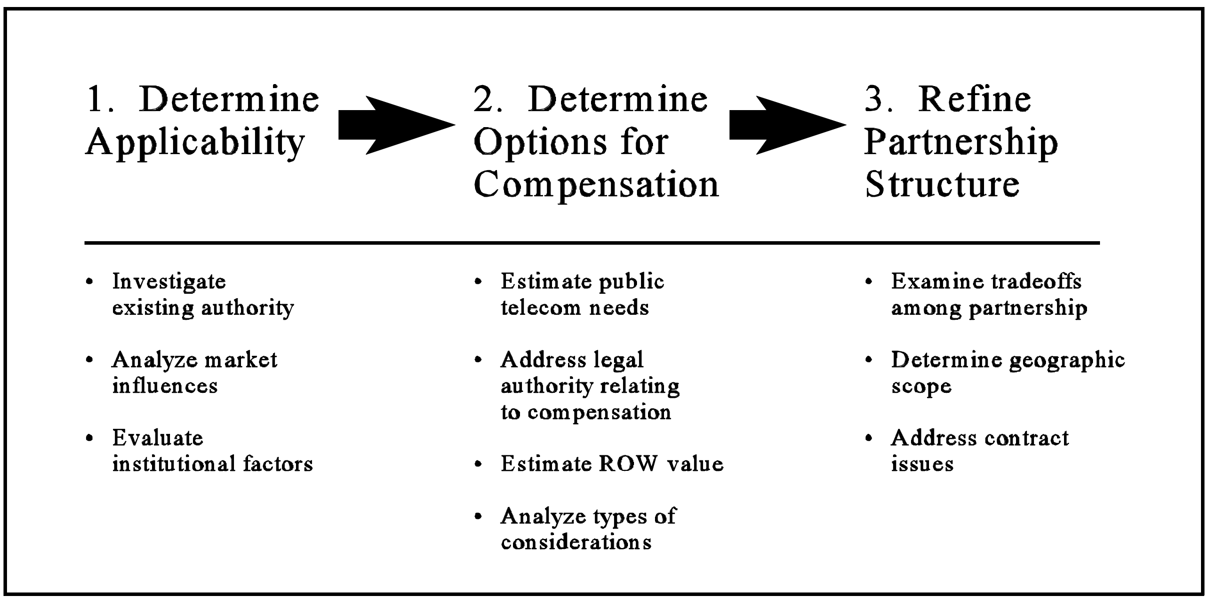

Figure 9-13. Key Decisions and Supporting Information in Evaluating the Need for a Shared Resource Project. [14]

Although shared resource projects have been heralded as an innovative approach to satisfying public sector needs, they are only one of several ways to provide for these communications needs. They are hardly the universal solution. Before initiating a shared resource project, public agencies must evaluate their telecommunications needs (including private sector-supplied services), and then evaluate the appropriateness of each alternative in light of specified needs. Figure 9-13 graphically summarizes the basic stages in developing a shared resource project. [14]

In addition, the public sector needs to realize that shared resource partnering is market-driven. Because it is market-driven, an upper limit exists to how much compensation will be paid. Furthermore, private agencies will not wait extended periods for access rights to a public agency's right-of-way. Therefore, public agencies must be ready to act when the opportunities present themselves.

The highway right-of-way has no "inherent" value. Concerning telecommunications access, value is derived from the potential revenue telecommunications companies can gain by using the right-of-way as tempered by the cost of other rights-of-way that might be available at that time.[14]

Similarly, market conditions dictate response time for prospective partnering. As market forces and technology change, demand for access to highway rights-of-way may also change. In fact, timing can be a critical factor in the choice among options in structuring a shared resource project. Because the window of opportunity is often narrow and because private sector partners can have access to non-highway right-of-way for infrastructure, public agencies interested in effecting shared resource partnerships must address the associated issues in a timely fashion; otherwise, a public agency may have to wait until market expansion or industry restructuring generates new demand for right-of-way use.[14]

For more information about the issues associated with shared resource projects, the user should consult *Shared Resources: Sharing Right-of-Way for Telecommunications.* [14]

TRANSIENT PROTECTION

Electronic traffic control equipment is subjected to a wide range of electromagnetic threats, including lightning, electrostatic discharge, internally and externally generated inductive switching transients, and radiated electromagnetic interference (EMI) from radio, TV, radar, and mobile communication transmitters. Lines providing electrical power and cable interconnecting equipment to sensors, communications systems, or peripheral hardware provide a direct path for the conduction of disruptive and damaging electrical transients and other EMI into traffic control equipment. In general, traffic control and communications systems can be protected against transients through the following mechanisms: [15]

- Proper grounding of power supply and communications systems.
- Adequate shielding of equipment and interface cables.
- Proper bonding and corrison control.
- Use of terminal protection techniques such as amplitude limiters and filters.
- Good interface designs that use balanced line inputs and fiber optics.

The most severe electromagnetic threat to traffic control equipment is lightning. To determine the level and extent of protection required against lightning-induced transients, the traffic control professional must know the lightning threat levels at traffic controller inputs, the rates-of-occurrence of lightning transients, and the effects of the lightning discharges on electronics within traffic control equipment. The lightning levels will vary depending on the type of interface, the length of the interconnecting lines or cables, and whether the lines are shielded or not.

NCHRP Report 317 Transient Protection, Grounding, and Shielding of Electronic Traffic Control Equipment describes techniques for protecting against transient and electromagnetic interference.(15)

COMMUNICATIONS WITHIN THE CONTROL CENTER

Providing adequate communications systems within the control center is critical to the success of the control center. In general, the types of communications systems implemented in a control center need to allow operators to communicate with the following personnel:

- Other control center operators.
- Supervisory personnel.
- Maintenance dispatchers/forces.
- Computer system operators/ maintainers.
- Incident management personnel.
- Public relations personnel.
- Media.

In general, the types of communication systems that need to be included in the design of the control center include the following:

- Local area computer networks where information and data can be transferred from one computer terminal to another.
- Voice communications systems

Module 10 provides more information about these types of communications systems.

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