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Communications in Traffic Control Systems

Volume II: Final Report

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWORD

This report is the second of a two-volume series resulting from the study, "Investigation of Successful Traffic Control System Design, Installation and Operations Practices." The report will be of interest to designers and operators of traffic control systems or those interested in possibly implementing a traffic control system.

In recent years, traffic control systems have become increasingly popular as a means of combating urban traffic congestion problems. However, many systems have experienced implementation problems ranging from cost overruns during construction to excessive hardware and software malfunctions during system operation. The objectives of this study were to prepare guidelines for the successful implementation of traffic control systems and to critically assess the performance of new and emerging communications technologies in traffic control system applications.

This second volume provides a detailed discussion of the results of the communications technology assessment portion of the study. The first volume is an executive overview of the communications technology portion of the study. Another two-volume report series resulting from this study (FHWA-RD-88-013 and 014) covers the guidelines developed for the successful implementation of traffic control systems.

The research reported herein is part of Nationally Coordinated Program (NCP), Program Area B.1, "Traffic Management Systems."

Copies of this report are being distributed to selected FHWA Headquarters elements and field offices, and to selected transportation officials. Additional copies of this report for the public are available from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. A charge will be imposed for each copy ordered from NTIS.

R. J. Betsold
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Office of Safety and Traffic
Operations R&D

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16. Abstract

The communications element of a traffic control system has proved to have the greatest risk in terms of the successful implementation, operation, maintenance, and expansion of a system. It is also one of the most costly elements.

The purpose of this report is to provide understandable information on communications in general and on specific communication technologies to those persons involved in the planning, design, and implementation of computer-based traffic control systems. The report includes a brief tutorial on communications technology and terminology; guidelines for conducting a thorough communications trade-off analysis; a detailed discussion of communications media which have been widely used in traffic control and of how these may be successfully designed and installed; and a discussion of newly developing technologies that have had limited use (if any) in traffic control systems, but may have wider application in the future.

An executive summary of the information is provided in Volume I, publication no. FHWA-RD-88-011.

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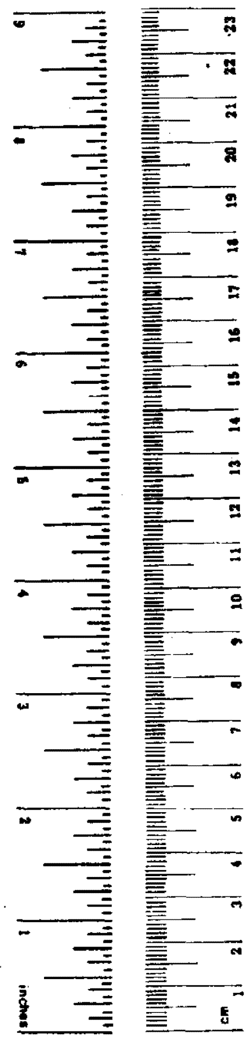
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

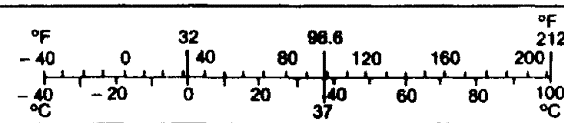
NOTE: Volumes greater than 1000 L shall be shown in m^3.

	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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1. INTRODUCTION

This report has been prepared for the study entitled "Investigation of Successful Communications and Traffic Control System Design, Installation, and Operations Practices". The project objectives were to:

- Develop through investigation of in-depth case studies, guidelines for the design, procurement, installation, and operation of successful traffic control systems.
- Assess the performance of existing and new or emerging communications technologies for use in traffic control systems.

The information contained herein focuses on the second objective. The report discusses several communications technologies and their potential applications in computer-based traffic control -- both signal systems and freeway surveillance/control systems. Guidelines for analyzing and selecting the "best" technology for a particular system are also presented.

BACKGROUND

For the many benefits of a traffic control system to be fully realized, all of the major components (e.g., computer and peripherals, communications media and interface hardware, local control hardware and detectors, etc.) must work in concert with a high degree of reliability. Of these, the communications subsystem is perhaps the most critical and least understood.

The communications element of a traffic control system has the potential of being the most costly item. It has also proved to have the greatest risk in terms of the successful implementation, operation, maintenance, and expansion of a system. Yet the communications subsystem often receives less attention than other system components.

The orientation of this project, therefore, was to provide understandable information on communications in general and on specific communication technologies to those persons involved in the planning, design, and implementation of computer-based traffic control systems. The overall goal is that this information can and will be used to develop efficient communication subsystems for traffic control applications and, at the same time, to minimize the associated costs and risks.

PROJECT OVERVIEW

Information on communication technologies and their use in traffic control systems was obtained from the following sources:

- Review of applicable literature.
- Visits to existing traffic control systems. Several traffic control systems were visited to obtain a complete perspective of communication technologies which are currently being utilized for traffic control. These evaluations addressed technical considerations, design and installation concerns, and institutional constraints.
- Investigation of communication applications in other industries. Other process systems and communication manufacturers were visited to identify the potential of technologies which are not widely used for traffic control applications. The focus of the surveys was to determine how these communications technologies may be used, and what development is necessary to make them competitive with existing techniques.

REPORT ORGANIZATION

This report is organized into five chapters, including this introductory chapter. Chapter 2 is a brief tutorial on communications technology and terminology. It is intended to provide the reader with a basic understanding of communication systems and concepts.

Chapter 3 presents guidelines for conducting a thorough communications trade-off analysis. The various tangible and intangible considerations are discussed, as well as the integration of the process into the overall traffic engineering analysis required by FHWA.

Chapters 4 and 5 discuss the various communication technologies. Chapter 4 addresses those media which have been widely used in traffic control systems, including twisted-pair cable, leased telephone (Telco), coaxial cable, and Community Antenna Television (CATV). Chapter 5 discusses newly developing technologies which have had limited applications (if any) in traffic control systems. These "emerging" technologies include, fiber optics, microwave, atmospheric infrared, and radio. The final chapter provides a brief overview of what the future may hold for traffic control communications.

The state of the art in communications is rapidly and continually changing. The reader is therefore cautioned to check the date of this report (1988), and take any subsequent advances into account. This is particularly true for the new and emerging communication technologies. Potential future developments have been addressed wherever possible; but the authors' crystal ball is, at best, somewhat near-sighted.

Very little cost information has been included in the report. The costs of communications media and their supporting hardware (conduit, interface equipment, etc.) can vary significantly by location and by time. Furthermore, the temporal variations are not uniform. Some media are escalating in cost, while others are experiencing a decrease in costs as manufacturing and installation practices become more standardized and efficient. Thus, general statements concerning relative cost differences might prove erroneous in the not-too-distant future.

Finally, this document does not presume answers. The various factors which affect a communications subsystem are numerous and interdependent. To make any broad statements that a specific medium is the "best" for a particular type of system would be pure folly. What this report does provide is information -- information that can be used by planners, designers, and construction managers in making the necessary and critical decisions regarding communications in traffic control systems.

2. COMMUNICATIONS OVERVIEW

A computer-based traffic control system is comprised of many different elements. There are field components such as signal controllers, ramp meters, field masters, and variable message signs; surveillance hardware such as detectors and television cameras; central equipment such as computers, peripherals, and television monitors; and the human element -- operators and maintainers. For the system to operate properly, each of these components must exchange information with other system elements. The information may be voice messages, video pictures, or control and surveillance data. It is the communications subsystem that provides the connecting link for the transfer of this information.

This chapter presents an overview of communication concepts. The field of communications is very broad and complex; and traffic control represents only one type of process system requiring communications between the various system components. The purpose of this brief tutorial is to provide the reader with a basic knowledge of communications and the associated terminology as it pertains to applications in computer-based traffic control. The information provided herein will also be useful to the reader in understanding and comparing the various communications media which are discussed in subsequent chapters. A glossary of terms is provided at the back of the report.

BACKGROUND

To better understand the functions performed by the communications subsystem, it is useful to summarize the overall data requirements of a traffic control system. A significant factor affecting the data communication characteristics is the assignment of processing tasks between the computer and the field hardware. There are three basic configurations:

- Centralized system with direct computer control of all field hardware -- In this system, the central computer performs all processing functions required for system control and processing. The local hardware performs only simple load switching and minor timing logic. For this system configuration, vehicle detectors transmit data representing each vehicle presence to the computer. The computer processes the detector information and, if it is in a traffic responsive mode of operation, selects an appropriate timing pattern for use by the traffic signal and/or ramp meter controllers. This timing information is transmitted to the controllers as once-per-second control commands (e.g., HOLD, FORCE-OFF, YIELD, FLASH, etc.). The controller, in turn, transmits its current state (e.g., phase green, preempt, ramp signal status, etc.) once every second. The computer processes this information to verify that the field components are functioning properly in response to the transmitted commands. An example of this type of central system is a typical UTCS traffic signal system.

- Centralized system with downloading and uploading -- In this system, some of the processing functions are removed from the central computer and placed in microprocessor-based field hardware capable of performing these functions. The result is that some of the data communications between the central and the field hardware occur less frequently as compared to the direct central configuration. An example of a centralized system with downloading and uploading is a freeway surveillance system where detector data is preprocessed and transmitted to the central computer once-per-minute. Another example is a traffic signal system where complete timing plan information (e.g., plan numbers, cycle lengths, splits, offsets, etc.) is downloaded to the controllers on an as-needed basis and stored in the local microprocessor. The computer selects the appropriate timing plan by transmitting a PLAN SELECT command.

- Distributed system -- In a distributed system, the processing functions are significantly removed from the central computer such that it is used primarily as a clearing-house for system information, operator interface, and display functions. The local field hardware possess intelligence and are coordinated by a series of field-located zonal processors. These zonal processors, or field masters, perform monitoring and surveillance functions, and communicate with the local field hardware in a manner similar to the central system with downloading and uploading. The zonal processors communicate preprocessed data to and from the central processor on an as-needed basis. An example of this system configuration is a distributed master (closed-loop) signal system.

Each system configuration may be further complemented by special features and functions, such as closed-circuit television surveillance (CCTV), variable message signs, computer peripherals at a remote site (e.g., maintenance shop), or emergency vehicle preemption schemes. These and other special features will also impact the communications subsystem.

As the processing characteristics and communication requirements of a traffic control system change, so does the most appropriate communications subsystem. Furthermore, the various attributes of the communication subsystem -- the type and amount of information to be transferred, the rate of information transfer, the communications media, the transmission techniques, the reliability of transmissions, and the communications interface hardware -- are interrelated. A decision on one of these variables will likely influence the decisions concerning the others.

BASIC CONCEPTS

This section identifies and briefly defines the basic components of any communications system as shown in figure 1. These communication system components are discussed in greater detail, with an emphasis on traffic control applications, in subsequent sections.

Communications is the transfer of meaningful information from one location (the **source** or **transmitter**) to another location (the **destination** or **receiver**). The path over which the information flows from transmitter to receiver is called the **transmission link** or **channel.** The make-up of the transmission link is known as the communications **medium**, and may consist of a physical connection (**waveguide**) or air-path.

Most communication systems use some form of **modulation** in transmitting the information. The **modulator** converts the information into a form, or signal, that can be efficiently transmitted over the channel. The **demodulator** performs the opposite function, taking the received signal and converting the information back into its original form, or into some form suitable for use by the destination.

It is inevitable that the signal will deteriorate during the transmission/reception process. This may be the result of the signal strength becoming weaker (**attenuation**) as the transmission distance increases, some distortion in the communication system itself, and/or the introduction of some unwanted signals (**noise**) from an external source. Noise and distortion may introduce errors into the transmitted information or even totally destroy it.

Electronic Communications

In electronic communication systems, the signal is transmitted over the channel as electrical energy, which is propagated in the form of a sinusoidal wave (figure 2). This **carrier wave** has the shape of the mathematical sine function and is defined by the following parameters:

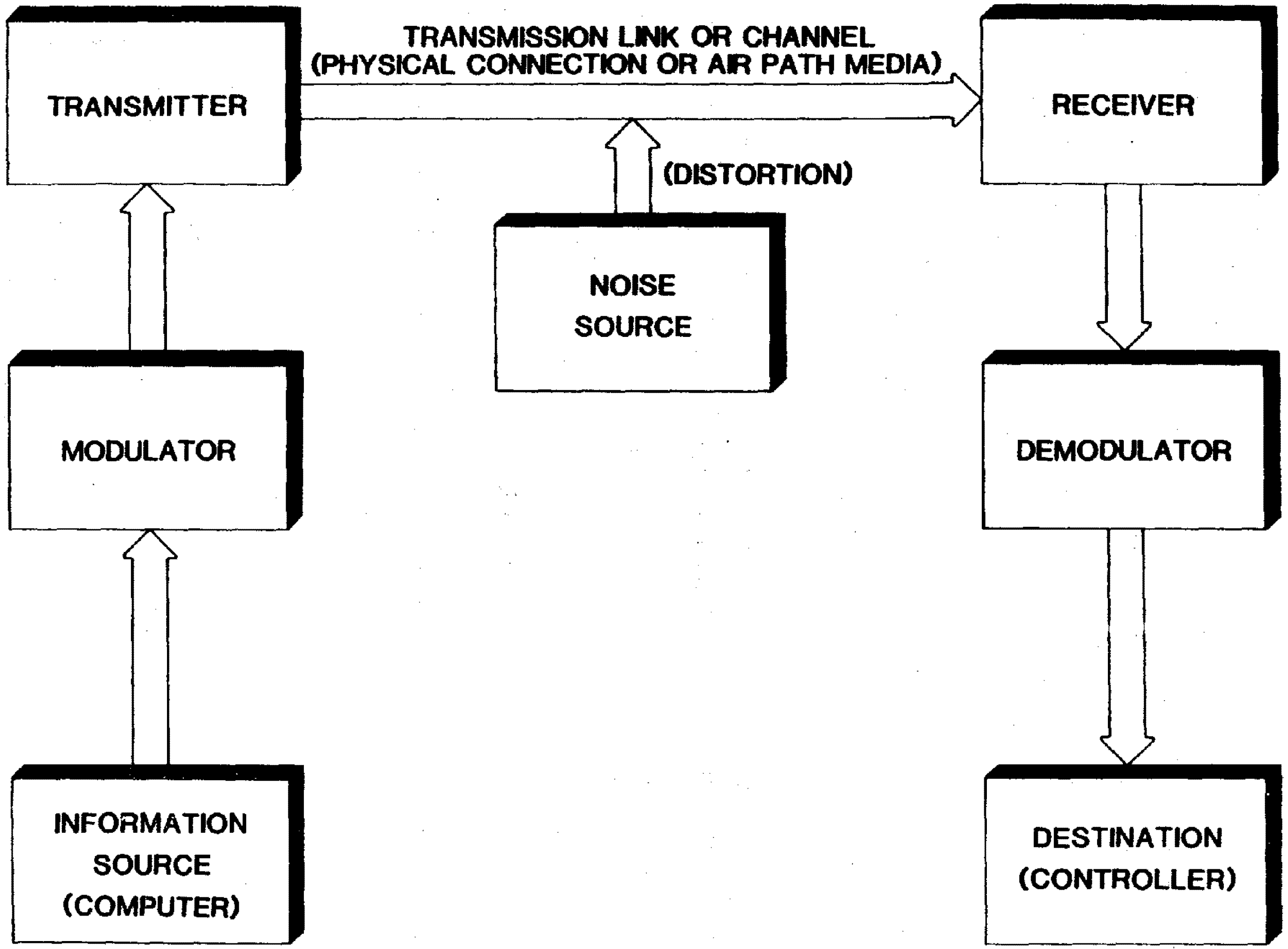


Figure 1. Basic communications system.

- **Wavelength** - the distance between successive peaks of the energy wave.
- **Frequency** - the number of cycles per second measured in **hertz (Hz)**, where 1 Hz equals 1 cycle per second.
- **Speed** of the wave - speed varies with the transmission medium; in freespace the wave travels at the speed of light (= 300 million meters per second).
- **Amplitude** - the strength of the carrier wave.

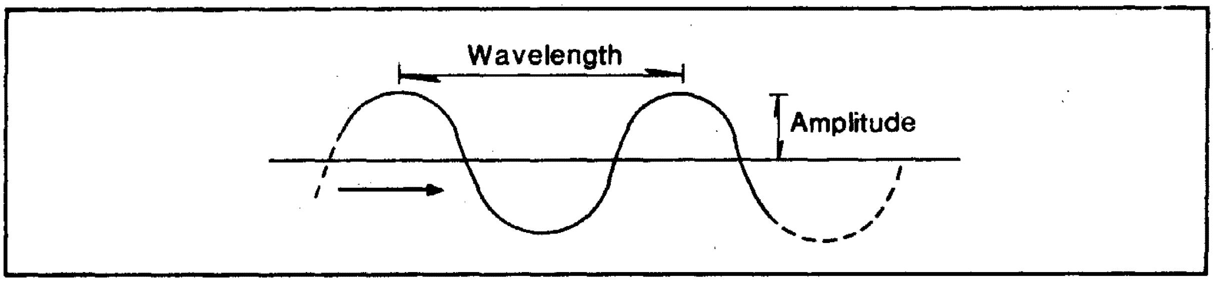


Figure 2. Sinusoidal carrier wave.

The relationship between the frequency, wavelength, and the speed of the traveling sinusoidal wave is given as:

$$\text{Frequency} = \text{Speed (of Light)} \div \text{Wavelength}$$

Thus, common commercial power, with a frequency of 60 Hz, has a wavelength of 5000 kilometers (approximately 3,000 miles), although this traveling wave is not apparent in any transmission line of normal length. As the frequencies increase, the wavelengths become correspondingly smaller. For example, commercial television frequencies as established by the Federal Communications Commission (FCC) range from 54MHz (wavelength of 5.6 meters) to 980 MHz (wavelength of 0.31 meters). Higher frequencies, such as visible light, have even smaller wavelengths.

Electronic communications are used for traffic control systems. Referring back to figure 1; the source is the traffic control computer, the output from which is converted to an electrical signal. This carrier wave is then modulated to represent the necessary information and so that it is suitable for transmission over a channel consisting of a wire or air-path medium. Once the electrical signal is received at the destination, the demodulator converts the information into its final form (e.g., HOLD, FORCE-OFF inputs to an intersection controller). There is also the possibility that noise, such as electrical interference from nearby power lines or lightning, may interfere with the proper transmission and receipt of the traffic control information. Since traffic control systems require 2-way communications, the information flow can also be reversed, with the field hardware acting as the source and the computer becoming the destination.

Communication Networks

Before discussing the basic components of a communications system in greater detail, it is important to briefly describe the various ways that a communications network may be organized. One consideration is the manner in which a single source (e.g., central computer, field master) and multiple destinations (e.g., signalized intersections, ramp meters) are linked. In a **point-to-point** network (figure 3), a separate transmission link is provided between the central facility and each field location. For every link there is one transmitter and one receiver. A special application of point-to-point is **trunking.** A trunk is distinguished by the large amounts of data transmitted between the source and the destination, and the fact that there are no drops between them. An example would be a transmission link connecting the central computer with a remote area computer. (The area computer, in turn, might serve a local distribution network consisting of multiple field drops connected to the area computer.)

In very large communication networks, point-to-point can result in an untenable number of cables being returned to the central facility and a corresponding increase in costs. One alternative is a **point-to-multipoint** scheme as shown in figure 4. Point-to-multipoint combines two or more receivers on the same transmission link, thereby reducing the total number of channels in the system. Because of the presence of multiple receivers on the same channel, a method is necessary for establishing communication between the information source and the proper receiver. This is accomplished through multiplexing, which is addressed later in this chapter.

Another alternative is to interconnect the various drops with a series of point-to-point links. This "daisy-chain" configuration is shown in figure 5. The information is received by the first location, which demodulates the signal for its use, and then remodulates the signal and transmits the information to the second location; and so forth. A potential problem with a daisy-chain configuration is that a communications

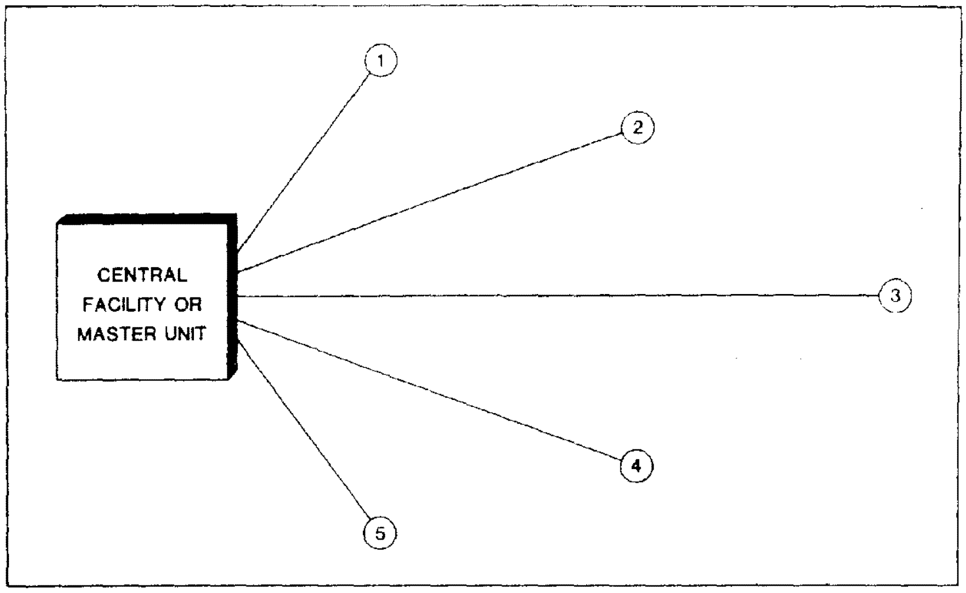


Figure 3. Point-to-point configuration.

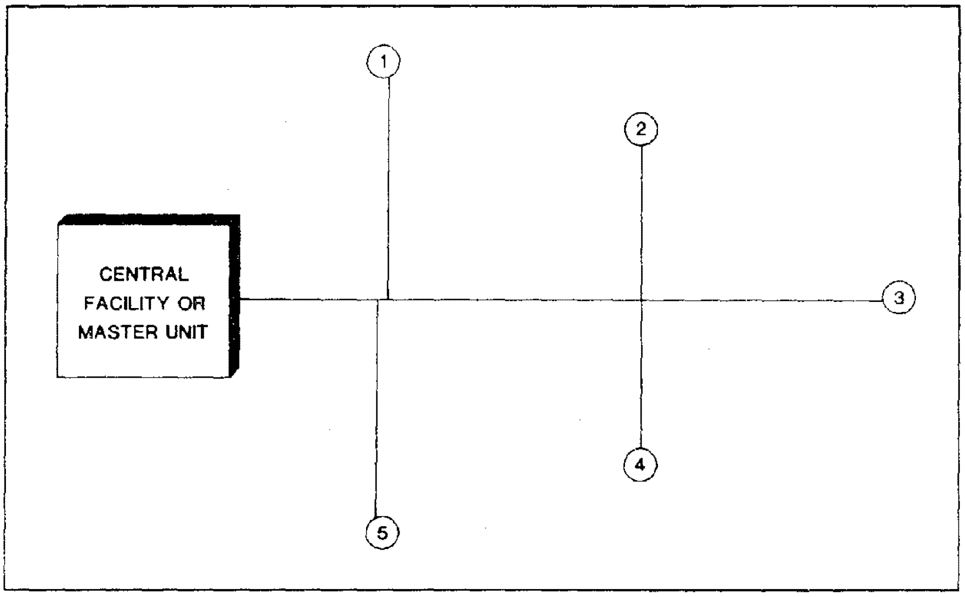


Figure 4. Point-to-multipoint configuration.

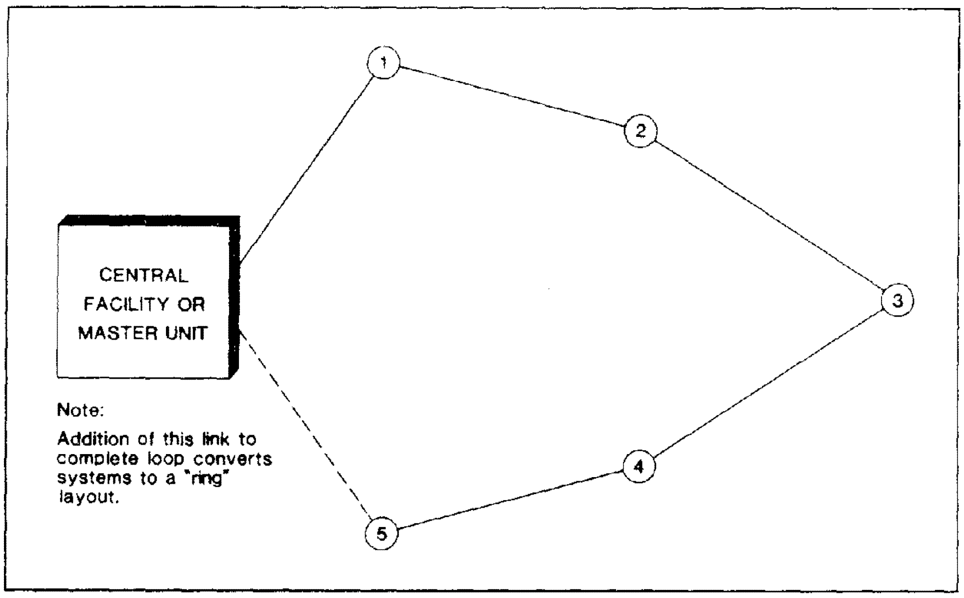


Figure 5. Daisy-chain configuration.

failure at one location will disrupt all succeeding transmissions to the remaining locations in the network. To minimize this problem, a **ring** configuration is often employed such that communications can occur in either direction of the loop, thereby circumventing the failed location.

TRANSMISSION LINK

A transmission link may be defined by the frequencies that are used over the channel. The entire range of frequency alternatives available is called the **electromagnetic spectrum.** As shown in figure 6, modern electronic communications utilize a wide range of frequencies, from a few hertz to the visible light range. Transmissions between 300 Hz and 3,000 Hz are categorized as "voice-grade" because this is the range of frequencies that provides the easiest recognition of the human voice. In a similar manner, a channel that uses frequencies greater than one gigahertz (a billion hertz) is called a microwave link.

A transmission link can also be described by the direction of information flow over the channel:

- **Simplex** - the flow of information is in only one direction (e.g., commercial radio and television broadcasts).
- **Half-Duplex** - the information may flow in either direction, but the link operates in only one direction in a given time frame.
- **Full-Duplex** - information may flow in both directions simultaneously.

Bandwidth

The information-carrying capacity of a transmission link is influenced by its **bandwidth** -- the range of frequencies that can be transmitted over the link without significant distortion or attenuation. In general, the greater the quantity of information that must be transmitted over the link for a given period of time, the wider the bandwidth required for the channel.

Communications media, whether they be physical connections (e.g., twisted-pair cable, coaxial cable, fiber optics) or radiation through space (e.g., microwave, radio, laser) are also characterized by their respective bandwidth. For example, as shown in figure 7, the **frequency response** of a standard telephone circuit (i.e., twisted-pair

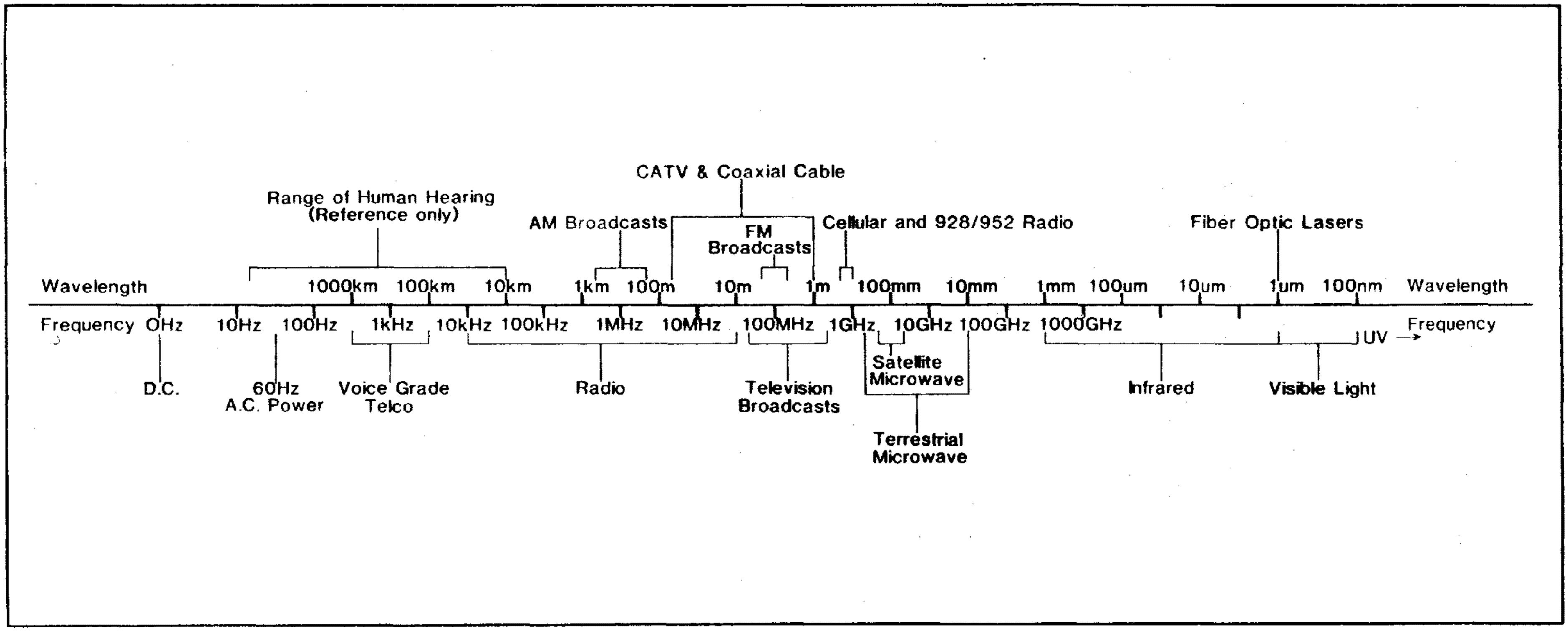


Figure 6. Electromagnetic frequency spectrum.

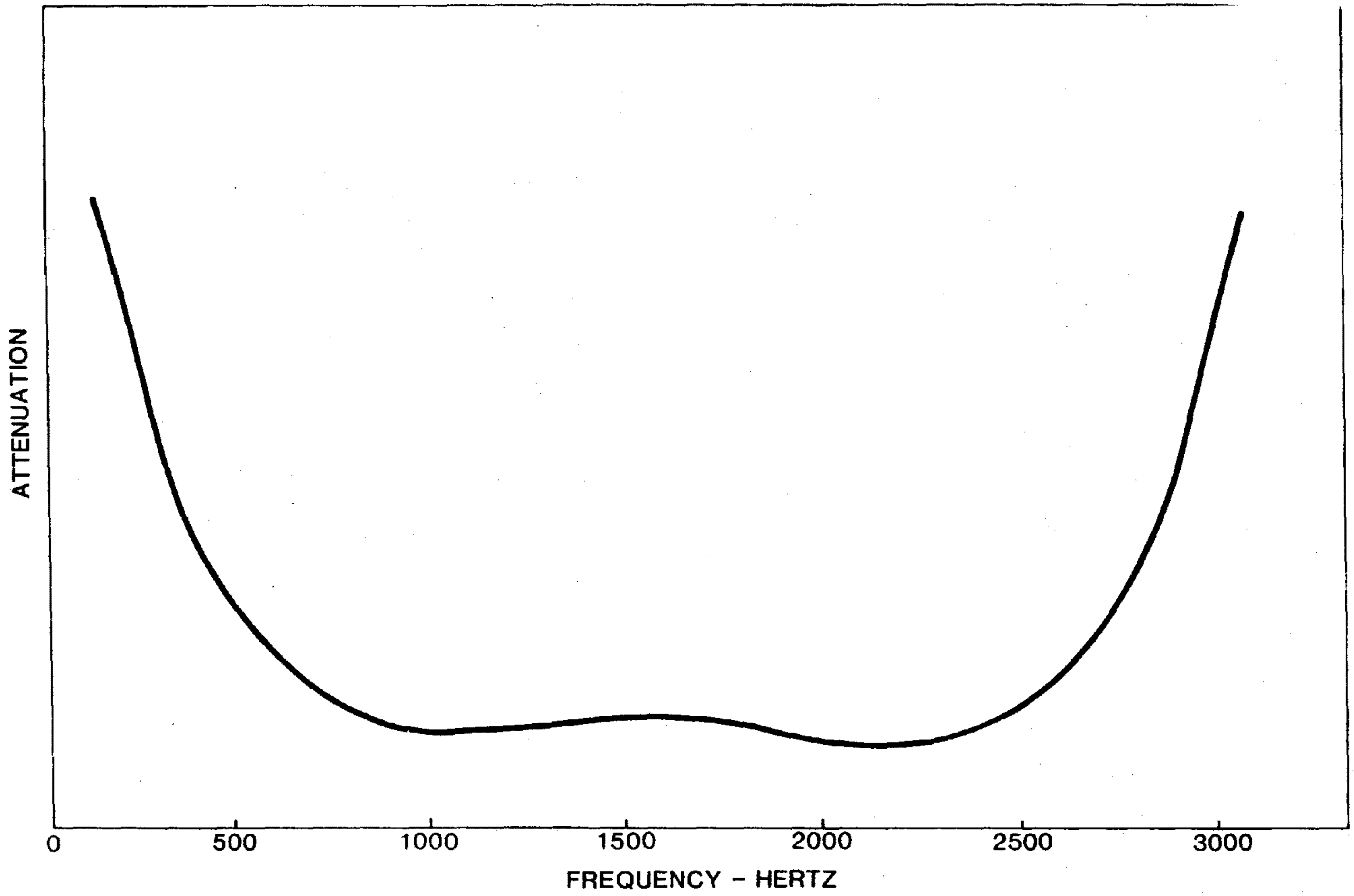


Figure 7. Frequency response of a typical voice-grade channel.

cable) provides a usable bandwidth of between 300 Hz and 3000 Hz -- a voice grade channel. With physical media, the bandwidth is constrained primarily by the properties of the materials comprising the medium (e.g., copper in twisted-pair cable, glass in fiber optics) and its construction. With air-path media, the available bandwidth is controlled primarily by FCC regulations and international agreements which define how the electromagnetic spectrum may be used; but physical constraints (e.g., antenna size, power) are also a factor. A detailed discussion of the various transmission media, their bandwidths, transmission characteristics, traffic control applications, and design considerations is provided in chapters 4 and 5.

Attenuation and Repeaters

As previously noted, attenuation is the weakening of the signal strength associated with the transmission process. Attenuation is typically measured as a ratio of the received signal strength to the transmitted signal strength. This ratio is expressed in **decibels (dB)** which is a dimensionless logarithmic unit.

At some point along the transmission link, the attenuation (i.e., power loss) will become so great that the signal will no longer be discernable. It then becomes necessary to install a **repeater**. A repeater is simply an amplifier that receives the electronic signal from the source (or from a previous repeater), boosts its power, and transmits it to the next repeater or the final destination as the case may be. As the frequency of the transmitted signal increases, attenuation per unit distance also increases and, correspondingly, the distance between repeaters (or the maximum non-repeatered distance between source and destination) must be decreased.

Attenuation in physical media is primarily caused by the resistance properties of the communications cable. When air-path transmissions are at frequencies with millimeter or shorter wavelengths, the electromagnetic energy is susceptible to absorption by water drops. The droplets, having a similar size as the wavelength, act like tiny antennas. As the frequencies increase, the air becomes more and more opaque to the radiation and, accordingly, the repeater distance must be decreased.

INFORMATION

The communications network for a traffic control system must provide for the transmission of one or more of the following types of information: voice, video, and data.

Voice circuits or "channels" are often included in the communications network of a traffic control system. (Note: The term "channel" is often used in this context to refer to a particular type of frequency range or transmission over a link; such as voice "channel" or television "channel".) Voice channels may be used to permit an operator at the central facility to talk with personnel in the field to facilitate maintenance and system debugging. Two-way voice call-box systems have been included in several freeway control systems for motorist aid. Highway Advisory Radio (HAR), which consists of a low-powered AM transmitter matched to either a roadside cable or a series of vertical antennas, has also been used in conjunction with freeway surveillance systems to provide highway and traffic-related messages to the driver over the car's AM radio. As previously noted, a voice channel requires a bandwidth of 2700 Hz (300 Hz - 3000 Hz).

Video channels are included in traffic control systems for closed circuit television (CCTV) surveillance. The bandwidth of the inbound video channels (from the field cameras to television monitors at central) is usually 6 MHz per camera in order to provide full-motion video. An outbound data channel, consisting of a much smaller bandwidth than the inbound channels, is usually employed for camera control (tilt, pan, zoom, etc.).

Data channels provide for the communication of control commands and monitoring information between the central computer and various field hardware. Data channels are also necessary for communications between the central computer and remote peripherals (e.g., CRT in the maintenance shop). The bandwidth requirements of data channels are dependent on several variables, including the type and quantity of data to be transmitted, the rate at which the data needs to be transmitted, the number of drops (i.e., intersections, ramp meters, variable message signs, etc.) on each multipoint channel, and the required accuracy of the data.

Centralized systems, with their once-per-second data requirements, generally require a transmission link with a larger bandwidth and/or a greater number of channels as compared to a distributed system which has less-frequent transmissions. It is noted that detector data is often the critical item in determining the data channel requirements. A detailed discussion of the data requirements for the three system configurations (central, central with downloading/uploading, distributed) is provided in reference 4.

Digital Communications

Data communications in traffic control systems depend on digital electronics. Digital communications use discontinuous signals -- the information is carried in patterns of discrete binary digits (**bits**) which have a value of either 0 or 1, rather than having the continuous variations characteristic of analog signals. The square wave in figure 8 is an example of a digital signal, while the sine wave in previous figure 2 is an example of an analog signal.

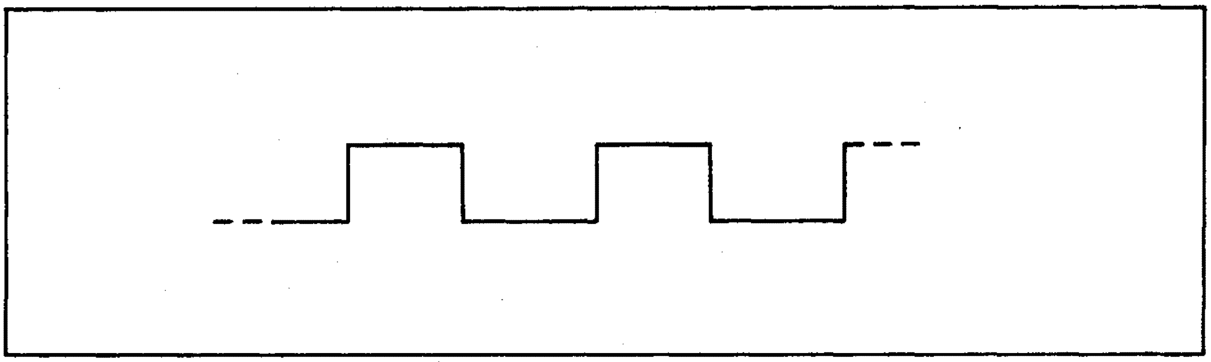


Figure 8. Square wave form.

Groupings of bits represent data in accordance with various standards (e.g., the binary numbering system). A **byte** is a "word" of data, consisting of 8 consecutive bits.

In **serial** data communications, the data bits are transmitted sequentially (i.e., one bit at a time) over a single channel. There are two basic serial data formats used:

- **Asynchronous** - In asynchronous transmissions, the signal is held at a constant level or state until the data are to be sent. When the source begins to transmit, the signal changes level or state. The receiver detects this transition and begins to receive the data. After the last bit in the byte has been received, the receiver checks the signal to see if it has returned to the original constant state.

- **Synchronous** - This approach is useful when long strings of bits are to be transmitted. At the start of a transmission, a special sync character is sent. Upon recognition of the character, the receiver begins receiving valid data. At the end of a transmission, a second sync character is sent and the receiver stops receiving data.

Asynchronous communication is relatively simple and low cost. This method is typically used in most traffic control applications. When large blocks of data must be transmitted at high rates, such as between two separate control computers, synchronous transmissions are used.

Parallel data is the simultaneous transmission of a group of bits, usually one byte long. In other words, all 8 bits arrive at the receiver at the same time over separate channels. Parallel communications are used for transmitting data over very short distances -- for example, between a computer and peripheral equipment. Parallel data are not used in traffic control systems for transmitting information from the central computer to the various field drops.

The **bit rate** is the measure, in bits per seconds, of the digital information being transmitted. The transmission speed of a data channel is often referred to as the channel's **baud rate** or signaling rate. In a binary system, such as is used in most traffic control systems, the baud rate and the bit rate are the same. (It is noted that in communications systems which encode the data in such a way that more than one information bit can be placed on each signaling pulse, the information bit rate will exceed the baud rate.)

MODULATION/DEMODULATION

Two elements of the previous discussions bear repeating -- first, the data output of a traffic control computer or microprocessor is digital (e.g., square wave); and secondly, the electrical energy that is transmitted over the communication channel is analog (e.g., sine wave). Modulation is the process by which the binary digital information is superimposed on the sinusoidal waveform of the carrier wave. Modulation is also used to translate an analog information source (e.g., video, voice) to a different frequency range for efficient propagation over the particular communications media (e.g., output from a camera being shifted to the assigned channel of a coaxial cable).

The modulation process changes the characteristics of the carrier wave such that it reflects the different values of the information being transmitted. Three modulation processes are described as follows:

- **Amplitude Modulation (AM)** changes the strength of the carrier wave, using a signal of large amplitude to represent the 1 condition, and a signal of lesser amplitude to represent the 0 condition. Because the valid reception of an AM signal depends upon the measurement of the received signal strength, it is possible for line noise to severely degrade AM reception (e.g., static on a radio). For that reason AM is not often used in traffic control communication systems. Figure 9 is a simplified graphic of amplitude modulation.

- **Frequency Modulation (FM)** uses a center frequency that is shifted to a higher frequency to represent one, and a lower frequency to represent a zero. When digital FM is used, only the two frequencies representing the 0 and 1 are transmitted as shown in figure 10. Digital FM is known as **frequency shift keying** (FSK). FSK is the most commonly used method for transmitting digital data in traffic control systems.

- **Phase Modulation (PM)** varies the phase of the carrier wave relative to a constant-phase reference signal. PM is known as **phase shift keying** (PSK) when used for digital communications. In a binary system, the phase is usually shifted 180 percent (out of phase with the reference signal) to represent a 1, but left unchanged (in phase) for a zero. (Refer to figure 11). PSK requires rather sophisticated electronics to precisely measure the transmitted signal and the reference signal. PSK is often used for high speed transmissions.

Modem

The term **modem** is a contraction of the terms MOdulation and DEModulation and, as the name implies, both functions are included in a modem. The modem serves as the interface between the computer and the transmission link, and between the field hardware and the transmission link. When used for transmitting, the modem accepts digital information and converts it to analog for use in modulating the carrier wave. At the receive end, the modem converts the modulated carrier wave to recover the data.

Modems are classified by the parameters summarized in table 1. The terms associated with modem operation are defined as follows:

- Request to send (RTS) is an electrical signal applied to the modem by the data source notifying the modem that data is ready to be transmitted.

- Clear to send (CTS) is an indication by the modem to the data source that it (the modem) is prepared to transmit. A clear-to-send delay, the length of which is programmed into the modem, allows the receiving modem time to detect and lock to the transmitting modem's carrier before data transmission commences.

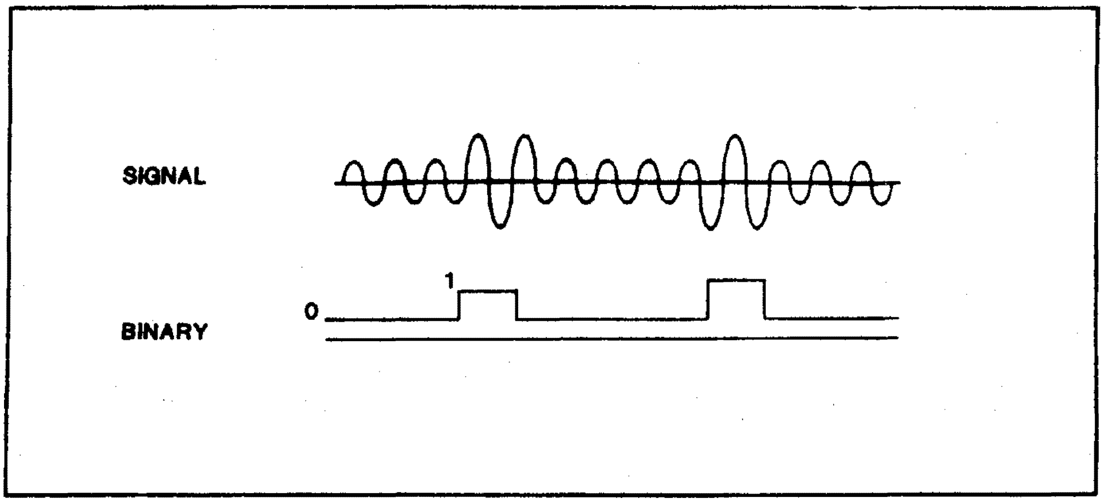


Figure 9. Amplitude modulation.

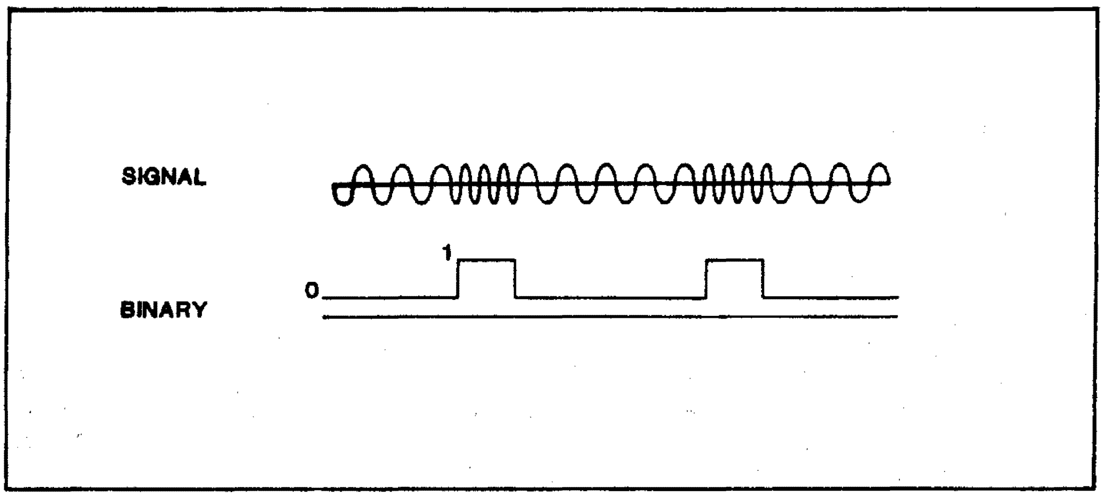


Figure 10. Frequency modulation.

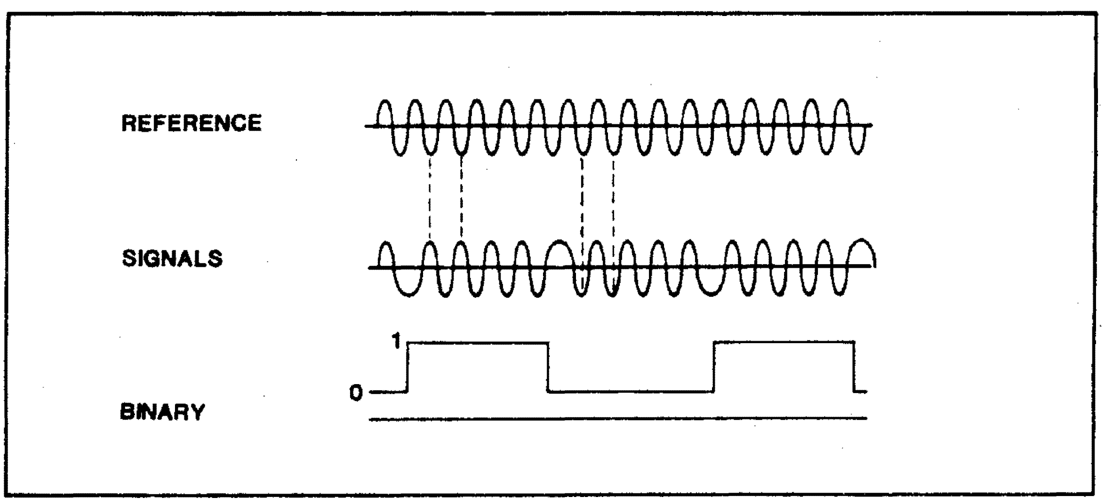


Figure 11. Phase modulation.

Table 1. Modem classifications.

<u>SPEED</u>

- Low Speed - up to 600 bps
- Medium Speed - 1200 to 2400 bps
- High Speed - 3600 to 9600 bps
- Wideband - 19,200 bps and above

<u>TRANSMISSION MODE</u>

- Half-duplex
- Full-duplex

<u>MODULATION</u>

- FSK
- PSK

<u>DATA INTERFACE</u>

- Examples include RS-232, RS-422, RS-423, and RS-449. These interfaces have been defined by the Electronics Industries Association (EIA) to ensure compatibility between data sets and terminal equipment. The EIA standards address connectors, pin assignments, length of interconnection cable, voltage levels, etc.

<u>LINE INTERFACE</u>

- Twisted pair 2-wires
- Twisted pair 4-wires
- Coax
- Fiber Optics

- Turnaround time is the time required to reverse the direction of transmission on a half-duplex line. It is also sometimes used in full-duplex systems to indicate the time from receipt of the end of the command message, to the beginning of transmission of the response.

Multiplexing

As previously discussed, in a multipoint communications network, two or more receivers are placed on the same transmission link. A communication technique known as **multiplexing** allows information to be transmitted to these multiple receivers over the same channel, and ensures that the data are received by the appropriate destinations.

Frequency Division Multiplexing (FDM) breaks the total available bandwidth into a series of subchannels, each of which occupies a portion of the band (figure 12). The frequencies assigned to these channels within the bandwidth must not overlap. In fact, in order to assure separability at the receiver, guard bands of unused frequencies must be provided between channels. In FDM, each frequency band is allocated to a specific destination or functions. The various subchannel frequencies are transmitted simultaneously. Separate modulation is required for each band, and specific channel frequencies are sorted out electronically at each receiving end. FDM is seldom used for traffic control systems with twisted-pair cable networks (although it was used in many of the early systems in the 60's and early 70's). It is commonly used in coaxial networks because the technique allows space for multiple TV channels, camera control channels, and data channels on the same cable.

Time Division Multiplexing (TDM) divides the total time on the channel (say one second) into a number of discrete segments or time slots (figure 13). Each time slot occupies a portion of the second and is typically allocated to a specific field drop (intersection, ramp meter, etc.). The central computer sends command data to a single drop and receives all monitoring information from that field drop within the time allocated to the corresponding time slot. It then repeats this process with the next drop, and so on, until all drops in the multipoint group have been **polled,** at which time the polling of all drops in the group begins again.

TDM requires a unique **address** for each receiver. The information transmitted from the computer during each time segment includes an address identifier. All drops in a multipoint group receive the transmitted information, but a drop will only respond if its address matches the message address identifier.

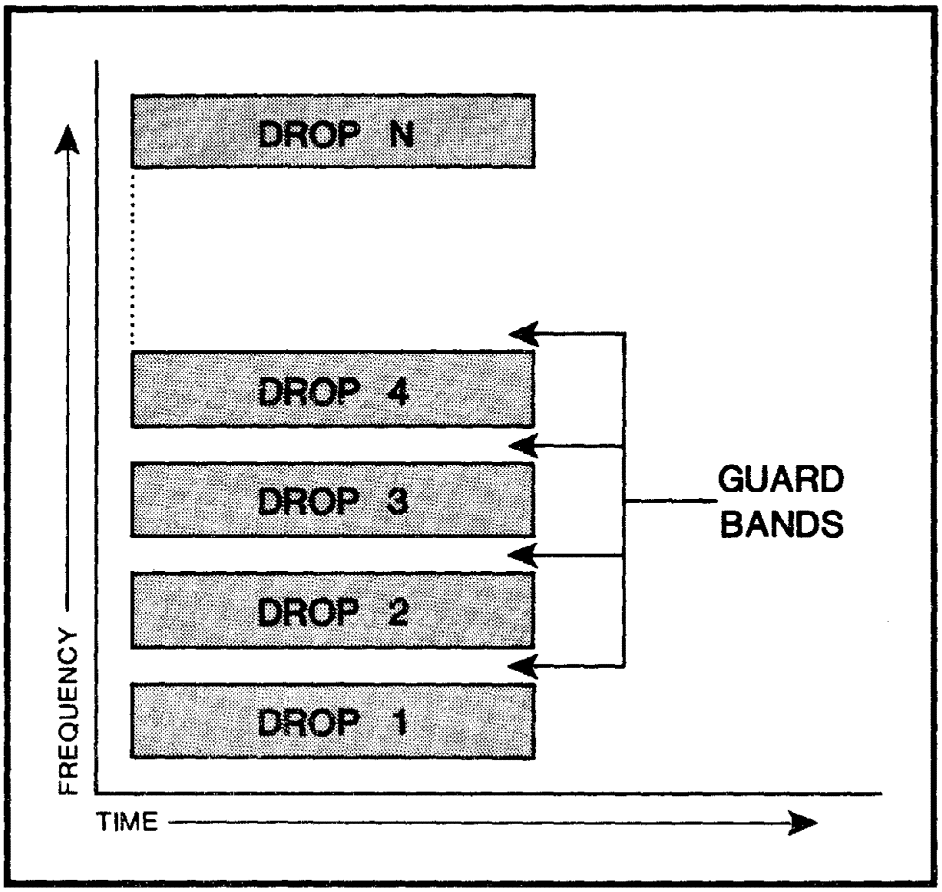


Figure 12. Graphic representation of frequency division multiplexing.

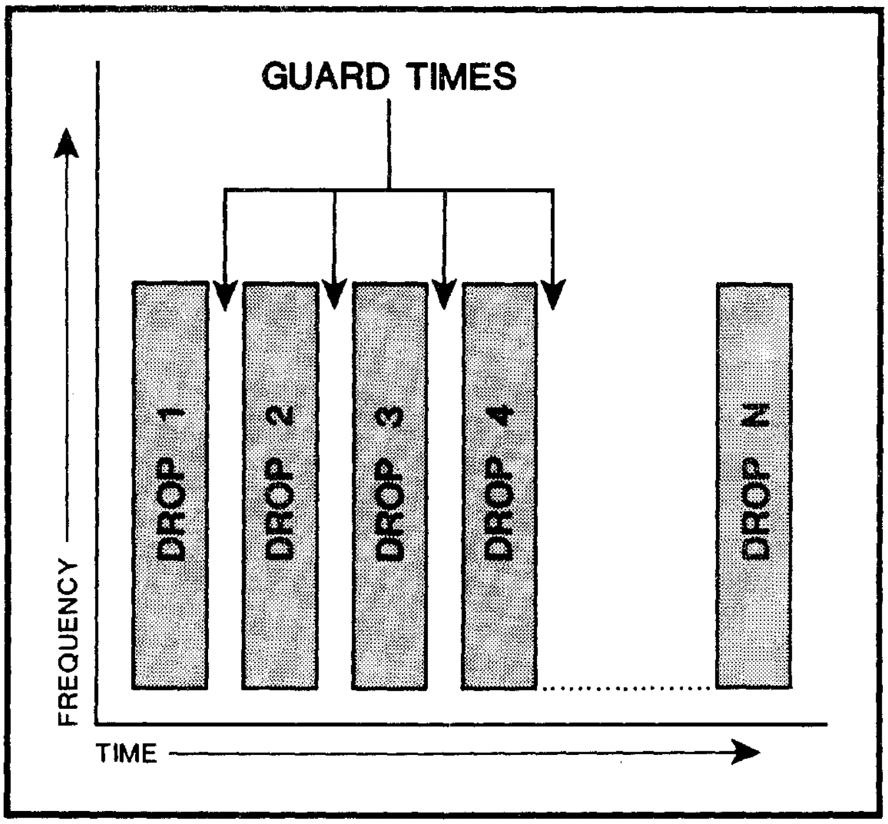


Figure 13. Graphic representation of time division multiplexing.

Communication Interface Units

Communication Interface Units are devices that handle all or part of the communications interface requirements, including:

- Input/Output interface with field device (controller, ramp meter, variable message sign, etc.).
- Error checking and handling.
- Message formatting.
- Modem control.
- Other tasks associated with the operation of the communication system.

At the central facility, this computer-line device is often called a **Central Communications Unit (CCU).** By off-loading the communication function from the computer, more of the computer's capability is made available for traffic control and other function.

The field counterpart of the CCU is commonly referred to as a **Remote Communications Unit (RCU).** An RCU may be a separate "black box" installed at each signalized intersection, ramp meter, variable message sign, or other field drop; or its functions (including the modem) may be an integral part of the controller.

NOISE AND INTERFERENCE

Noise is any unwanted form of energy from an external source that interferes with the accurate and easy reception of the intended signals. Many disturbances of an electrical nature (e.g., lightning and power line splices) produce noise, masking or modifying the transmitted carrier wave in an unwanted manner. For example, in radio receivers, noise may produce hiss or static in the loudspeaker output; whereas in television receivers, "snow" or lines can become superimposed on the picture.

Interference (or distortion) may be created within the communications system itself. An example is **cross-talk,** which is the reception of portions of a signal from one channel by another channel. Cross-talk can occur in any transmission network which conveys more than one signal simultaneously (e.g., multiple frequency bands in the same coaxial cable, multiple twisted-pair circuits in the same telephone cable.)

As is discussed in chapters 4 and 5, the various communications media are resistant to noise and interference to different degrees depending on their physical makeup, the frequencies used, and strength of the carrier signal. Furthermore, the susceptibility of a communications network to noise and interference is greatly influenced by its design and construction.

Error Control

Error detection and correction is employed with serial data transmission to counteract the effects of electrical noise and interference. Error detection techniques, such as those listed in table 2, require additional bits in the data stream and therefore use some of the available bandwidth. These techniques also require additional equipment. Thus, a trade-off must be made to determine the optimum number of bits to be used. Generation and utilization of these check bits can be done either by software or hardware.

Error correction can be accomplished by using the following methods:

- Request for repeat transmission.
- Automatic correction at the receiver based on the received patterns of error correction code bits (forward error correction).
- Automatic repeat transmission.

The repeat request approach has proven to be the more efficient and reliable of the three, particularly in a burst noise environment. A combination of forward error correction and repeat request (when correction fails) can also be used. Automatically repeating the transmission of all data is used in some systems (e.g., in a centralized system, two identical messages are transmitted every second). When this is done, the receiver assumes that the message is error-free if the received messages in a pair are identical. If an error-free message pair does not arrive, the message is ignored until a new pair of messages is transmitted.

For traffic control applications, the rate at which information is transmitted may influence the choice of error correction technique. For example, with a centralized system using once-per-second communications, a single undetected

Table 2. Typical error control techniques.

Techniques	Comments
Repeat transmission	Repeated strings of bits representing a character are compared by receiving device. Typically reserved for critical items such as field cabinet addresses or traffic signal commands.
Parity	Requires one added bit for each character to provide odd or even sum of logical ones. Detects all errors except even number of bits added to or subtracted from logically unlike bit positions by noise.
Checksum	All bits of each character, byte, or word are summed over a complete block or message. The partial or full sum is transmitted at the end of the block or message and compared at the receiving device. This method will detect almost all errors of the same type (added or dropped) except if number of bits added equals the number of bits dropped.
Cyclic redundancy check	The transmitting equipment generates a code derived from the information bits using shift register techniques (hardware or software), and the receiver uses similar techniques to decode. Such codes are efficient and easily implemented. They may also be used for forward error correction.
Validity check	If not all possible binary codes are used for information transfer, validity checks will detect errors resulting in an invalid code.

error in detector data represents only one second's worth of sampling time and can therefore be disregarded. Also, an undetected erroneous controller command which causes mistiming will normally be automatically corrected within 2 or 3 cycle lengths. Thus, a relatively modest amount of error correction could be considered for this type of system, since the consequences of undetected errors are generally not serious. It is emphasized, however, that this may not always be the case. Erroneous or missed cam ADVANCE commands, or SPECIAL FUNCTION commands operating a blank-out sign, may cause an unsafe condition on the street 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 timing pattern data), requires more elaborate error correction techniques in order to avoid the more serious consequences of undetected errors. Fortunately, the added bandwidth required for such error correction is usually available with this type of system because of the long periods between data exchanges among the processor units.

3. COMMUNICATIONS TRADE-OFF ANALYSIS

The Federal-Aid Highway Program Manual requires that "traffic surveillance and control system projects shall be based on a traffic engineering analysis".(2) A crucial element of this analysis is to examine communication alternatives and to select the communication system which best fits into the overall traffic control system picture.

Alternative communication systems can be differentiated by several different, yet related, parameters. As discussed in the previous chapter, these communication system variables include the type and amount of information to be exchanged, the rate of information transfer, the communications medium, transmission and modulation techniques, the reliability of data transmissions, and the type of interface hardware. Nontechnical elements must also be considered, including procurement of the communications system and its continued maintenance; agreements, legal requirements, and similar institutional arrangements; ownership of the communications network and the potential for sharing facilities; and costs and funding requirements. These various elements are interdependent -- a decision on one of the variables will affect decisions concerning the other elements. Furthermore, their relative importance is not fixed, but depends on the type of traffic control system being considered and the location.

This chapter presents guidelines for conducting a thorough communications trade-off analysis. The recommended procedure is summarized in figure 14, and an example is provided in the appendix. It is emphasized that the communications trade-off analysis is more of an iterative process involving both tangible and intangible considerations, rather than a simple analytical comparison of a number of alternatives. Furthermore, the process is integral to the overall system traffic engineering analysis. Any decision regarding a particular component of the communications subsystem will not only impact the other communication elements, it may also affect the capabilities and functions of the overall traffic control system; and vice versa.

TRANSMITTED INFORMATION

The traffic engineering analysis involves the evaluation of alternative traffic control system concepts. As discussed in the previous tutorial chapter, there are three

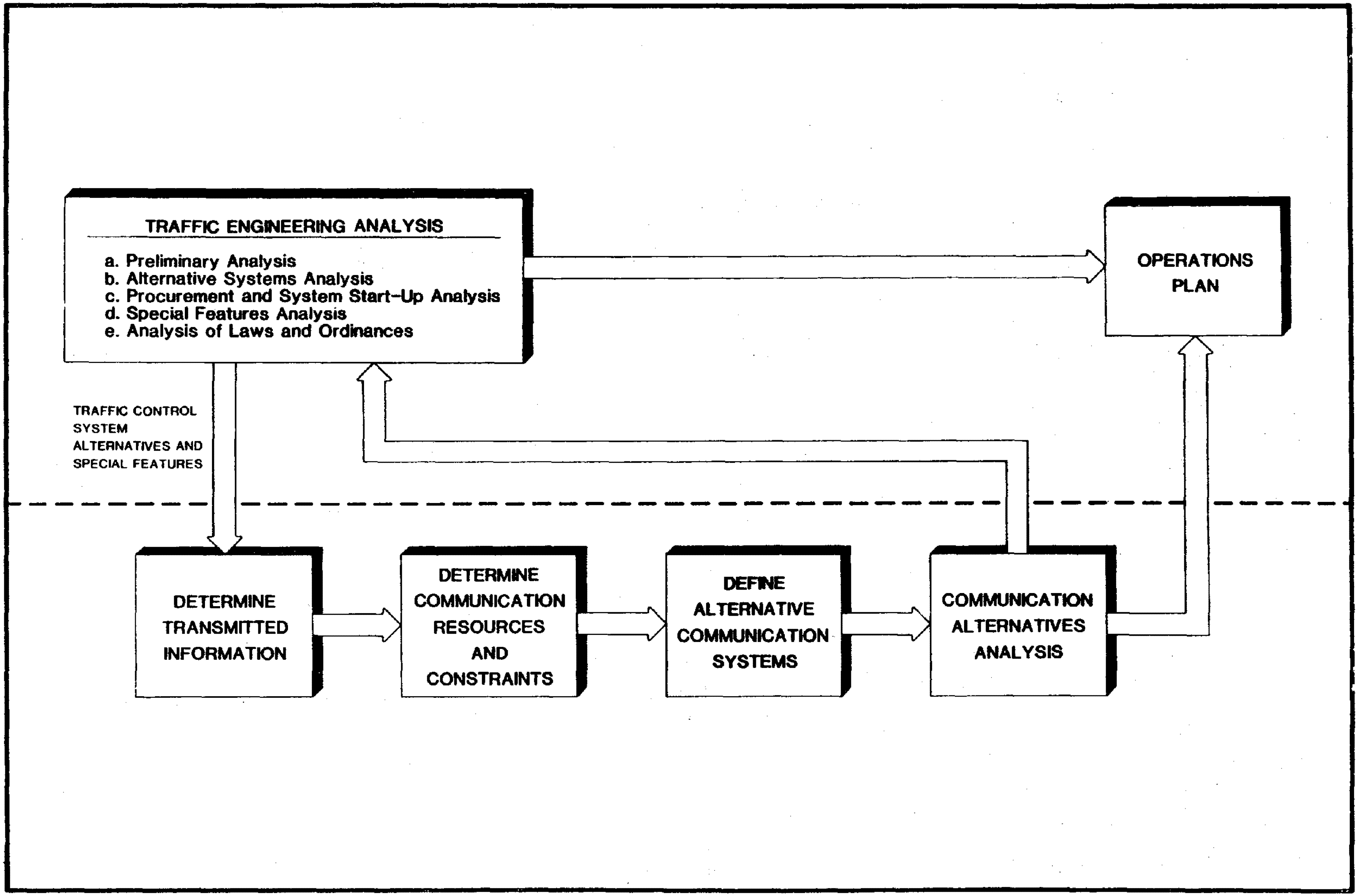


Figure 14. Communications trade-off analysis.

basic configurations a traffic control system can take: centralized with direct control; centralized with downloading/uploading; and distributed. Each one of these systems has different communication requirements.

In this initial step of the communications trade-off, it is necessary to determine the following basic communication parameters for each traffic system alternative:

- Type of information to be transmitted.
  - Data (control commands, monitoring information, detector data, etc.)
  - Voice
  - Video

- Quantity of information.
  - Frequency of transmissions (e.g., once per second, once per minute, as-needed)
  - Bandwidth required
  - Minimum baud rates

- Quality of information.
  - Allowable undetected errors
  - Error control techniques

- Network configuration (path of information).
  - Point-to-point/point-to-multipoint/daisy-chain/ring
  - Full-duplex/half-duplex

Special Features

Unique or special features which are being considered for inclusion in the traffic control system must also be analyzed with respect to their information requirements. Examples of these special features include emergency vehicle priority control, back-up systems, closed circuit television (CCTV), and advanced traffic control strategies such as Critical Intersection Control (CIC) and 1.5, 2nd, and 3rd generation control of traffic signals.

The incremental information required by many special features will have little or no impact on the communications subsystem. On the other hand, some special features can have a significant effect, and may become the critical factor in selecting and designing a communications network. For example, the relatively large bandwidth (6 MHz per camera) required by real-time CCTV will typically dictate the use of coax cable, fiber optic cable, or some high-speed air-path medium.

The additional data loading from system detectors is an important consideration. Advanced traffic control strategies require significant detectorization -- for example 1.5GC and 2GC signal systems require an average of 2 to 4 system detectors per signalized intersections. As the number of system detectors increases, so does the quantity of information that must be transmitted from the field to central. Accordingly, it may become necessary to utilize field communications hardware (RCU's) which preprocess the detector data prior to transmission (with a corresponding reduction in the frequency of the data transmissions), reduce the number of drops on each multipoint channel, or a combination.

COMMUNICATION RESOURCES AND CONSTRAINTS

A determination of existing communication resources and constraints is an important part of the preliminary analysis. This effort is essentially an inventory of locality-specific factors which have a large impact on communication costs, and which can markedly influence the selection of a communication system and its subsequent design. A summary of the physical features and institutional considerations that should be included in this communications "treasure hunt" is provided in table 3.

COMMUNICATION ALTERNATIVES

The next step of the trade-off analysis is to develop alternative communication networks for each traffic control system configuration that is being considered in the overall traffic engineering analysis. These alternative communication systems must be configured to function within the constraints identified during the previous step, and to adequately handle all of the transmitted information including any special feature requirements. Alternative networks which can not accommodate all the desired system features and functions may also need to be configured and analyzed as a

Table 3. Existing communication resources and constraints.

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
- Location of telephone and CATV terminations relative to field cabinets
- 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

Table 3. Existing communication resources and constraints (continued).

INSTITUTIONAL FACTORS

- Rights-of-way
- Franchise agreements between utility companies and government agency
  - Right of the agency to use utility conduits and pole lines
  - Responsibility for clearing ducts and utility adjustments
- Franchise agreements with CATV
  - Government use of cable
- Telephone company tariffs and policies
- Other agreements (formal and informal)
- National and local codes
  - National Electric 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 skills/experience in installation of communication networks

fall-back position.

Alternative communication subsystems may be differentiated in terms of their media, ownership, and interface hardware.

Media

At the heart of a communications subsystem is the transmission medium. Each communications medium has inherent characteristics -- such as frequency response and bandwidth, susceptability to interference and noise, allowable baud rates, repeater requirements, physical constraints, etc. -- which determine its suitability for use in a particular traffic control system. The media listed in table 4, as of this document's date, are being used to meet the information needs of the various traffic control system concepts and functions. A summary of these and other communications media is presented in table 5. Detailed information on communications media is presented in chapters 4 and 5.

Ownership

Communication networks may be owned, leased, or shared. They may also consist of a combination of owned and leased -- a hybrid network where part of the system communications is over owned-transmission links, and the remainder is handled by leased channels. Examples of combined networks include:

- A distributed system where owned-interconnect cable is used between field masters and the signalized intersections; and leased dial-up circuits are utilized between the field master and the central microcomputer.
- A centralized system where a group of intersections comprising a multipoint circuit are interconnected with owned-cable; and this "channel" is tied to the central facility via leased lines.

Owned Network

The initial step in configuring a jurisdiction-owned cable network is to plot any existing communication resources (e.g., cable, conduits, pole lines) on a map. Cable routings connecting the field drops with the central facility (or field masters) should then be developed in priority of the following categories:

Table 4. Communications media currently used in traffic control systems.

CENTRALIZED (Direct Control and Uploading/Downloading)

- Twisted - pair cable (owned and leased telephone)
- Coax cable (owned and leased CATV)
- Fiber optics cable

DISTRIBUTED (Field Master - Intersections)

- Twisted - pair cable (owned and leased telephone)
- Fiber optics cable

DISTRIBUTED (Field Master - Central Microcomputer)

- Twisted - pair (owned and leased "dial-up" telephone)
- Radio

VIDEO INFORMATION

- Coax cable (owned and leased CATV)
- Fiber optics
- Microwave
- Twisted-pair (slow-scan)

TRUNKING

- Fiber optics
- Microwave
- High-speed digital telco

Table 5. Summary of communications media.

Comm. System	Own/ Lease	Media	FCC Coord.	Carrier Freq.	Bandwidth	Bandwidth Proportional to distance	Repeater distance	Data bps	Voice #ch.	Video #ch.
Twisted Pair	O	Copper pair	No	1.7 kHz	2.7 kHz	No	15-25 km	2.4 kbps	1	-
Voice Grade Telephone Channel	L	Varies	No	1.7 kHz	2.7 kHz	No	N/A	2.4 kbps	1	-
Coaxial Cable	O	Coaxial Cable	No	5-350 MHz	Up to 300 MHz	No	1-5 km	Up to 10 Mbps	100	Up to 50
CATV	L	Coax/Microwave	No	5-350 MHz	6 MHz/ch.	No	N/A	Up to 7.5 Mbps	100	1/ch.
Fiber	O	Fiber Optic Cable	No	850-1550 nm	Up to several GHz	Yes	1-20 km	Up to several Gbps	100	Up to 16
Terrestial Microwave	Both	Atmosphere	Yes	2-23 GHz	Up to 220 MHz	No	2-32 km	Up to 50 Mbps	100	Up to 16
Satellite Microwave	L	Atmosphere	Yes	2-6 GHz	Varies with service	No	N/A	Up to 50 Mbps	100	1
High-Speed Digital Telco	L	Varies	No	Baseband	Varies with service	No	N/A	Up to 6 Mbps	Up to 96	-
Atmospheric Laser	O	Atmosphere	No	830 nm	10 kHz-6 MHz	Yes	1-15 km	Up to 1.5 Mbps	Up to 24	1
Radio-928/952 MHz	O	Atmosphere	Yes	928-952 MHz	25 kHz/ch	No	15-30 mi	Up to 9.6 kbps	1	-
Radio-Cellular	L	Atmosphere	Yes	825-890 MHz	30 kHz/ch	No	N/A	1.2 kbps	1	-

- Existing cable and routing.
- New cable in existing jurisdiction-owned underground conduit.
- New cable on existing joint-use pole lines and/or in existing joint-use conduits.
- New cable on new jurisdiction-owned pole lines.
- New cable in new underground conduit/new direct burial cable.

The use of existing cable and conduit can significantly reduce the cost of the communications network, thereby reducing the overall cost the traffic control system. It is imperative, however, that such "gift horses" be carefully examined to ascertain their adequacy for traffic surveillance and control applications. The design or installation quality of the existing resources may be unsuitable, or the facilities may have severely deteriorated since their installation.

Any existing cable plant which is being considered for the traffic control system must be thoroughly tested. The cable should be surveyed by sending the appropriate signals through the various transmission links, returning the signal from the opposite end of the link, and comparing the returned signal with the transmitted signal to determine the suitability of the existing cable network for system communications.

Existing conduit runs should be physically rodded to ascertain where the conduit may have collapsed or broken. It can then be decided whether to have the conduit repaired, or to install a new conduit run. Another conduit test, in lieu of rodding, is to tug on any existing cables at each junction box and termination point. If the existing cables move freely, then the conduit can likely be used. If the cables are stuck, it implies a constriction or blockage in the conduit, and a new conduit run should be installed. This latter survey is easier and less time consuming than rodding; but it may result in more new conduit than is actually required -- the conduit "blockages" may simply be mud or silt which are easily cleared by rodding.

Another concern with existing conduit is its size and layout. Important considerations include:

- Sufficient conduit capacity for the new communications cable(s).
- Lay-out of the conduit network is appropriate for pulling and terminating the new communications cable(s) (e.g., spacing between pull boxes, number of conduit bends between pull boxes, radii and degree of bends, etc.).

- Possible code violations.

It is often possible to install communication cable in a spare conduit of a utility company duct network, or to use space on joint-use utility poles. Such arrangements should be based on a franchise agreement with the utility company. However, in some cases, they may be based on less formal arrangements or even on a verbal understanding. In the latter case, it may be worthwhile to formalize the agreement with a letter of understanding prior to commitment of funds for the communications system's installation.

Alternative cable routings that use existing joint-use pole lines must be checked in the field, with utility representatives, to determine the adequacy of the pole line and if any utility adjustments will be required. Utility adjustments can be extremely costly, particularly on poles where perpendicular lines intersect, or on poles with primary or secondary transformers. Utility company representatives may be helpful in suggesting alternate cable routings that would result in lower costs.

Utility companies usually have regulations governing the installation of cable in their ducts -- for example, the requirement that a utility inspector be present at any time work is underway in their facility; limitations on the type of cable and transmissions which are permitted in their ducts; and, in some instances, the requirement that utility company personnel install the cable. Another important consideration is the delineation of responsibilities between the utility company and owner (e.g., who is responsible for clearing a blocked duct or repairing a collapsed duct). These utility requirements may impact the cost of a communications alternative and should be analyzed during the trade-off study.

When new poles and conduit are required for a communications alternative, the proposed routing and layout should be checked in the field to determine if any additional right-of-way will be required, to identify any obstructions that may affect the routing, and to provide an accurate estimate of quantities. Of particular concern, is the amount of underground conduit to be installed in trench as compared to new conduit installed under pavement.

The effort involved in cable testing, surveying existing conduit and poles, and field checking proposed communication facilities can be time consuming and somewhat costly. It is essential, however, that it be accomplished either during the traffic engineering analysis or at the very beginning of system design. Only in this manner can reliable costs be developed for the communications network alternatives -- cost estimates which are a major factor (although not the only one) in selecting the "best" communications system for each traffic control alternative.

More often than not, the money and time spent during this step of the communications trade-off analysis will pay significant dividends in the end. There have been numerous instances where the acceptability of existing communication facilities was just assumed resulting in major unanticipated increases in construction costs, project delays, and contractor claims. For example:

- New conduit had recently been installed during a freeway reconstruction project as part of a staged construction plan for a surveillance and control system. During system design it was assumed that, since the conduit was new and contained no other cables, there would be no blockages to restrict pulling of the new communications cable. This assumption turned out to be true. However, the conduit had been installed in accordance with the jurisdiction's standard specifications which permit up to 360° of conduit bends between junction boxes. This is adequate for power cables used in street lighting. But it was impossible to install 3/4-in coaxial cable in this conduit as was required by the system plans and specifications. A change order was issued to the contractor to install several miles of new conduit.

- The contract documents for a system called for the use of existing conduit in the CBD. The condition of the conduit network, however, was never checked. Shortly after the contractor started work, several problems were identified:

  - Much of the conduit was more than 40 percent full (in violation of the National Electric Code).

  - Much of the conduit contained power cables (which can cause significant noise problems).

  - Several manholes had been paved over, with no contract provisions as to who would locate and raise them to grade.

  - Existing pull box covers could not be removed without breaking them.

  The contractor refused to install cable under these circumstances and stopped work. The job was shutdown for over a year; a claim had to be settled before work resumed; and, because of limited project funds, new conduit could not be installed and the CBD had to be eliminated from the system project.

- The cost of new communications conduit was estimated based on a "representative sample" of freeway (i.e., proportion of conduit in trench as compared to conduit under pavement), and then expanded over the entire freeway surveillance and control system. This representative section turned out to be very atypical, and significantly more conduit under pavement (which was more expensive than conduit in trench) was required during construction. The impact to the project budget was an increase of several million dollars.

When using existing conduit for communications cable, it may be worthwhile to include in the contract documents pay items for cleaning the existing conduit runs and for repair of the conduit. The special provisions should also address any existing cables in the conduit -- are they to be removed; can they be pulled out and re-pulled with the communications cable; what are the contractor's responsibilities if they are damaged, etc. Additional contingency funds should also be included in the project budget.

Leased Network

The alternative to jurisdiction-owned cable is a leased communications network such as telephone company (Telco) circuits or CATV. Developing the configuration and cost of a leased communications system can only be performed by working closely with representatives of the local telephone company and CATV company. These representatives should include engineering, sales, and data transmission personnel. They should be advised of the information to be transmitted, the data rates and bandwidth required, the quality desired, the operational aspects of the system (e.g., once-per-second/dial-up communications, full/half-duplex, etc.) and the field locations (e.g., controller/ramp meter cabinets) to be included in the system.

The following information must be clearly defined and understood by all parties:

- The characteristics of the leased channels and equipment restrictions. This would include data rates, transmission characteristics and quality; frequency allocations; and any limitations (e.g., maximum number of multipoint drops on a channel; dial-up times, etc.).
- Capability of the local telephone/CATV company to furnish service to the field locations and capability for expansion.
- Estimated period of the time until service can be provided.
- Location of the nearest access point to the Telco/CATV cable from each field cabinet, and the division of work between the telephone/CATV company and the user in connecting to this point.

Some companies will bring the service to the controller for a fixed charge, while others terminate at some point (e.g., top of pole, manhole) and the jurisdiction must provide conduit or other facilities from the termination point into the cabinet.

- Rules regarding leased circuit terminations at the field cabinets, and any special requirements for isolating the telephone/CATV lines from controller equipment. A separate access door or separate cabinet mounted on the side of traffic control cabinet is usually required for telephone company termination equipment.

- Rules regarding leased circuit terminations at the central facility, including any equipment which must be furnished by the jurisdiction.

- Complete understanding of the Telco tariff/CATV franchise agreement (e.g., how are costs computed, what happens if a telephone exchange boundary is crossed, etc.).

- Firm quotation of costs -- both one-time charges and monthly fees.

- Pending rate increase requests, if any, and an estimate of expected increases in leasing rates.

- Respective maintenance responsibilities of the telephone/CATV company and of the jurisdiction. Maintenance policies of the telephone/CATV company, including response time and method for determining charges if fault is determined to be in the jurisdiction's equipment after Telco/CATV maintenance has been called for and provided.

Once the above information has been obtained, leased network configurations can be developed to obtain cost estimates for the trade-off analysis. In addition to the Telco/CATV fees and charges, the cost of leased alternatives must also include the construction of connections facilities (e.g., conduit laterals) between the Telco/CATV termination point and the controller/ramp meter cabinets, and the cost of any special hardware required to interface with the Telco/CATV circuits.

Integrated Communication Networks

The discussion so far has focused on configuring communication networks that have a single function -- the transmission of information for a traffic control system. Another possibility is to share the communication links with one or more additional independent systems. An example of this would be a jurisdiction-wide communications network encompassing police, fire, data processing, and other transmissions in addition to the traffic control system. Other less involved examples include using the same twisted-pair cable network for both traffic control and fire call boxes, and a traffic control system and parking advisory system using the same cable. While the functions of the various entities would be completely independent, the communications medium would be integrated and shared.

Several of the available communications media, such as coaxial cable and fiber optics, have a relatively large bandwidth which may be substantially underutilized by just the traffic control system. Given that the communication system is frequently the most costly element, it may be in the best interest of the local jurisdiction to utilize the communications medium for as many functions as possible.

Cost sharing is a major advantage of an integrated communications system. Furthermore, the incremental cost of providing a communications network which is capable of handling multiple systems and functions is significantly less than the cost of multiple independent communication networks. Additional information on integrated systems -- systems which share some of the same data or a common hardware element -- is provided in reference 1.

Interface Hardware

As discussed in chapter 2, the communications interface hardware performs such functions as input/output, data processing, modulation and demodulation (modem), data message formatting, and related tasks. The specific features and performance characteristics of the interface units will vary depending on the basic configuration of the traffic control system. The interface hardware will also vary depending on the communications media used. Different media require different types of modems as well as different communication line connectors. The availability and the sophistication of the communications interface hardware, and the corresponding costs and maintenance requirements, must be considered when configuring and comparing alternative communication systems.

The communications interface hardware can have a major impact on other traffic system components, particularly controllers. This interface can be accomplished either by a separate external unit, or internal to the controller. An internal communications interface is provided in the Type 170 controller and for most off-the-shelf distributed ("closed-loop") signal systems. The majority of centralized systems (e.g., UTCS) have used external interface hardware.

There are advantages and disadvantages to each approach. An internal communications interface has three advantages over the use of a separate unit:

- The cost of a controller with an internal interface is usually less than the cost of a controller (without this internal capability) plus the cost of the separate RCU.
- Space is often a problem in controller cabinets. Using a controller with internal communications reduces the space required in the cabinet and may permit the use of a smaller, less expensive cabinet than is required by having an external communications unit.
- An internal interface permits the system to access controller memory. This allows for uploading and downloading of controller settings (e.g., Min Green, Walk, Clearance, etc.). External units are limited to coordination inputs (HOLD, FORCE-OFF, Cycle, etc.)

These advantages may be offset by other considerations. Most controllers with internal communication units have been designed to interface only with twisted-pair cable (owned or leased). If another medium is to be used, then a separate external processor will be required to convert the data signal into a form that the controller can accept. Another major disadvantage of using an internal communications interface is that most, if not all, of the existing controllers will have to be replaced with a particular controller type and model possessing the specific internal processing capabilities. This is not a major concern if most of the existing controllers need to be replaced anyway due to age or maintenance considerations. However, if a majority of the existing controllers can otherwise be retained, then the use of an external communications interface will significantly reduce costs. Similarly, external communication units also permit interchangeability of controllers.

Standardization

One of the more serious problems confronting the traffic control system industry today is the absence of a usable standard for communications interface. Type 170 controllers do feature a standard internal interface for twisted-pair cable and leased telephone lines. This standard addresses the voice-grade modem, input-output requirements, and connectors.

The interface hardware for NEMA and pretimed controllers, however, are manufacturer dependent. As previously noted, most of the distributed signal systems offered by controller manufacturers incorporate a proprietary internal communications interface. Thus, the manufacturer's specific controller model must be used when initially installing the system and during subsequent expansions. Numerous centralized systems have used an external controller interface; but the RCU's have been designed and manufactured to meet the particular specifications of each individual system project, thereby giving the original vendor a significant cost advantage, if not outright proprietary, during system expansions. These unique designs, coupled with relying on a single source of supply, have caused problems in traffic control systems, including:

- Inability to change RCU/controller manufacturers (without excessive costs) when expanding the system, or because of unacceptable equipment performance.
- Inability to provide technical or hardware support between systems. If one city is experiencing an unusual communication problem, assistance in the form of skilled personnel, spares, or test equipment cannot be provided because of the differences in system design.
- Inability to use standard equipment already available in the commercial marketplace -- products are uniquely designed for the traffic control industry.

Efforts are being made to correct these problems. A preliminary communications interface standard has been developed and field tested under a FHWA research contract.(5) In order to achieve interchangeability between controllers, this proposed standard is restricted to external interface units. The National Electrical Manufacturers Association (NEMA) is working on a new standard (tentatively called TS2) which will address internal communications interface and coordination.

At least one systems management firm offers a license agreement which provides a jurisdiction with full access to the RCU firmware for the exclusive use in the system. Detailed fabrication drawings and specifications of the RCU hardware are also provided. This approach eliminates any risk of proprietary procurement during future system expansions. Compatible and interchangeable RCU hardware, which can be built by numerous firms in accordance with the hardware drawings and specifications, may be procured through competitive bids. There are no future software development costs since the jurisdiction already "owns" the RCU software as noted above.

Other

Other issues that must be considered during the trade-off study include:

- Repeaters; including capabilities, power supply, and housing.
- Line-of-sight paths between intersection transceivers, repeaters, and central antenna for air-path media.
- Location and installation of air-path hardware.

ALTERNATIVE SYSTEMS ANALYSIS

The previous steps of the trade-off analysis will result in alternative communication networks for each traffic control system under consideration. The various construction techniques, hardware components, maintenance levels, and institutional arrangements required for each of the subsystems will also have been defined. From this information, cost estimates can be developed and assessed along with qualitative elements.

The cost estimates should include both one-time costs (i.e., installation) and recurring charges as summarized in table 6. These costs should then be converted to an equivalent life-cycle cost for a system life of 10 to 15 years. In general, the one-time communication expenses are eligible for Federal-aid highway participation, while the recurring costs must be funded by the owner. There are, however, some special rules and guidelines relative to Federal-aid participation for leased Telephone and CATV networks. These policies are discussed in the next chapter.

The selection of the optimum communications network for each traffic control system alternative should not be based solely on life-cycle costs. There are numerous intangibles which must be assessed including:

- Disruption of existing system operations during construction of new communications network.
- Ability to expand the communications system, both geographically (add field drops) and functionally (add special functions) at a later date.
- Ability to procure expansion hardware and spare parts in the future (e.g., what happens if a single source of supply discontinues the product line or goes out of business).

Table 6. Communication system costs.

ONE-TIME COSTS (Installation)

- Cable

- Underground Installation
  - New conduit in trench
  - New conduit under pavement
  - Junction boxes
  - Termination/splice cabinets
  - Repair/cleaning of existing conduit
  - Manhole entry
  - Controller cabinet entry

- Overhead Installation
  - New poles
  - Utility adjustments on existing poles
  - Aerial drops

- Hardware
  - Central communications interface (modems and processors)
  - Remote communication units and connections
  - Modifications to existing controllers
  - Auxiliary cabinets
  - Repeaters
  - Antennas
  - Air-path transceivers
  - Surge protection devices

- Other
  - One-time Telco/CATV charges
  - Test equipment
  - Maintenance training and documentation
  - Licensing fees

RECURRING COSTS

- Maintenance*
  - Additional staff/higher skill levels
  - Contract maintenance
  - Spare parts

- Leasing Fees
  - Telephone company lease charges
  - CATV charges
  - Utility duct rental fees

*Note: A rule-of-thumb for computing annual communications maintenance costs is 10% of hardware costs (RCU's, CCU); and 5% of cable costs (not including conduit costs).

- Availability and required skill level of in-house and/or contract maintenance personnel; training opportunities; potential turnover of trained personnel.
- Priority of maintenance response -- in-house staff, leased Telco/CATV, contract maintenance.
- General quality of signal to be provided -- electrical interference rejection, immunity from current surges and weather (e.g., lightning).
- Vulnerability to deterioration and damage (e.g., water infiltration in cable, cabinet knockdowns, damage from construction activities, etc.).

Given the many intangibles involved, the deciding factor in selecting a communications system may be engineering judgement, coupled with a consideration of costs. The optimum communications network for each alternative traffic control system is then integrated with the overall traffic engineering analysis.

OPERATIONS PLAN

The final element in the traffic engineering analysis is an Operations Plan. Prior to authorization of Federal-aid highway funds for system construction, there must be a commitment to the Operations Plan. The Operations Plan should address the communication related items summarized in table 7.

PLANNING AHEAD

Having communications resources available or franchise provisions for communications facilities at the time a traffic control system is being developed can be quite valuable. Accordingly, it is often good practice to develop such resources or provisions in advance. Examples include:

- Conduit installed in advance in conjunction with major utility work (such as water main project).
- Conduit installed in conjunction with utility relocation and street reconstruction project.
- Utility company agreement to reserve one or more ducts in multi-duct installations.

- Conduit installed in conjunction with freeway reconstruction project (e.g., conduit in median barrier construction).
- Provision for traffic control communications, including functional performance criteria, negotiated into new franchise agreements for cable TV or utility agreement with a new telephone/data communications firm.
- Provision for traffic control communications in an integrated communications system.

It is essential, however, that the technical requirements, design, and construction management for such "pre-system" elements be commensurate with the intended system use. For example, if there is a possibility that coaxial cable will be used in the system, then any conduit that is installed during an earlier construction project must be designed and installed accordingly. It is noted that the costs of communications subsystem elements (e.g., conduit) which are to be installed under an earlier project may be eligible for Federal-aid participation; provided that there is a level of commitment to the traffic control system project, and the service life of the communications element can be expected to be commensurate with the timetable for the initiation, installation and operation of the traffic control project.

Table 7. Communications elements - system operations plan.

NEEDED LEGISLATION AND AGREEMENTS

- Changes in existing rules or ordinances to permit installation of communication system
- Agreements with telephone company, utility company, CATV
- FCC license

SYSTEM DESIGN

- Hardware design (off-the-shelf, custom, product development, etc.)
- Design responsibility

SYSTEM PROCUREMENT

- Responsible entity (e.g., contractor, utility company, jurisdiction) for installing communications network (e.g., cable, terminations, etc.)
- Responsible entity for furnishing/installing communications hardware
- Responsible entity for integrating communications system with overall traffic control system
- Special qualifications (i.e., prequalification requirements) for responsible entities
- Schedule relative to other traffic control system elements

CONSTRUCTION MANAGEMENT

- Monitoring and inspection of communication system installation
- Qualifications of inspectors; hiring; training
- Acceptance testing requirements
- Test equipment

Table 7. Communications elements - system operations plan (continued).

- Entities responsible for conducting and monitoring communication acceptance tests
- Process for review and approval of communication submittals and change orders

OPERATIONS AND MAINTENANCE

- Maintenance responsibilities (e.g., in-house, contract, utility company)
- Training to be provided to maintenance personnel, by whom, and when
- Maintenance documentation to be provided
- Spare parts
- Test equipment
- Future availability of hardware for maintenance and expansion
- Commitment to provide the necessary budget and staffing

4. EXISTING COMMUNICATION TECHNOLOGIES

This chapter addresses those communication technologies which have been widely used in computer-based traffic control systems. The discussion focuses on the communications media -- their characteristics, transmission techniques, and associated advantages and disadvantages. Twisted-pair cable, leased telephone channels, coaxial cable, and CATV are described. Guidelines for the successful application of these media in traffic control systems are also presented.

TWISTED-PAIR CABLE

Characteristics

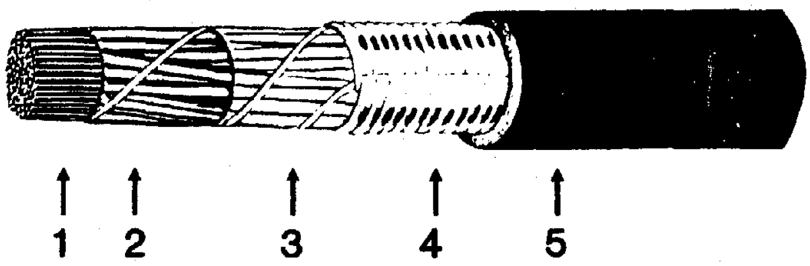
Jurisdiction-owned twisted-pair cable is one of the most widely-used communication mediums for traffic control systems. Physically, this medium consists of individually insulated copper wires twisted into pairs, and combined into a shielded cable. The requirements for multipair cables are governed by the Rural Electrification Administration (REA) specifications for telephone cables. Some of these requirements and the various types of twisted-pair cables are summarized in table 8.

REA twisted-pair cable is manufactured in several standard numbers of pairs -- 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, and even more depending on the wire gauge. On cables having more than 25 pairs, the twisted-pairs are arranged in bound groups, with each group containing 25 pairs.

The wire pairs are color coded for easy identification and so that each pair is distinguishable from all other pairs. The color code uses a scheme whereby a different color combination of insulation is provided for each pair in a 25-pair group. Colored or imprinted bindings are used to distinguish the individual groups from each other. The REA color code is provided in table 9.

Table 8. Summary of REA cable specifications.

BASIC CABLE CONSTRUCTION



1. CONDUCTORS - solid annealed copper; available conductor sizes are 19, 22, 24, and 26 gauge (Note - The larger the gauge size, the smaller the diameter of the conductor.)

2. INSULATION - High-density polyethylene or polypropylene.

3. BINDING TAPE - overlapping high dielectric tape.

4. SHIELD - 0.008" corrugated aluminum tape (coated and overlapping).

5. OUTER JACKET - low density, high molecular weight polyethylene; with sequentially numbered length markers along the outside.

Some cables are **filled** -- the entire cable assembly under the outer cable jacket is 100 percent flooded with a petrolatum-polyethylene gel filling.

Table 8. Summary of REA cable specifications (continued).

CABLE TYPES

SPEC	DESIGNATION	DESCRIPTION AND TYPE INSTALLATION
PE-22	CA	Air core - underground conduit, and aerial supported by separate messenger cable.
PE-23	BJA	Air core - direct earth burial. Cable includes a polyethylene inner jacket between the binding tape and shield.
	BJG	Same as BJA, but has a bi-metal or alloy shield for installation in gopher or other severe service areas.
PE-38	CAK	Air core - aerial, self-supporting. A 1/4-in. steel messenger cable is integrated with the outer jacket in a "figure 8" configuration.
PE-39	BJFA	Filled - underground conduit, aerial supported by separate messenger, and direct earth burial in non-gopher areas.
	BJFC	Same as BJFA, but with a copper shield.
	BFCX	Filled - direct earth burial in gopher or other sever service areas. Cable includes a steel shield over the aluminum shield.

Table 9. REA color code.

25-PAIR GROUPS

Pair No.	Color Tip	Color Ring	Pair No.	Color Tip	Color Ring
1	White	Blue	14	Black	Brown
2	"	Orange	15	"	Slate
3	"	Green	16	Yellow	Blue
4	"	Brown	17	"	Orange
5	"	Slate	18	"	Green
6	Red	Blue	19	"	Brown
7	"	Orange	20	"	Slate
8	"	Green	21	Violet	Blue
9	"	Brown	22	"	Orange
10	"	Slate	23	"	Green
11	Black	Blue	24	"	Brown
12	"	Orange	25	"	Slate
13	"	Green			

GROUP BINDINGS

Color of Bindings	Group Pair Count	Color of Bindings	Group Pair Count
White - Blue	1 - 25	Black - Green	301 - 325
White - Orange	26 - 50	Black - Brown	326 - 350
White - Green	51 - 75	Black - Slate	351 - 375
White - Brown	76 - 100	Yellow - Blue	376 - 400
White - Slate	101 - 125	Yellow - Orange	401 - 425
Red - Blue	126 - 150	Yellow - Green	426 - 450
Red - Orange	151 - 175	Yellow - Brown	451 - 475
Red - Green	176 - 200	Yellow - Slate	476 - 500
Red - Brown	201 - 225	Violet - Blue	501 - 525
Red - Slate	226 - 250	Violet - Orange	526 - 550
Black - Blue	251 - 275	Violet - Green	551 - 575
Black - Orange	276 - 300	Violet - Brown	576 - 600

Transmission Techniques

Twisted-pair cable provides a voice-grade transmission link with a usable bandwidth from approximately 300 Hz to 3000 Hz. Typical data rates achievable with twisted-pair cable are limited to around 1200 bits per second with acceptable error. If a higher data transmission rate is required, the cable must be conditioned by the addition of electronic equipment (loading coils) to improve the transmission characteristics.

In traffic control applications, the data are frequency shift keyed (FSK). As previously discussed in chapter 2, FSK is the binary form of frequency modulation (FM). Other types of modulation have been used with twisted-pair communications cable, but FSK provides a good combination of noise immunity, low error rates, and data rates. Another advantage of FSK modulation with twisted-pair media is that transmitters can be turned on and off very quickly (less than ten bit times). This allows several field drops to communicate over the same multipoint channel using time division multiplexing (TDM) techniques.

A channel consists of one pair operating half-duplex, or two pair operating full-duplex for the FSK modems typically used. The modems can be configured for either full- or half-duplex operation. Although much of the actual transmission is half-duplex, the two pair termination if generally used to avoid the turnaround problems associated with single pair terminations.

Attenuation in twisted-pair cable networks is influenced primarily by frequency and conductor size. As the operating frequency increases, attenuation in twisted-pair cable increases at a rate approximately proportional to the square root of the frequency. Attenuation is also greater in larger gauge (i.e., smaller diameter) conductors. Assuming no loss of signal from other factors, at a frequency of 1000 Hz, a 19 gauge cable exhibits a 1.25 dB/mile loss, a 22 gauge cable exhibits a 1.79 dB/mile loss, while a 26 gauge cable exhibits a 2.85 dB loss.

Each channel must be repeatered (i.e., amplified) approximately every 10 miles; depending on wire gauge, noise levels, operating frequency, transmission levels, and receiver sensitivity. Repeatering in twisted-pair systems requires that each and every pair be amplified separately. In very large systems and/or large areas, this can become a limiting factor.

Noise and Interference

A multipair cable can transmit several channels of information -- one channel for every two pairs in a full-duplex network. Since the cable is conveying more than one signal simultaneously, it can experience crosstalk which, as discussed in chapter 2, is the reception of portions of a signal from one pair by another adjacent pair. This inductive coupling of signals between pairs is minimized by the twisting of pairs. As shown in figure 15, the same electrical current flows in each conductor of the pair, but in opposite directions. Thus, the electromagnetic fields radiated from the two conductors are also in opposite directions. The two induced fields essentially cancel each other out, thereby minimizing the amount of energy transferred to adjacent pairs. It is also important to keep all signal levels to a minimum.

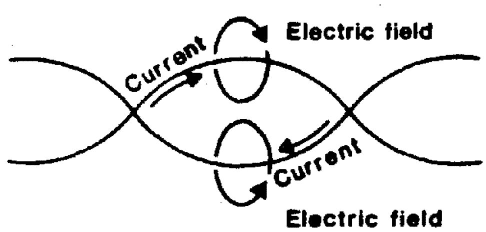


Figure 15. Crosstalk reduction.

The chief source of noise in twisted-pair cables is from 60 Hz power sources. 60 Hz noise does not have a significant effect on the modems typically used in twisted-pair system (e.g., Bell 202 standard) as they filter out signals below 750 Hz. However, harmonics -- multiples of the fundamental power line frequency -- may cause interference. The cable shield also drains off induced signals and noise.

Noise levels in twisted-pair cable can be held to very low levels if proper care is taken in the design and construction of the cable system. Ideally, the shields of all the cables should be bonded together (providing a continuous shield) and grounded at a single location. Multiple grounding locations and/or unbonded shields will permit noise to enter the cable network, disrupting system communication. It is noted that when a single ground is provided in a large cable network, the electrical potential on the shield can become quite large and, therefore, constitute a hazard to anyone working in a field cabinet should they inadvertently come in contact with the shield. In these circumstances it is best to divide the cable network into "grounded sections". Each section has a single ground location and the cable shields within a section are continuous to the ground; but the shields are not bonded between sections.

Traffic Control Applications

Twisted-pair cable is widely used for the transmission of traffic control data. Centralized systems are configured with between 4 and 16 controllers on each TDM channel. The exact number of drops depends on the amount of data to be transferred between central and the field locations, and the rate of transfer. Since many twisted-pair communications channels are involved in a traffic control system, a Communications Control Unit (CCU) is normally used to reduce the processing load on the central computer. The CCU provides an interface between the modems and the central computer.

As previously noted, a twisted-pair cable provides voice-grade channels. Thus, this medium is very suitable for voice communications. Provision of a voice channel between the central facility and the field locations (for maintenance purposes) requires a dedicated wire-pair connecting the central site with each field drop.

Traditionally, CCTV has not been able to use twisted-pair cable for video transmissions because of bandwidth limitations. A recent technique -- Slow-Scan TV -- now permits the use of twisted-pair cable for CCTV in some applications. Slow-scan digitizes the picture, and transmits frames at a rate of one every 2 to 5 seconds with reasonable picture quality. Where full-motion video is not essential, slow-scan over twisted-pair cable (or telephone lines) may offer a cost-effective solution.

Design and Installation

In designing a twisted-pair communications network, consideration must be given a number of factors, including:

- Number of pairs required for initial system and subsequent expansions. This is a function of the total number of field drops, the maximum number of drops allowed on each channel, and the network configuration.

- The types of cable to be installed (e.g., air core, filled, figure 8, direct burial) and gauge of conductors.

- Cable routing and installation techniques. This is a function of the field drop locations, existing communication facilities, cable termination requirements, and minimizing costs.

- Environmental effects, such as moisture entry, noise, and transients.

- Other considerations such as repeaters, special functions of the system, and testing.

All these many factors are interrelated. For example, use of a smaller gauge (i.e., larger diameter) conductor will offer lower attenuation thereby increasing repeater distances. But the overall diameter of the cable is larger, which might present a problem if an existing conduit network with limited space is to be used. In a similar manner, filled cable (PE-39) is often used to prevent problems associated with moisture migration in the cable, but the increased stiffness of filled cable may make installation more difficult.

The installation of twisted-pair cable can be accomplished by one or a combination of three method(s):

- Underground, in conduit.

- Underground, by direct burial.

- Aerial, utilizing existing/new utility poles (either self-supporting or strapped to messenger).

As discussed in chapter 3, the method(s) selected will have a significant impact on cost. There are also important maintenance considerations. Aerial installations are subject to the same interruptions experienced by power and telephone company cables such as falling trees and other storm induced damage. Conduit affords the cable added protection and should be used in areas where continuing construction activity poses a risk to directly buried cable.

In designing a twisted-pair cable network, close attention must be paid to the cable sizes, the minimum bending radii, and the cable weight. The cable diameter and stiffness will impact the design of a new conduit network, and will determine the suitability of any existing conduit and pole lines. Important design issues include available conduit and pole space, the size of handholes and junction boxes where the cable changes directions, and the bend of the conduit as it enters a cabinet or junction box. The weight of the cable will affect its installation on pole lines. Information regarding these design characteristics for 19-gauge twisted-pair cable is provided in table 10.

Moisture in twisted-pair cable networks is a major problem. It increases attenuation and leakage, and can also increase cross-talk and cable noise by introducing signal reflections. Cable splices are the primary source of moisture entry. Thus, the cable network should be designed and installed such that splices are made only on telephone-type terminal blocks inside weatherproof cabinets or, in the case of aerial installations, in non-reenterable waterproof splice enclosures.

Another source of moisture entry is imperfections in the cable jacketing. Great care must be taken during installation to ensure that the cable does not drag on the pavement nor rub against jagged conduit ends which might cause cuts or abrasions. It is also important to seal the cable ends during pulling operations to prevent moisture entry.

It is essential that the maximum pulling strength of the cable not be exceeded during installation. Otherwise, the conductors, shield and/or jacket may be damaged. The cable installation specifications should, therefore, require either hand-pulling or tension monitoring using a strain gauge.

Twisted-pair cable networks are subject to electrical transients from natural phenomena such as lightning. The probability of a cable being struck by lightning is not only a function of the storm incidence in the area, but also of terrain and the type of cable installation -- aerial cable routed in open terrain being more susceptible to hits than either buried cable or aerial cable in built-up areas. Maintenance activities can also inadvertently cause electrical surges on the cable. To prevent damage to sensitive electronic devices connected to the cable, it is necessary to provide transient protection.

The protective devices most commonly used provide two-stage protection. The primary stage consists of a three-element gas discharge tube, while the secondary protection consists of solid-state voltage clamps. These 2-stage devices provide a path to ground for current surges of up 10,000 amps, respond within a few nanoseconds, and provide automatic recovery after the transients are removed.

Protective devices are available in several mounting arrangements, including circuit board connection, terminal block, plug-in, and stud fastening.

Table 10. Multipair cable design characteristics.

REA PE-22 (Air Core) 19 Gauge

No. Pairs	Diameter (In.)	X-Sect. Area (Sq. In.)	Weight Lb./K ft.	Minimum Bending Radius (In.)
6	.5	.20	150	6.0
12	.6	.31	252	7.6
18	.7	.42	339	8.8
25	.8	.53	446	9.8
50	1.1	1.00	790	13.6
75	1.3	1.39	1116	16.0
100	1.5	1.84	1508	18.4
150	1.8	2.57	2118	21.7
200	2.1	3.43	2731	25.1

REA PE-39 (Filled) 19 Gauge

No. Pairs	Diameter (In.)	X-Sect. Area (Sq. In.)	Weight Lb./K ft.	Minimum Bending Radius (In.)
6	.6	.28	170	7.1
12	.8	.45	286	9.1
18	.9	.58	387	10.3
25	1.0	.79	519	12.1
50	1.3	1.34	917	15.7
75	1.5	1.99	1356	19.1
100	1.8	2.50	1766	21.7
150	2.2	3.20	2567	26.0
200	2.5	4.91	3401	30.0

Protective devices should be installed on all cable pairs and placed at both ends of the cable circuit -- where it enters the central facility, and where it enters each field cabinet. In aerial installations, the messenger cable should also be grounded.

After a twisted-pair cable network has been installed, it should be thoroughly tested. Cable tests should include, as a minimum, end-to-end continuity for each pair, the insulation resistance for each conductor (to ground and to the paired-conductor), and attenuation.

Summary

Twisted-pair cable is a reliable and proven technology. A properly designed and installed twisted-pair communications system features reasonably low maintenance requirements in terms of the average time between failures, the average time to repair, and the necessary levels of skill and equipment required for proper maintenance. Expansion of a well designed twisted-pair communications system can be accomplished with relative ease -- tapping into the cable installed during the initial system implementation and adding repeaters depending on the expanded transmission distances.

The continued use of twisted-pair cable in traffic control systems is expected for the foreseeable future. As modem technology improves, it is probable that a cost effective 2400 bps modem with turn around times in the 10 ms range will be commercially available. This will mean more controllers per channel, which translates to fewer channels and fewer cable pairs. Such enhancements will provide an opportunity for cost and maintenance reduction while maintaining all of the inherent advantages of a twisted-pair network.

LEASED TELEPHONE FACILITIES

Characteristics

In general, leased telephone facilities can be considered for any traffic control system in which twisted-pair cable is an appropriate choice of communications medium. The most common type of leased Telephone company (Telco) channel in traffic control applications is the 3002 conditioned analog circuit conforming to the characteristics of the Bell Telephone System Interstate Tariff FCC No. 260. This channel transmits voice-grade data (300 Hz to 3,000 Hz), and can be used as a twisted-pair channel with multiple controllers operating on a TDM channel. Typical data rates achievable with 3002 are limited to 1200 bits per second with acceptable error rates. Voice frequency FSK modems, such as those discussed in the previous section on twisted pair communications, are required and can be configured for either full- or half-duplex operation.

The transmission characteristics and performance of Telco channels are equivalent to a twisted-pair cable network with only a few exceptions. For example, the distance of the transmission line is not a consideration when the channel is leased from the telephone company. All repeatering considerations are handled by the telephone company, and the owner is assured a channel meeting certain specifications and tolerances regardless of distance; although the technical considerations do become more complex when the receiver and transmitter are located in different telephone exchanges. Another important difference is that, unlike a twisted pair cable network, Telco channels may not provide a continuous electrical path to the remote field locations. The channels may be digitally multiplexed into large groups of channels and then transmitted over fiber optics, microwave or coaxial cable. While voice frequency modems, such as those used in most computer-based traffic control systems, operate properly over these channels, older system technologies such as DC Switching cannot operate over digitized channels. As the phone company installs more and more fiber and digital equipment, direct copper connections will be more difficult to obtain and keep, making obsolescence of older systems operated on leased lines a very real concern.

Applications

Leased voice-grade telephone lines are used in much the same manner as twisted-pair cable. The interface hardware and software required for leased Telco lines is very similar to and compatible with that for a twisted-pair cable network. In fact, both technologies may be used in the same system. There are, however, some substantial differences between the two media in terms of their respective costs, system design and installation, and maintenance considerations.

Costs

The most significant difference between jurisdiction-owned twisted-pair cable and leased Telco channels is cost. On the positive side, leased telephone lines normally offer a very low initial installation cost as compared with a jurisdiction-owned network -- especially if the cable plant must be installed underground in new conduit. There is, however, a recurring (i.e., monthly) leasing fee which is subject to change during the life of the system. This fee is usually the major factor affecting the ultimate life-cycle cost of a leased Telco alternative.

There are numerous instances where the telephone rates have increased dramatically. As a result, several traffic control systems have converted to a jurisdiction-owned cable network. For example, the monthly lease costs in Washington, D.C. increased 500 percent over a 5-year period and the signal system had to be disconnected. Washington is now in the process of installing a new computer-based signal system utilizing city-owned twisted-pair cable.

Telco rates and charges are established by tariff and are subject to approval by State regulatory agencies. This results in a wide variation, and eliminates the possibility of generalizing about Telco costs. The method by which the communication costs are assessed also vary. Some tariffs use "Drop-to-Central Office Mileage", in which the distance from each drop (intersection, ramp meter, or traffic control facility) to the Telco central office serving that exchange is measured in distance increments (e.g., quarter mile), and the charge per increment is assessed. Other tariffs use "Drop-to-Central Office Fixed", in which a fixed charge per drop is assessed regardless of the distance; while some use a combination of methods. It is therefore important to have a complete understanding of the local tariff when considering a leased-line alternative. Common leased line terminology includes:

- Control/Service Point - Location at which telephone company connects to customer.
- Control/Service Terminal - Point of demarcation between telephone company and customer.
- Installation Charge - One time charge by the telephone company to place a service terminal at a service point.
- Special Construction Charge - One time charge by the telephone company to extend its lines from an existing point to a service point.

This extension, at the option of the telephone company, will be done by them, their contractor or the customer's contractor. In the third case, this charge is, of course, not made by the telephone company.

Federal-Aid Participation

The portion of the monthly rate associated with the Telco plant capital costs is eligible for Federal-aid highway participation if these costs are lumped into a one-time payment. The remainder of the leased line charges are billed to the user on a monthly basis and are paid by the jurisdiction.

In 1973, the then American Telephone and Telegraph Company, in cooperation with FHWA, developed a method for developing one-time and recurring charges for the private-line services required for computerized traffic control systems. The concept involves separating the monthly rate into the following two categories:

- Capital costs.
  - Depreciation
  - Cost of money
  - Income taxes
- Operating expenses.
  - Maintenance
  - Administration
  - Property taxes
  - License contract fees

The capital costs are extracted from the monthly rate over a 5-10 year time frame and lumped into a single up-front charge. This lump sum and any Telco special construction charges are combined into a single payment in which FHWA may participate. The remainder of the leased charges, representing operating expenses, are billed to the jurisdiction on a monthly rate. At the end of the time period, a new rate is negotiated -- either the standard tariff charges or a new single payment plan.

While this alternate billing arrangement is financially equivalent to the telephone company's standard tariff for 3002 voice-grade channels, it offers the advantage of significantly lower monthly rates. The exact amounts to be lumped into a one-time charge and to be retained as monthly fees must be determined on the basis of specific system projects. Furthermore, the local telephone company must be willing to offer such a prepayment arrangement.

An example of this type of tariff is shown in figure 16. In this specific example (from Southern New England Telephone in Connecticut), the monthly costs for local channels and bridging arrangements are 30 percent of the standard rates for these voice-grade circuits.

Design and Installation

From the jurisdiction's point-of-view, the design and installation effort is greatly simplified with a leased Telco communications subsystem. Many of the design factors encountered with twisted-pair facilities are not a concern with leased lines because the telephone company provides the cable network and is required to accommodate all repeater, transient protection, and balancing requirements. In addition, physical obstacles such as railroad yards, bodies of water, etc. are not design considerations as is the case with jurisdiction owned cable networks.

Generally, the jurisdiction is required to furnish a separate and dedicated conduit between the field drops (controller, central facility, etc.) and a nearby telephone manhole or pole for the leased cable. Some form of auxiliary cabinet (integral to or mounted on the controller cabinet) is also required to house the Telco cable terminations. Installation of the cable and terminations are provided by the telephone company.

Perhaps the most important aspect of "designing" a leased Telco network is to negotiate a contract or letter of agreement with the local telephone company. This contract should include the following provisions:

- Type of channels (e.g., 3002) to be provided.
- Number of channels.
- Certification that all channels comply with the appropriate specifications (e.g., Bell technical publication No. 41004).
- Number of field drops and their locations.
- Facilities to be provided by the jurisdiction for use by the telephone company during construction of the communications network (e.g., conduit laterals with pull wire), and when the facilities will be provided.
- Facilities and services to be provided by telephone company (e.g., cable, terminations, protection devices, etc.).

PRIVATE LINE SERVICES AND CHANNELS

The Southern
New England
Telephone Company

Tariffs Part IV
Section 6
Sheet 3

6. Other (Continued)

6.2 Private Line Data Channels Provided for Computerized Traffic Signalling

6.2.1 General

Private Line half and full duplex data channels, as described in Tariffs Part IV, Section 2 and 3, may be provided for computerized traffic signalling systems using the payment plan in 6.2.2 below in lieu of the monthly rates in Section 3 above. This payment plan combines a high one-time charge with a compensating lower monthly rate to enable governmental customers to take advantage of federal grants.

This alternative rate plan is available only to State and Municipal government customers who have access to federal grants for the establishment of traffic signalling systems and additions to such systems, and only for half and full duplex data grade channels.

6.2.2 Rates and Changes

	Monthly Rate	One-Time Charge
Local Channel		
Two-Wire Interface	$ 3.62(I)	$ 425.00(R)
Four-Wire Interface	5.32(R)	624.00(R)
Interoffice Channel		
Two-Wire Interface	8.55	1,000.00
Four-Wire Interface	17.10	2,000.00
Interexchange Mileage	1.26	177.00
Channel Terminals	3.60(I)	455.00
Bridging Arrangements		
Half Duplex	3.90	548.00
Full Duplex	4.50	632.00

In addition to the above rates and charges, non-recurring charges associated with local channels and interoffice channels apply as set forth in Tariffs Part IV, Section 3, Sheet 19.1.

The rates and charges in this plan are derived from and are the economic equivalent of the rates for multi-point data channels as set forth in Tariffs Part IV, Section 3. They are subject in the future to the incorporation of changes in the underlying rates on which they are based.

Figure 16. Example tariff for computerized signal systems.

- Testing requirements prior to acceptance of the communications network (acceptance tests should demonstrate that the channels satisfy the appropriate technical specifications).
- Maintenance responsibilities of Telco and jurisdiction.
- Maintenance response priority.
- Rates and charges.
- Term of the agreement and what occurs after expiration.
- Expansion of the communications network during the terms of the agreement.

Maintenance

As with twisted-pair communications, leased line technology offers reliable and proven communications with low maintenance requirements. However, the maintenance of the lines themselves is performed by the telephone company, and this can be a source of difficulties. These include slow response times, poor channel quality, and disputes concerning the location and responsibility of a communications problem, (i.e., is the problem in the leased facilities or in the jurisdiction-owned facilities).

The jurisdiction should have maintenance personnel within the organization who have had training and experience with telecommunications. This will facilitate locating and correcting maintenance problems, and minimize "false calls" to the telephone company for maintenance service (i.e., contacting Telco about a problem in the jurisdiction's equipment). Good coordination between the maintenance staffs of the jurisdiction and the telephone company is also a must.

Summary

In light of the recurring costs associated with leased Telco channels, the unpredictability of future rate increases, and maintenance concerns, many agencies considering traffic control systems have avoided leased line communications alternatives. Leased telephone channels have nevertheless been successfully utilized in several applications. A 1981 study by the California Department of Transportation concluded that "leasing of Type 3002 private lines is presently the most cost-effective medium for traffic control applications." Reasons given included:

- Leased-channels are most convenient and simplest to install. Telephone cables are in-place virtually everywhere.
- Flexibility for modification and future expansion.(3)

The prepayment arrangement can also make a leased Telco communications network a cost-effective alternative.

Leased voice-grade facilities will benefit from advances in modem technology in the same way twisted-pair applications are benefited. As data rates increase, the number of channels required will decrease, resulting in lower costs. There are also other advancements in leased facility technology that are of interest for traffic control system data communications. These are discussed in chapter 5.

DIAL-UP SERVICES

Another service provided by telephone companies is direct dial-up. This is basically a system with dial-up modems connected to the public telephone network. Data transmitted over DDD lines is routed through public telephone exchanges as would a normal telephone call. This service is available nationwide and needs only the identification of the communicating station to operate. It is a convenient and inexpensive technology for low data volume application.

Dial-up services are not considered suitable for most traffic control system communications (e.g., centralized, centralized with downloading/uploading) for the following reasons:

- Uncertain error rate. These lines are also subject to noise caused by switching circuitry and Telco maintenance activities.
- Long dial-up time. The initial period for dial-up calls from a modem having the automatic dial-up system may be as much as 30 seconds.

This type of service does have application in distributed systems for as-needed communications between the field masters and the central computer.

COAXIAL CABLE

Characteristics

A coaxial cable (coax) consists of a center conductor within an outer cylindrical conductor, separated by a dielectric material (i.e., insulator). A schematic of coax cable construction is shown in figure 17. The center conductor is typically copper clad aluminum. The outer conductor (i.e., shield) is typically aluminum, and may be a braided metal fabric, a corrugated semi-rigid metal, or a rigid metal tube. The dielectric may be either a solid (e.g., foamed polyethylene) or a gas. In the case of a gas, the center conductor is separated from the outer conductor by means of insulating spacers. The outer jacket consists of low density, high molecular weight polyethylene. Armor (i.e., steel tape) may also be provided for direct burial in gopher areas.

Coaxial cable varies greatly in size and construction, from the flexible 1/4-in diameter cable (RG-59) used in a CATV subscriber drop, to 8-in diameter rigid coax used to carry television broadcast signals from the transmitter output to the antenna. In traffic control applications, a 3/4-in semi-rigid coax is most commonly used for trunk lines, with smaller diameters used for connections between the trunk and field drops. The characteristics of a 3/4-in coax cable are summarized in table 11.

The construction of coaxial cable results in some attractive electrical characteristics. First, the cable itself is extremely immune to noise and transients from external sources. Some systems today may seem to refute that statement; but it is important to realize that the coax itself is not susceptible to noise, but rather the connections to it. Secondly, very large bandwidths, on the order of 350 Mhz, may be transmitted over coax. This large bandwidth gives coaxial cable a great deal of latitude in communication systems, including applications for traffic control.

Transmission Techniques

Coaxial cable networks for traffic control typically use frequency division multiplexing. FDM is a very efficient technique for the wide bandwidths available in coaxial transmission as well as other broadband media such as microwave and radio transmissions. Individual television channels of 6 MHz, traffic control data channels of 100 kHz, and voice channels of 50 kHz can all be transmitted in the same cable simply by modulating each with a different carrier frequency.

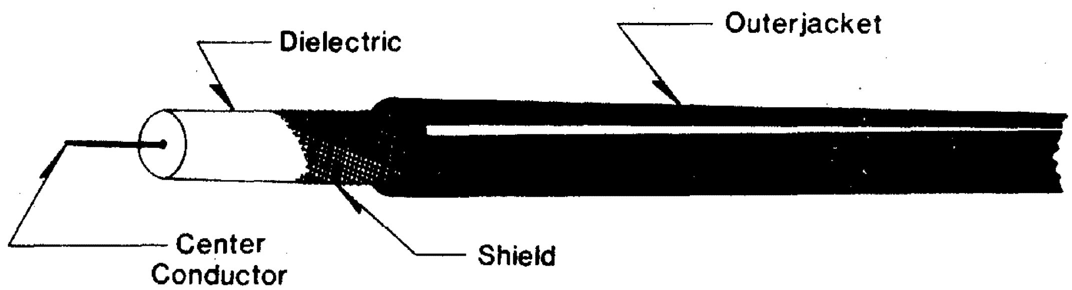


Figure 17. Coaxial cable construction.

Table 11. Characteristics of 3/4-in. coaxial cable.

- Impedance - 75 ohms
- Cable Attenuation (at 68 °F)

  5.3 dB per mile at 5 MHz
  18.0 dB per mile at 50 MHz
  26.4 dB per mile at 100 MHz
  38.5 dB per mile at 200 MHz
  48.0 dB per mile at 300 MHz

- Temperature Coefficient - attenuation varies approximately 1 percent per 10 °F
- Minimum Bending Radius - 9-11 in, depending on manufacturer

Most coaxial systems' frequency spectrums are divided into two parts. One range of frequencies is used for the upstream channels, while the other frequency range comprises downstream channels. Upstream and downstream are referenced to the **head end** of the trunk. The head end is usually at the control center in dedicated systems, in which case the upstream direction is from the field drops to the control center, and the downstream direction is from the control center to the field locations. The head end can be elsewhere in shared or leased facilities.

The split between the upstream and downstream frequencies may be heavier for a particular direction of transmission. The terms **low-split, mid-split,** and **high-split** refer to the relative position of the upstream/downstream split in the frequency band. Coax cable networks which are dedicated to traffic control and CCTV typically use a low-split arrangement with the upstream channels comprising the majority (and the higher frequencies) of the bandwidth allocation. For example, in one system the downstream allocation (for transmission of traffic control data, camera control data, and voice communications from central to the field) is 5 - 30 MHz. A bandwidth allocation of 45 - 300 MHz is used for transmitting traffic monitoring data, several television channels (one channel per camera), and voice communications upstream to the traffic control facility.

Due to the wide bandwidths and low noise levels in coaxial cable, many modulation techniques may be used in coaxial data transmission depending on data rates and other performance requirements. A wide range of data rates can be supported in a coaxial system, from less than 1200 bps to more than 10 Mbps. This makes coax very flexible. A single high-speed channel can serve an entire system, or the data can be distributed over many lower speed channels, simplifying the complexity of the field interfaces.

Most coaxial cable networks must branch out from the head end to serve multiple drops, whether they be controllers or television subscribers. **Splitters** divide the signal from one cable to two or more cables, or alternately combine the signals from two or more cables into a single cable depending upon the direction of the signal. A **directional coupler** couples signals propagating in one direction on a cable onto another cable, while having a substantial amount of isolation to signals from the opposite direction. **Taps** are used at field drops to divert the necessary signal to and from the trunk cable for proper operation of the field drop.

Repeater requirements in coaxial cable systems can be fairly extensive or reasonably simple depending on the transmission frequencies, cable size, and design tolerance of the system. Commercial subscriber networks have repeater spacings on the order of one-half kilometer. Dedicated systems, such as those used in traffic control, have repeater spacings on the order of one kilometer or greater.

An additional consideration in coaxial systems is that the signal is amplified as opposed to regenerated at each repeater. This means that the incoming signal, along with any amplifier noise and external noise, is amplified. So while the signal level is boosted, the signal to noise (S/N) ratio is not improved. These noise impacts are cumulative in each section of cable, and there is an upper limit on the number of repeaters which can be cascaded. With current coax systems that limit is approximately 60 repeaters, or 60 kilometers (37 miles). This has not been a limiting factor in systems to date. With the control center centrally located, an area greater than 60 miles in diameter could be covered without regeneration.

The broadband amplifiers used in coaxial systems are unidirectional. Thus, they must incorporate low-pass or high-pass filters so that they amplify the appropriate portion of the spectrum in the appropriate direction. The filters and amplifiers for both directions are usually packaged together as a single unit. Some systems use a separate cable for each direction of transmission so that these considerations are avoided completely. With the current technology, however, there is no technical reason to do this unless total capacity cannot be handled by a single cable.

Attenuation in coaxial cable varies as a function of temperature (refer to previous table 11). Amplifiers can automatically compensate for these thermal variations using **Automatic Gain Control (AGC). Pilot signal generators** are installed in the coax network to provide reference signal levels for the AGC circuits of the amplifiers. Nevertheless, it may be necessary to manually retune the amplifiers on occasion depending on the temperature extremes.

Noise and Interference

Noise is one of the most significant obstacles to the installation and maintenance of high reliability coaxial cable systems. Noise on coax can come from many different sources. Transmission frequencies in coaxial cable (5 - 300 Mhz) are the same as many over the air transmissions -- television broadcast, radio broadcast, public use radio frequencies, FAA communications frequencies, and the list goes on. Interference can also come from nonbroadcast sources such as high speed microprocessor circuits, power line harmonics, and natural sources. This interference is known collectively as Radio Frequency Interference/Electromagnetic Interference, or RFI/EMI.

As previously noted, coaxial cable itself is very resistant to interference from these sources because of its construction. However, in practical applications, noise can infiltrate the cable in many ways. Coaxial cable connections (e.g., splices, couplers, taps, amplifiers, etc.) are one of the most common culprits. The large temperature variations to which the connectors are exposed can cause them to expand and contract to such an extent that the connectors are not effective in rejecting noise, and it is injected into the cable. This is known as **ingress** when interference from external sources is introduced into a cable.

Egress occurs when the signal in the cable leaks out into the surrounding environment. Because of the potential of egress from a cable system, there are regulations on signal levels in certain frequency ranges, especially in the air to ground communications bands.

Both ingress and egress can be controlled by careful system design, quality connections, and regular maintenance. In addition, the impacts of ingress can be minimized as well. One method is to determine what frequencies are noisiest in a certain area and avoid channel assignments near those frequencies. If this is done properly, when ingress occurs, it usually does not affect the data channels and can be detected, isolated, and corrected without disruption to the system.

Traffic Control Applications

Coaxial cable communications systems have many applications in both traffic signal systems and in freeway control and surveillance systems. This type of communications system is equally well suited for the transmission of voice, data, and video signals. In addition, as previously discussed, many channels of information can be multiplexed onto a single cable which can serve the entire system. This is a big plus in urban areas where cable sizes may be limited by available conduit space. The cable can also support shared use in integrated systems.

For data communications, the modems required in a coaxial cable system are available off-the-shelf from multiple vendors. Modems are available to support data rates from 1200 bps to 10 Mbps with computer industry standard data interfaces such as RS-232 and RS-422. A critical concern in the selection of a modem for a traffic control system is the operating temperature range. Many commercial grade modems have temperature ratings far below NEMA temperature specifications for traffic control devices. These devices are very sensitive. If the maximum (or minimum) temperature is exceeded, their output can drift outside of the allocated frequencies, interfering with adjacent channels and disrupting system communications.

A CCU may not be necessary in a coaxial system, especially if the data rates are 56 kbps and higher, as there will be only one or two channels. However, lower data rates, very large systems, and less powerful computers may still indicate the use of a CCU. These devices are usually configured for each specific application.

Coaxial cable is also an excellent choice for video transmission of CCTV or other video applications. As coaxial cable is commonly used in CATV networks, video transmission is very well supported. Also, due to the wide bandwidth in coaxial systems, many video channels can be supported over a single cable along with data and other channels (including control channels for the CCTV cameras).

Voice transmission is also well supported over coaxial cable, with many suppliers offering broadband voice modems.

Design and Installation Considerations

The design of a coax network is more complex than a twisted-pair network. The system may only require a single cable with taps to each field drop, but there are numerous other design issues -- determining the locations of amplifiers, couplers, splitters, and pilot generators; providing power for the amplifiers; compensating for temperature extremes and the rate of change; minimizing RFI/EMI; developing the optimum split between upstream and downstream channels; and allocating frequencies to the channels.

Many of the installation considerations for twisted-pair cable also apply to coax. Coaxial cable may be installed underground in conduit or direct burial, or overhead on utility poles. The conduit must not have any bends between pull boxes other than gentle curves leading to and from the pull boxes/cabinets. If coax is pulled through a severe bend, it may cause the outer conductor to collapse as well as cause a permanent shift of the inner conductor from the center. The maximum pulling tension specified by the manufacturer must not be exceeded. Additionally, cable splices and connections should be performed only in weatherproof cabinets to minimize moisture entry and noise ingress.

It is also important that the cable installation specifications and construction supervision provide for good quality control. It may be worthwhile to include prequalification requirements (e.g., previous experience) in the contract documents for the contractor/subcontractor responsible for installing the coaxial cable network. Furthermore, the entire installed cable network should be thoroughly tested from end to end and under various weather conditions (e.g., temperature) before acceptance.

The skill level and test equipment complexity required for maintenance of a coaxial cable system is greater than that of twisted-pair networks. This is due to the higher frequencies and lower tolerance for noise and interference encountered with coaxial cable. However, with proper equipment, staff, and training, local jurisdictions can properly maintain a coaxial communications system.

Summary

Coaxial cable is a very versatile medium which offers a wide bandwidth, good industry support, and the ability to accommodate transmissions of multiple channels of voice, video, and/or data. However, coaxial cable systems can be more costly than twisted pair systems; are subject to degradation due to noise and interference if not properly designed, installed, and maintained; and require a higher level of expertise and special equipment to design, install, and maintain.

CATV (COMMUNITY ANTENNA TELEVISION)

Characteristics

Because CATV (cable television networks) are usually implemented on coaxial cable, the characteristics of CATV channels are very similar to those of dedicated coaxial cable systems. There are two major exceptions to this. One is that the available bandwidth on CATV, which is a function of the network loading and the franchise agreements, may be limited. The other exception is that not all CATV systems are designed for bidirectional communications. In that two-way communications are mandatory for traffic control systems, all further discussions of this alternative will assume that the CATV system does provide bidirectional communications.

Data transmission techniques used for CATV networks are very similar to those discussed in the previous section on coaxial cable. There may be some constraints on the transmitter output levels of narrowband modems so that a constant power-to-bandwidth ratio is maintained over the entire spectrum. However, since noise power is evenly distributed over the frequency spectrum, signal to noise ratios for data channels remain approximately equal to those in the video channels, and this usually does not adversely affect data transmissions.

Repeater requirements and noise considerations are the same as in dedicated cable systems, except that they are handled by the CATV franchise. If a choice of frequencies is given on the cable network, examining the channels with a spectrum analyzer can provide an indication of which channels are the least likely to suffer from excessive noise and interference.

Traffic Control Applications

Because of their similarity in media and design, CATV networks are appropriate for nearly all of the applications previously discussed for dedicated coaxial cable systems. However, CATV is both a shared resource and a leased medium, which makes it unique in certain respects. These differences result in advantages and disadvantages.

Most CATV networks are designed and installed with the emphasis on downstream transmission of video signals to cable subscribers. These video channels may take up most of the available bandwidth. Thus, the bandwidth available to traffic control may be very narrow -- ranging from a single 6 MHz channel to 4 or 5 channels. This can have a significant impact on CATV utilization. For example, while a single 6 MHz channel would be quite adequate for data transmission, it would not support video transmission in addition to the data communications.

An associated problem is that the frequencies of the available channels are often the least desirable in terms of their susceptability to noise and interference. Additionally, the quality of the video signal required for CATV is considerably less than that required for data. Noise which does not adversely affect video transmissions (e.g., lines on a TV picture) may wreak havoc on data transmissions. In one CATV application, the noise problems were so great that the traffic control system never reached an operational state, and it became necessary to design and install a twisted-pair cable network.

CATV subscriber facilities are sometimes concentrated in residential areas while service to the CBD and industrial areas is sparse or nonexistent. Thus, another potential problem with CATV is that the area of coverage and the network layout may not coincide with the traffic signal density.

In some CATV systems, there may be a second separate coax network for the express purpose of providing bidirectional services to commercial subscribers. These networks are called Institutional networks (I-nets) and generally provide very good levels of service to subscribers. Nevertheless, the traffic control system may have to compete with other public sector users for the more desirable channels.

CATV does possess certain characteristics which are very attractive to traffic control applications. For instance, the network is already in place, so the design effort and initial installation costs are much lower than when installing a dedicated coax system. Furthermore, the franchise agreement may provide for government use of the CATV cable and bandwidths at reduced rates or free, thereby reducing the recurring costs of the system. It is noted, however, that a 1979 Supreme Court decision, Federal Communications Commission (FCC) vs. Midwest Video Corporation, et al., 440 U.S. 689 (1979) abolished mandatory access and channel capacity requirements cited in 47 CFR 76.254. The validity of a CATV franchise agreement will depend on its exact language. Franchise agreements which indicate that the franchise "must comply with 47 CFR 76.254" cannot be enforced. Franchise agreements which state that "channels of the type indicated in 47 CFR 76.254 must be provided to the local government" may still be enforceable. Jurisdictions considering use of CATV as a communication medium should review the franchise agreement to ensure that channels for traffic control will be available from the CATV company.

Assurance as to the acceptability of CATV rates must be obtained prior to Federal-aid highway participation. FHPM 1-7-2 requires an audit evaluation to determine the proper charges for CATV when the contract amount is more than $50,000. In determining the contract amount, the total life of the system should be considered, not just the first year. When the contract amount is less than $50,000, assurance may be obtained as follows:

- Review of FCC Form 326 (Annual Report Cable Television Systems) to determine that the rates are comparable to rates charged other users.

- Obtain a certification from the CATV company that the rates are the lowest charged other users and that there are no other discounts or rebates to those users. In addition, a list of comparable subscribers should be obtained and independently verified by telephone.

Design Considerations

Any consideration of CATV as a communication medium for a traffic control system should include a number of elements as summarized below:

- Review franchise agreements to ensure that upstream and downstream channels are available for such use; and that the frequency allocation is adequate. Feasibility testing of the CATV network may prove worthwhile in this regard.
- Assurance of cooperation by the CATV company, and assistance for implementation of the communication links to the controller cabinets and to the central signal control facility.
- Acceptance test criteria for the CATV communication network should be developed and reflected in a contractual agreement between the system owner and the CATV company. These should also be reflected in the specifications for the systems contract. This will allow blame to be affixed and correction required of the appropriate party if the integrated system does not operate properly. The contractual agreement should also clarify maintenance responsibilities and stipulate response time for repair.
- A firm commitment from the franchise to the support and maintenance necessary for reliable communications.

Maintenance

Like other leased facilities, maintenance is handled by external parties. In CATV this can be an advantage or a disadvantage, depending on the responsiveness of the CATV operator and the terms of the franchise and other agreements. As previously noted, the upstream direction is not very critical to CATV operation. Therefore, if there is a problem which does not affect the majority of the subscribers, it may be difficult to get expedient service and repair. On the other hand, it is noted that some CATV franchises are very conscientious in the maintenance of their system for data transmission.

Summary

A significant percentage of the attempts to use CATV facilities in traffic control systems have unfortunately produced less than acceptable results. There are many different reasons for the failure of these applications, but the vast majority are related to the fact that CATV industry standards and practices are based on the requirements of one-way (i.e., downstream) video transmissions; not two-way data communications. In some instances, there has also been a lack of commitment to the traffic control application by the CATV franchise. Nevertheless, the technical and institutional obstacles associated with CATV are surmountable, and CATV has been successfully used for traffic control systems.

5. NEW AND EMERGING COMMUNICATIONS TECHNOLOGIES

This chapter addresses those communication technologies which have had limited, if any, application in computerized traffic control systems -- specifically, fiber optic cable, microwave and satellite, optical infrared, leased digital data channels, and various radio technologies. Their respective characteristics, transmission techniques, and potential applications for traffic control are described. Future developments which might make some of these technologies more competitive are also discussed.

In general, the communication technologies addressed herein have emerged as a result of the ever-increasing need to transmit larger amounts of data at faster speeds, and over longer distances. Current traffic control systems -- with their relatively low data volume per control location -- are at the opposite extreme of the focus of this development activity. Thus, these new and emerging technologies are offered, not so much as alternatives to the existing media discussed in chapter 4, but as additional resources and options which can be used for special system features and for overcoming certain constraints.

Traffic control systems have changed and will continue to evolve; and so will their communication requirements. This fact, coupled with continuing developments in the communications field, will likely make some of these newer technologies viable alternatives for traffic control in the not-to-distant future. Fiber optics, which is discussed first, is rapidly approaching this status, particularly in freeway surveillance and control applications.

FIBER OPTIC COMMUNICATIONS CABLE

Characteristics

A fiber optic waveguide is a very thin cylinder of glass which has very low attenuation properties at certain infrared frequencies. A simple optical fiber is constructed of two concentric cylinders as shown in figure 18. The inner section of the cylinder is called the **core**, and the outer section is called the **cladding.** Fibers are classified by the ratio of the outside diameters of each section --for example, a fiber with an 80-micron diameter core and a 125-micron total diameter (core + cladding) is referred to as an 85/125-micron fiber. A fiber optic cable may consist of a single fiber or multiple fibers, and includes an outer jacket to protect the fiber(s).

Both the core and cladding are constructed of the same basic material, but the core possesses a lower refractive index than the outer cladding. This causes lightwaves which strike the cladding below a certain angle of incidence to be reflected back into the core. This process continues throughout the waveguide; and in this manner, light is propagated until it exits at the end of the fiber.

Light which is reflected back into the fiber will continue to be reflected at the same angle unless it it disturbed. All light being reflected at the same angle follows the same path, and is said to be propagating in the same **mode.** The number of modes supported by a fiber is related to the diameter of the core -- the larger the diameter, the greater the number of modes which may propagate along the waveguide. Optical waveguides which support many different modes of propagation are called **multimode** fibers (figure 19). It is possible to make optical fibers so thin and with the appropriate refractive indices that only a single mode of propagation is supported in the fiber. These are called **single mode** fibers.

The information carrying capacity, or bandwidth, of fiber is related to the spreading or **dispersion** of the light pulses. A pulse of light broadens as it travels down a fiber. If the pulse is spread enough so that the last portions of one pulse arrive after the first portions of the following pulse, then **intersymbol interference** occurs and the individual pulses can no longer be distinguished from each other. Pulse dispersion is a function of both pulse width (data rate) and distance. For this reason, the capacity of fiber optic systems is expressed in Mbps-km -- the products of the data rate and the repeater spacing. Practical systems in 1985 had capacities of up to 20,000 Mbps-km (500 Mbps at 40 km), and experimental efforts had achieved 500,000 Mbps-km (4 Gbps at 117 km). Even higher capacity systems are being built today, so it is clear that even relatively "low performance" fiber optic systems can provide ample capacity for the typical traffic control application.

Transmission Techniques

A fiber optic waveguide is ideally suited for digital data transmissions which do not require large signal-to-noise ratios for accurate detection. Analog sources (e.g., voice, analog data) are **Pulse Code Modulated (PCM)** to convert them to digital data for transmission over fiber. Even though PCM requires larger bandwidths than

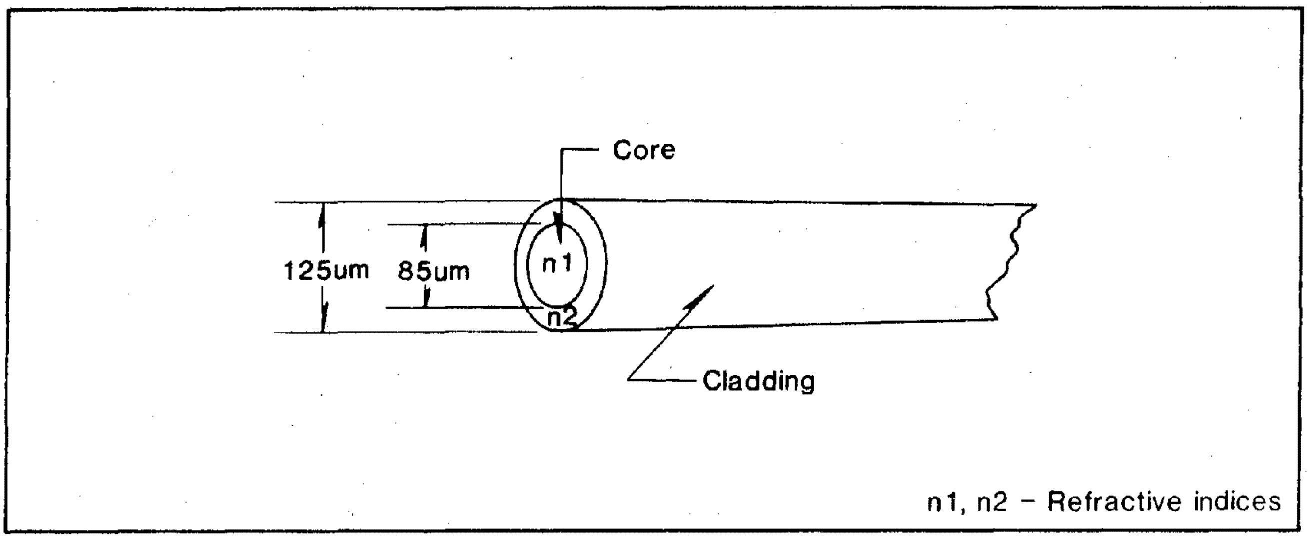


Figure 18. Fiber optics cable.

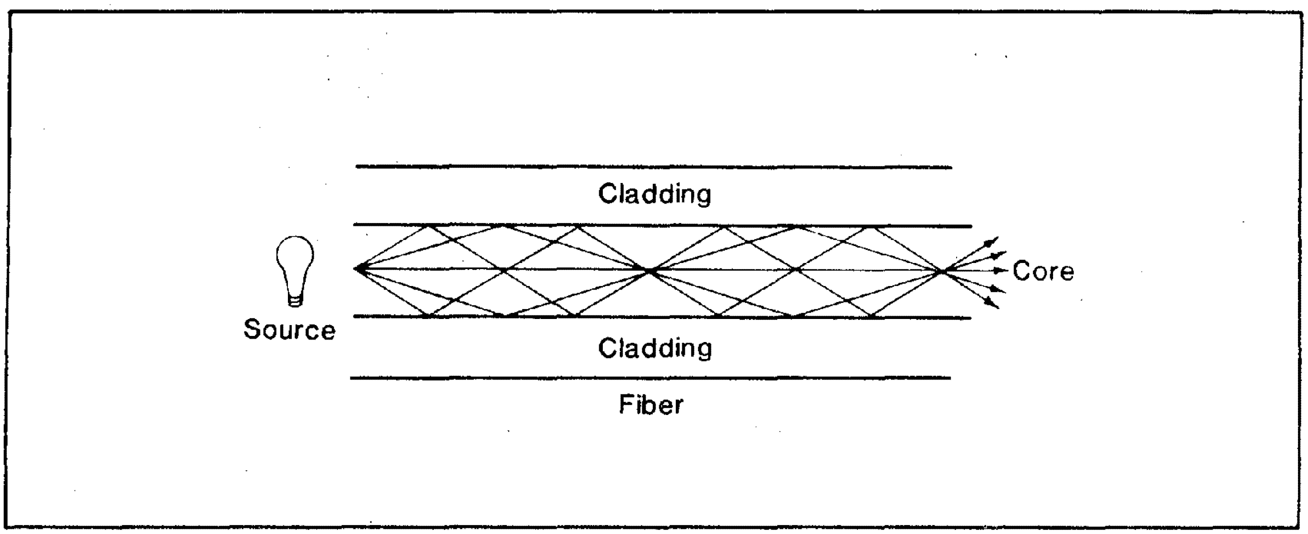


Figure 19. Multiple modes of propagation.

analog transmission, fiber has such large bandwidths that this is not usually a limitation.

No techniques currently exist for frequency modulating an optical source. While fiber does not share all of the flexibility of the frequency division multiplexing techniques used in coaxial cable, an optical counterpart of FDM, called **Wavelength Division Multiplexing (WDM)** has been developed. WDM uses optical sources of different wavelengths to transmit multiple channels of video or data over a single channel. The wavelengths are separated at the receiving end by optical filters and detected by discreet optical receivers. WDM is fairly new in commercial applications, and the associated electronics currently have a relatively high cost.

Most multiplexing in fiber is achieved via Time Division Multiplexing. TDM in fiber applications is typically achieved on a bit-by-bit basis as opposed to the message-by-message technique used in twisted-pair systems. Sophisticated multiplexers are used to combine many low- to medium-speed digital data channels into high-speed channels (e.g., T1 (1.544 Mbps) or T2 (6.312 Mbps) channels which are discussed in a later section on leased high-speed digital channels.) In many cases, the operation of these multiplexers is totally transparent to the end user.

Although all of the above multiplexing techniques are used in fiber optics communications, one of the most common and easiest methods for providing multiple channels is to simply install a multiple-fiber cable, and use a separate fiber for each channel. Because the fibers are so small -- over 200 bare fibers can be placed side-by-side in the space of an inch -- a cable of 12 or even 50 fibers is smaller than a single 25-pair copper cable. In addition, because additional fibers cost less than sophisticated multiplexing electronics, installing multiple fiber cables can be quite cost-effective.

Attenuation in fiber results in a dimming of the light signal as it travels through the fiber. Optical attenuation is caused by absorption of the light rays by impurities in the fiber, scattering, and minute distortions in the fiber's geometry (microbends) which can shift a mode's angle upon impact with the cladding. Single-mode fibers have low attenuation in the range of 0.4 - 1.0 dB per kilometer.

Fiber optic repeaters differ from other types of repeaters in that the optical signal is not amplified; but rather converted into its original electrical form and then converted back to an optical signal. This **regeneration** is required for two reasons: optical amplification is more difficult than electro-optical regeneration; and pulse dispersion would not be corrected by amplification alone. Fiber optic repeaters are sometimes called **regenerators.**

As previously discussed, the bandwidth of a fiber is related to the distance of the link. Thus, the maximum repeater spacing in fiber optic networks is a function of both the bandwidth of the transmitted signal and the signal attenuation. Repeater spacings from 40 to 60 km with data rates of 10 Mbps and higher are common in fiber networks. With the control area of systems generally within a 24 to 30 km radius, fiber systems can provide excellent unrepeatered performance over an entire control area.

Presently in commercial applications, if multiple drops are to communicate over the same fiber, each drop must intercept the optical signal, convert it to an electrical form for use by the device, inject a response if necessary, modulate the electrical signal back to an optical signal, and then retransmit it. This process also regenerates the signal. While this is done very rapidly and is quite feasible, such a daisy-chain configuration of multiple drops increases the complexity of the system and has a high failure potential -- any control point failure results in the loss of every drop beyond.

Development is currently on-going in off-the-shelf passive fiber devices, such as splitters and couplers, which allow the optical signal to be read and/or injected into a fiber without regeneration and without active devices. These are analogous to the passive taps used for coax. Some of these devices are commercially available now, including wavelength division multiplexer/demultiplexers (which combines light signals at two distinct wavelengths onto a single fiber, or splits two signals on the same fiber onto separate ones) and fused couplers (which are wavelength independent and function as beamsplitters). The costs are of these and similar devices is still relatively high, and they have not yet seen much use in commercial systems.

Most fiber optic transmitters and receivers are designed to conform to a standard electrical interface of the computer or communications industry. Interfaces supported include T-carrier interfaces for digital voice and many data multiplexers, IEEE local area network interfaces, RS-232 and RS-422 serial data interfaces, and NTSC composite and component video interfaces. Compatibility among different manufacturers at an optical level is not guaranteed, but since end users are not generally concerned with interconnecting one manufacturer's fiber transmitters with another manufacturer's receiver, this is not a problem.

As with coaxial cable equipment, not all fiber optics modems, regenerators, and multiplexers meet the environmental requirements for traffic control applications. Therefore, care must be taken when designing a fiber communications network to ensure that the interface equipment is designed to withstand the harsh environmental conditions found in traffic control systems.

Noise and Interference

A major advantage of fiber is its immunity to electrical interference. Since the signal is optical in nature and there is no metallic transmission medium, fiber optic transmissions are not affected by cross talk, ground loops, or ingress. This is especially attractive in urban environments where the cable is routed very close to power distribution networks and other sources of interference. Furthermore, optical fibers do not act as "ground rods" nor conductors of lightning strikes which can wreak havoc with twisted-pair cables.

Fiber as a data transmission medium inherently provides a very high level of data integrity. Additional levels of error control are implemented depending on the type of data transmitted. For instance, errors in pulse code modulated voice transmissions would be less critical than signal-phase control data in a traffic control system, and error coding could be implemented accordingly.

Traffic Control Applications

Fiber optics technology has numerous advantages -- large bandwidth, low attenuation, noise immunity, and a small flexible lightweight cable. Fiber, however, is by nature a point-to-point technology. This means that a single source and a single destination are required for any given link. This type of configuration imposes limitations in traffic control applications since most of these systems are point-to-multipoint.

In multipoint applications of fiber, the network is comprised of individual point-to-point segments connecting each field drop as shown in figure 20. In order to serve multiple drops on a fiber circuit, it is necessary to use a **drop and insert modem.** As previously noted, each of these active devices regenerates the optical signal. Thus, a single modem failure (with currently available equipment) can cause the loss of the remainder of the circuit.

There are, however, some techniques which can reduce some of these concerns. One is to use a ring configuration for the circuit. By wrapping the fiber from the end of the circuit back to the central (using a second fiber in the cable), it is possible to feed the fiber network from both ends, so that a single failure would not impact any other units. In addition, modems are currently under development which will optically connect the incoming and outgoing fibers automatically upon a failure condition. The failed modem simply becomes a passive connector and does not affect the remainder of the circuit.

More straightforward are the point-to-point applications of fiber optics. These include trunking where several low speed channels are multiplexed into a high-speed data channel and transmitted over a single fiber from a central point to a remote distribution point. At the remote location, the multiplexed signals are demultiplexed into low-speed channels and then transmitted over twisted-pair (or other conventional medium) to the field drops (e.g., controllers). Similarly, the responses from the controllers are gathered at the remote distribution location, multiplexed together, and transmitted back over another fiber to the control center where they are demultiplexed and read by the computer. This type of configuration has worked very well in situations where the control center is some distance away from a concentrated area of traffic signals, as is the case in some large urban areas. With fiber multiplexers that can transmit multiple channels of different types of information (e.g., high- and low-speed data, voice, and video), the point-to-point trunking application can be very effective.

Another point-to-point application is in the transmission of video over fiber. Typically, a separate fiber is run to each camera from the control center, plus an additional fiber common to all cameras (or another communications media) for camera control. As previously discussed in this section, multiple fiber cables are very small and economical. This, coupled with fiber's large bandwidth and the great distances fiber can be run without repeatering, makes fiber optics competitive with coax in many video transmission applications, such as freeway surveillance where the cameras are located in a linear arrangement (figure 21).

Design and Installation Considerations

As of the date of this report, fiber optics is being incorporated into the design of a number of traffic control systems. In one application, fiber is being proposed to interconnect the signalized intersections on an arterial with a field master. This design incorporates a ring configuration. In another application, fiber is being used for CCTV in the vicinity of a freeway bridge. The design is similar to the configuration shown in figure 21.

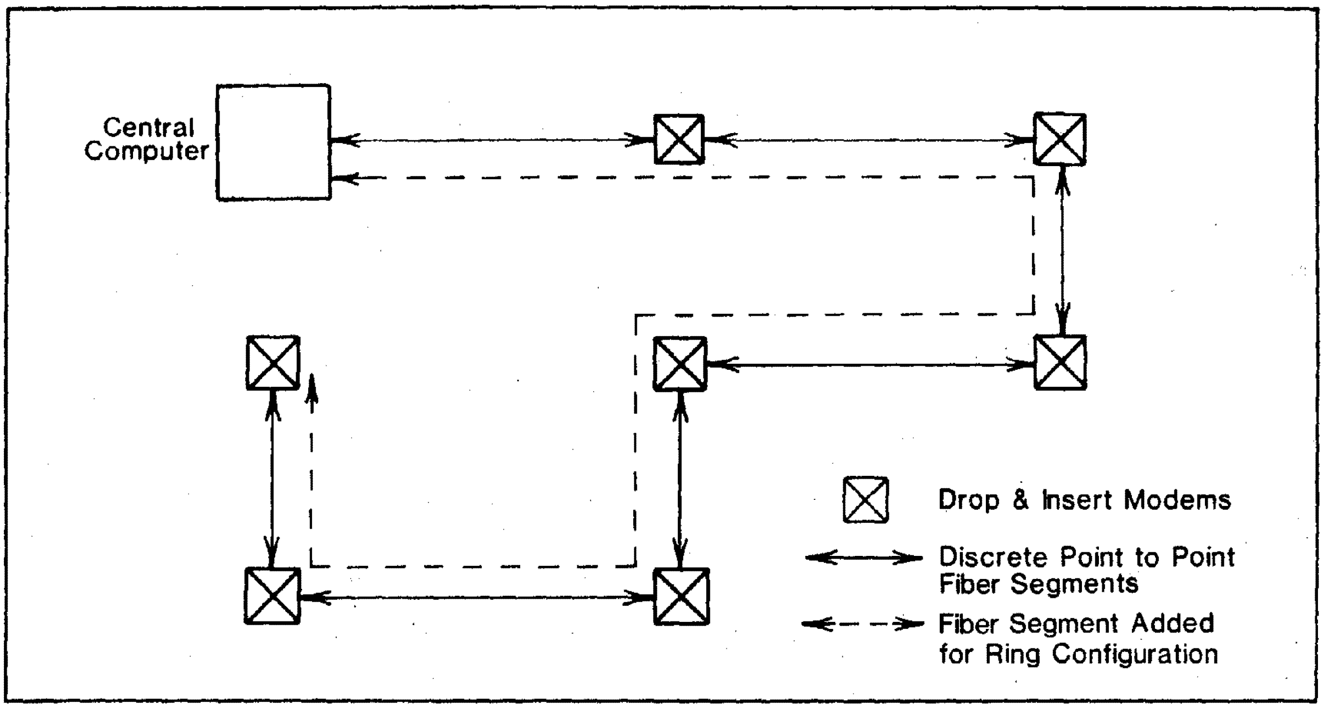


Figure 20. Multipoint fiber network.

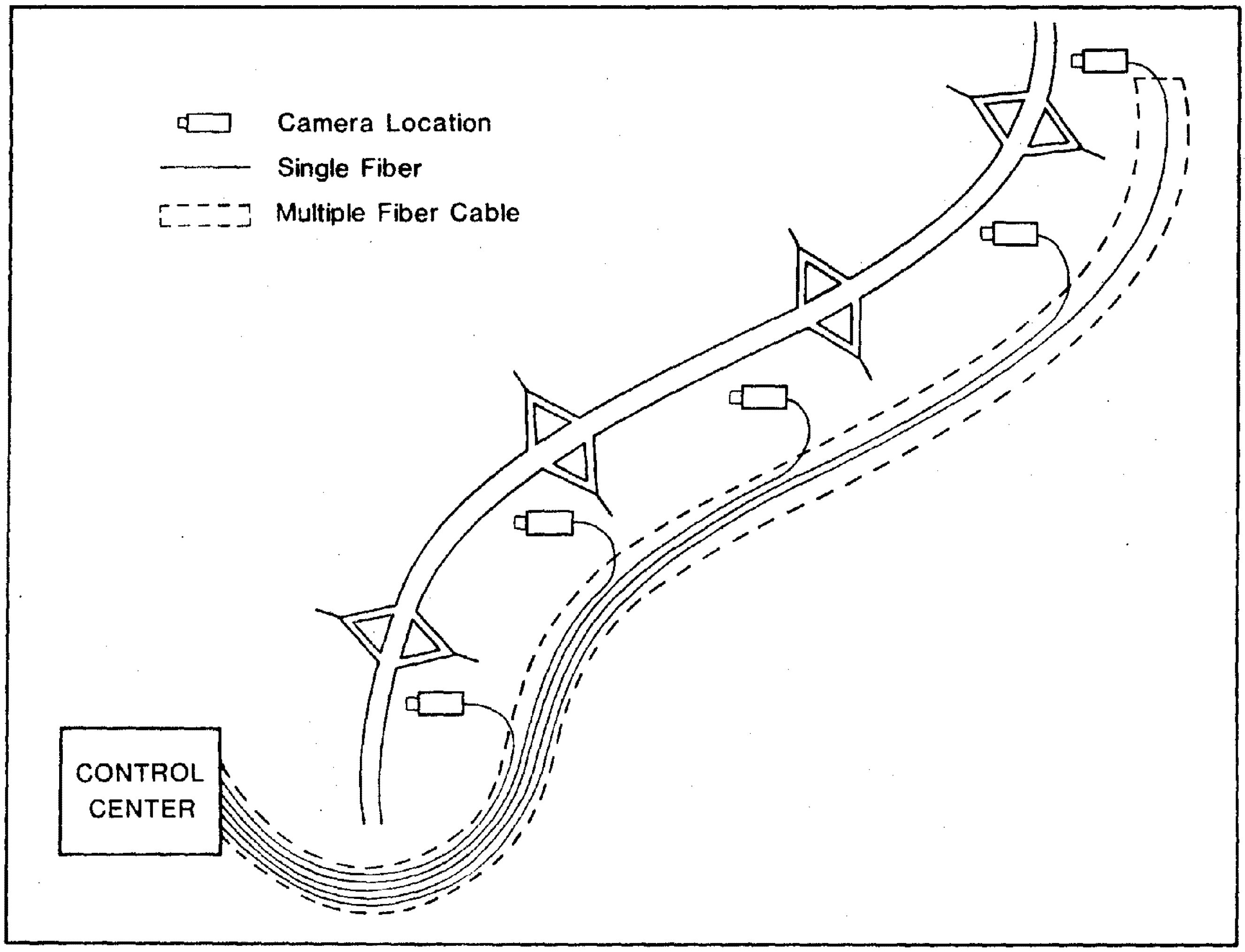


Figure 21. Fiber application in freeway surveillance.

In one freeway system, fiber will be installed and terminated at camera locations spaced approximately every mile. Any system hardware (e.g., detectors, lane control signals, etc.) located between these "hubs" will be interconnected with the hubs via twisted-pair cable. In this manner, the number of fiber terminations and drop and insert modems -- which are failure points -- will be minimized. The hubs will be interconnected via multimode fiber optic cable with "collector hubs", where the optical signals will be combined and transmitted over single mode fibers back to the control center.

Fiber optics cable may be installed in conduit, direct burial, or aerial. The design and installation considerations are much the same as for twisted-pair and coax media -- the cable must be sized appropriately (i.e., multimode vs single mode, number of fibers in the cable); there must be sufficient space in conduit or on poles for the medium; bends cannot be less than the minimum bending radius of the cable; and the maximum pull strength must not be exceeded.

There are two major differences and concerns. One, as previously discussed, is that fiber applications currently require active electro-optic transceivers and modems; and the increased failure potential of regeneration must be incorporated into the design (e.g., ring configuration). Secondly, field connections and splices between fibers require much more precision and cleanliness than for twisted-pair or even coaxial cables. Considering that the fiber waveguide is carrying hundreds of times more information than a copper wire, the consequences of a loss of signal through an improper splice can be severe. Advancements in connecting hardware and splicing techniques have made fiber optic splices and connections easier and less expensive. Nevertheless, special training is required. Accordingly, the specifications should require that the contractor/subcontractor responsible for constructing the fiber network be qualified and experienced in fiber installation. Additionally, special training should be provided to the technicians who will be responsible for maintaining the fiber network once it is constructed and operational.

Future Potential

The future potential for fiber in traffic control systems is certainly great. At this point, we are just beginning to see fiber as a cost-effective alternative to some of the more traditional media in traffic control communications. As fiber technology continues to advance, there will be more support for multipoint applications (e.g., passive-fail modems, passive couplers, and taps, etc.), and there will be a greater number of products designed for the harsh environments found in traffic control systems. In addition, the fiber and associated electronics will become more economical. Both of these processes will make fiber better suited for a greater number of applications in traffic control communications. Fiber will also be a viable alternative for integrated communication networks within an urban area.

POINT-TO-POINT TERRESTRIAL MICROWAVE

Characteristics and Data Transmission Techniques

Microwave frequencies are those frequencies in the range above 1 GHz (gigahertz). The frequencies currently allocated by the FCC for private and or common carrier use are in the 4-, 6-, 10-, 11-, 12-, 13-, 18-, 23-, and 28-GHz bands. The 4 and 6 GHz frequencies are used for satellite uplinks and downlinks as well as point-to-point terrestrial communications.

Microwave signals radiated from an antenna propagate through the atmosphere along a line-of-sight path. The frequencies used must be unique in that area and direction to prevent interference from other microwave transmissions. Because of this constraint, it can be very difficult to obtain microwave frequency allocations in a crowded urban areas. When frequencies are available, they are usually in the higher frequency bands.

Microwave links are simplex. Thus, separate inbound and outbound facilities and frequencies are required for two-way communications. All microwave frequencies are attenuated by the atmosphere, with attenuation increasing with frequency. Atmospheric phenomena such as rain and fog can be particularly detrimental to microwave transmissions. Because of this, margins of reliability must be designed into the microwave system to account for this attenuation.

Microwave has one very attractive attribute -- it does not require a physical connection between the transmitter and receiver. This characteristic is even more attractive in areas where no facilities are available or possible between two points. This can include areas where no space is available for conduit or for aerial cable, as well as areas where natural barriers exist such as a large body of water. At the same time, the line-of-site requirement can restrict its usage in areas with rolling terrain or densely developed urban areas. The need for repeater stations or tall buildings or hills may offset its advantage of not requiring a physical medium.

Microwave, being an air-path medium, is regulated by the FCC. Thus, the bandwidth available over a microwave link is basically a function of how much bandwidth has been allocated in the area of interest, and how much of the assigned bandwidth is still available. With channel widths between 50 and 220 MHz, a microwave link can have an enormous capacity, but only if the bandwidth can be obtained in the area and direction of the link. Maximum data rates achievable in microwave systems are also a function of the available bandwidth. But with the broad channels in the microwave spectrum and very efficient modem techniques, very high data rates can be transmitted via microwave. For example, a 10 Mbps data stream can be transmitted over a channel only 7 MHz wide. As mentioned above, microwave channels can range from 50 to 220 MHz wide, so it is unlikely that the data rates in a traffic control system would be limited by the capacity of the microwave link.

Many different modulation techniques can be used with microwave radio, depending on the type of information (high speed data, low speed data, video, etc.) and the amount of bandwidth available. Multiplexing in the microwave environment is somewhat similar to that in the coaxial systems. Using frequency division multiplexing techniques, channels carrying voice, data, and/or video information can all be multiplexed together over a single microwave link. The size and number of the channels is limited only by the available bandwidth. At the receiving end, these channels can be separated, or simply demodulated and transmitted over a coaxial cable system. The latter process is used in CATV to transmit signals from the central office to a remote head end. At the central office, the 6 MHz television channels are modulated to their ultimate cable channel frequencies and then the entire group is modulated to the frequency of the microwave link. At the cable head end, the cable channels are demodulated as a group and transmitted over the coaxial cable subscriber trunk.

Repeater spacings in microwave radio systems vary with frequency, antenna size, transmitter power, receiver sensitivity, terrain, and many other factors; and can range from less than 1 to more than 30 miles. The lower frequencies generally have longer repeater spacings. In metropolitan areas, the most commonly available frequencies are in the 18- and 23-GHz bands. These bands have repeater spacings on the order of 2 to 3 miles.

Microwave systems must be carefully designed because the system cannot be isolated from sources which produce noise in the atmosphere. While some constant noise sources can be taken into consideration, impulse noise and interference from atmospheric phenomena cannot. In addition, the microwave link is subject to interference from any out-of-band signals generated by other systems in the area. Systems designed with a higher reliability are more expensive, so there is usually a trade-off between many factors such as noise tolerance, repeater spacings, antenna sizes, and transmitter power.

Current and Potential Applications

Because of its directional antennas and narrow beamwidth, microwave is essentially a point-to-point communications technique. This, coupled with the cost of microwave transceivers, makes microwave an inappropriate medium for multipoint configurations such as communications between a central computer and numerous intersections. Microwave, however, can be used like fiber in trunking applications for data, and it can also be used for video transmission in CCTV systems.

Microwave is currently in use in a few traffic control systems, both for data and video transmission. Both of these applications are somewhat special cases. In one traffic signal system application, the signals along an arterial, which is located 10-15 miles from the control center, are interconnected into three full-duplex data channels via twisted-pair cable. These data channels are multiplexed together and transmitted to the control center over a microwave link In another application, microwave is used for video transmissions across a large body of water.

Although there are some low power, high frequency, single-channel links which are fairly low cost, building a microwave link is generally quite an expensive proposition. Because of this, applications where bandwidth can be borrowed or leased on an existing microwave link will likely be more cost effective than establishing a new link solely for traffic control communications. For example, most of the microwave facilities used in the signal system data link described above (e.g., central antenna, hardware, frequency allocations) were already existing -- they were not installed specifically for the traffic signal system.

Because of the difficulty in obtaining channel assignments, line-of-sight path restrictions, microwave's point-to-point nature, as well as the cost associated with establishing a microwave link, it is not likely that microwave will ever see widespread application in traffic control systems. Microwave is and will probably continue to be applied only as a special solution to unique situations, such as communicating with remote hardware where barriers (natural or otherwise) or large distances make a physical connection difficult or impractical in terms of costs. At this point there are no new developments on the horizon which will make microwave more practical for traffic control.

SATELLITE MICROWAVE

Satellite microwave is similar to terrestrial microwave in that some of the same frequencies are used for transmission of the signals through the atmosphere. In satellite microwave, however, instead of using a single direct line-of-sight transm ssion path, the microwave signal is directed at a satellite transponder. The transponder receives the transmission at the uplink frequency (usually in the 6 GHz band), converts the transmission to the downlink frequency (usually in the 4 GHz band), and retransmits the information back to earth.

There are a special technical considerations associated with this technology. First of all, satellite microwave communications requires a satellite in geosynchronous orbit. In addition, because most communications satellites are in orbit at around 22,000 miles above the earth, the transmitted signal must travel 22,000 miles without amplification or regeneration. This requires low microwave transmission frequencies (usually 4 GHz and 6 GHz bands), large antennas for both receiving and transmitting (especially transmitting), and high powered transmitters. These technical considerations alone make satellite technology an unlikely candidate as an alternative communications technique in traffic control.

While the technical considerations are great, the costs associated with satellite communications are even worse. Satellite communications is a very expensive proposition. Because of the enormous costs associated with building and launching a satellite, many techniques are used to make the most efficient use possible of the communications link. Even then, satellite channel space is an expensive commodity.

Satellite offers some outstanding advantages in terms of long distance communications and transmission of large amounts of information, making the costs justifiable in special applications. However, traffic control systems, with their limited data requirements and small, localized areas of control, are simply not good candidates for making efficient use of satellite communications.

LEASED TELCO DIGITAL DATA CHANNELS

Characteristics and Data Transmission Techniques

Many different services and facilities may be leased from the telephone company, ranging from a continuous unconditioned copper pair for DC switching, to a T2 channel capable of carrying over 6 Mbps. The physical media encountered may include twisted pair cable, coaxial cable, fiber optics cable, or terrestrial microwave.

As discussed in chapter 4, leased voice-grade channels have been used in traffic control systems for many years. Higher-speed data channels, especially end-to-end digital channels, are becoming available from the phone company in an increasing number of areas. These high-speed channels are becoming available and more economical because the phone company is relying more and more on the digital transmission of voice circuits as well as inherently digital data.

Because the telephone company's primary business is still voice communications, most of their digital transmission facilities are based on digitized voice channels. Therefore, in order to understand the leased digital data services which are available, it is helpful to understand the digital voice transmission techniques. At the lowest level, a single voice channel is converted (i.e., digitized) from a continuously varying analog signal to a series of discrete samples -- 8,000 per second to be exact. These samples are quantized, or assigned, to one of 256 discrete levels. Each quantized sample is then digitally encoded into an 8 bit word. Through this process, each voice channel is converted to a 64 kbps digital data stream.

These 64 kbps channels are time division multiplexed (TDM) into larger groups of channels. Twenty-four 64 kbps channels make up a T1 channel operating at 1.544 Mbps. The T1 channels are grouped into even higher data rate channels. This system is called the **T-carrier system.** Table 12 gives a summary of the structure for higher order multiplexing.

Table 12. T-Carrier system.

System	Bit rate	Voice Channels	Transmission Medium
PCM voice	64 kbps	1	Twisted-pair
T1	1.544 Mbps	24	Twisted-pair
T2	6.312 Mbps	96	Twisted-pair
T4	274 Mbps	4032	Coax or microwave
WT4	16 Gbps	240,192	Helical waveguide
Optical fiber	to 54 Gbps	to 800,000	Optical fiber

There are two types of channels which have potential applications in traffic control systems. The first type is the T1 or T2 channels. Much of the data multiplexing equipment available today is compatible with the T-carrier systems. One common multiplexer combines 54 1200 bps full duplex data channels into a T1 channel output. The outputs of four of these multiplexers could be multiplexed into a T2 channel with a capacity of 216 1200 bps channels. In a traffic signal system with 8 controllers per line, the single T2 channel could support 1728 controllers. Other multiplexer technologies offer even more subchannels per T1.

The second type of service which could be used is generically called Digital Data Service (DDS). This service is currently available only in larger metropolitan areas. It provides the customer with end-to-end digital service at 56 kbps (or optionally 9.6, 4.8, or 2.4 kbps). Because the 56 kbps channel only displaces one 64 kbps voice channel (essentially 1/24 of a T1 channel), it is potentially a very cost-effective data link.

The leasing telephone company guarantees end-to-end performance on its DDS and T-carrier channels (excluding user equipment). The minimum performance is specified by the applicable tariff. For example, one tariff for a northwestern State guarantees 95 percent error free seconds during operation.

Current and Potential Applications

The application of these high-speed leased Telco services in traffic control is limited to the transmission of data or digitized analog information (e.g., slow-scan TV). One application of these higher-speed digital channels would be in a large urban area where a trunk line is required between the central computer and an area computer. The cost and difficulty of obtaining or installing conduit over a long distance through a crowded urban underground might make a direct physical connection infeasible, even for a single fiber optic or coaxial cable. There might not be any available microwave channels (not to mention the hardware costs). Furthermore, leasing many voice-grade channels might be cost prohibitive. However, a single T1 or T2 channel leased from the phone company could provide a cost-effective connection from the central computer to a local distribution network for a particular area. Leased facilities can also be attractive as an interim or temporary measure to provide communications to an area which may later be served by other facilities, or between locations which may be subject to relocation (either central or field).

For the case of low-speed channels multiplexed into a high-speed channel, multiplexing/demultiplexing equipment is required at both the central location and the remote distribution site. This equipment is fairly common and standardized in the computer industry. Products of this type are available "off the shelf" from several manufacturers, however, these systems must be designed carefully to avoid incompatibilities. An additional consideration with such equipment is that it meet environmental requirements of the application.

Future developments in high-speed digital telephone company services will include expansion of availability of these services as well as new digital services. The telephone companies are also going through a period of flux as they try to establish new rate structures which more accurately represent cost of services. As a result, it is likely that we will see rate reductions for some of these services in the future. Both of these developments are likely to make these services more attractive for trunking in traffic control applications.

OPTICAL INFRARED ATMOSPHERIC TRANSMISSION

Characteristics and Data Transmission Techniques

Infrared signals are transmitted from an infrared light emitting diode (LED) or laser source, through the atmosphere along an unobstructed line-of-sight path, to the destination. The mode of transmission is similar to that of terrestrial microwave, although at a much higher frequency. Because of its narrow beamwidth and low power, unlike microwave, infrared atmospheric transmissions do not require coordination of transmission paths by the FCC. In fact, optical infrared atmospheric transmission is not regulated by the FCC at all.

Optical infrared atmospheric transmission is an air-path medium -- no physical connection between source and destination is required. As with microwave, this advantage is intensified in areas where no cabling facilities are available or possible between the two points requiring communications. Optical infrared atmospheric transmission is also not affected by rain as severely as are some microwave transmissions. However, other weather conditions such as fog, smog, or smoke, can cause degradation of the optical transmission.

Optical infrared atmospheric transmission is achieved by intensity modulating an infrared laser or LED source. This is similar to the modulation techniques used in fiber optic transmission. Usually only a single-channel can be transmitted over a link. Most of the multiplexing techniques discussed for fiber are not used in infrared atmospheric transmissions. One exception is the case of an external TDM multiplexer which feeds the transmitter a multiplexed aggregate for transmission.

The output of the laser or LED source is focused through lenses into a very narrow beam. Because of this narrow beamwidth, very stable mounting devices must be used to support both the transmitters and receivers, and the optical signals must be self-locking. In a typical link of 1 mile, the transmitted beam is only 5 meters wide at the receiver, and a variance of only 0.06 degrees in alignment can degrade the link. This translates into a movement of 0.3 millimeters at the source! Outdoor installations (e.g., transmitter receiver mounted on a signal pole or mastarm) are subject to stresses such as wind loading, thermal expansion, and changes in humidity. Accordingly, this potential problem must be given due consideration in design.

Like fiber optics, the bandwidth (and consequently the maximum data rate) of an infrared atmospheric communications link is dependent on distance. At relatively short distances (less than 1 mile), an infrared link can support full-motion video or a T1 data channel. Distances of up to 10 miles can support a 9.6 kbps serial data channel.

Typical optical infrared atmospheric transmission systems can transmit unrepeatered signals over distances from about 1/2 mile to 10 miles depending on bandwidth. Other parameters influencing maximum range include transmitter power and receiver sensitivities. Optical infrared atmospheric transmission systems are immune to common electromagnetic interference sources which can cause noise in radio and microwave systems. They are, however, affected by any obstructions interrupting or redirecting the beam, as well as signal attenuation due to fog, smog, or smoke.

Current and Potential Applications

Optical infrared atmospheric transmissions are point-to point in nature, and face many of the same limitations to applications in traffic control systems as discussed under microwave radio. One application of "airborne laser" technology to traffic control was attempted in the late 1970's. It consisted of a few multiple repeatered links along an arterial (from signal to signal). Custom designed transmitters and receivers were mounted on poles so that one intersection would receive the data, examine it and respond if required, and regenerate the signal to be transmitted to the next intersection down the street. This limited experiment proved successful. However, due to problems not associated with the communications network, the concept was abandoned.

Since that time, atmospheric optical infrared technology has improved considerably due to related efforts in the development of optical sources and detectors for fiber optic systems. Commercial systems are available which support a variety of data and video interfaces, including RS-232C and T1 channels. However, no other attempts have been made to use lasers for traffic control.

One potential traffic control application of atmospheric optical infrared technology would be in a trunking system, where many channels of data are multiplexed into a single high-speed channel for transmission to a distribution site. This concept was discussed in the section on fiber optics. Another potential application could be the transmission of CCTV video signals from the cameras to the control center, although distance restrictions might limit flexibility.

Because of its point-to-point nature and the potential alignment difficulties in multisegmented links, it is unlikely that this technology will see application in computer-intersection communications in centralized traffic control systems. However, atmospheric optical infrared may provide a cost-effective solution in special cases for a point-to-point wideband data link, for CCTV transmission, or for downloading/uploading transmissions between a field master and a few signalized intersections along an arterial.

RADIO

Radio communications refers to the transmission of radio frequency (RF) electromagnetic energy through space -- that is, the electromagnetic signal is not contained within a waveguide. Radio frequencies can range from the hundreds of kHz (10^5) all the way to 1 GHz (10^9). Within this range, there exist many different frequency groups which are defined by FCC regulations and/or their propagation characteristics.

Of all of these frequencies bands, only a few have potential for applications in traffic control communications. The most likely candidates for applications in traffic control are the 928/952 MHz bands, the 450/512 MHz bands, and the cellular radio bands. These are discussed below.

928/952 MHZ POINT-TO-MULTIPOINT RADIO

Characteristics and Data Transmission Techniques

Perhaps the frequencies of greatest interest at this point in time are the recent FCC allocations in the 928/952 MHz bands. These frequencies are reserved for point-to-multipoint, master-to-remote, duplex data communications -- exactly what is required for communications in a centralized traffic control system.

Radio wave propagation in this frequency band is essentially line-of-sight. Like microwave, frequencies along a particular transmission path must be unique to prevent interference.

Channel assignments are currently based on 25 kHz wide channels. Data rates of up to 9600 bps and higher can be supported over a single 25 kHz channel. The total bandwidth (i.e., number of channels) available is dependent on the number of users in the area, and how the channels are allocated. Because of the narrow channel width, radio channels in this band are not usually multiplexed beyond simple polling or other multiple access techniques.

Repeatering for radio systems is different from repeatering in physical media (e.g., twisted-pair, coax) and directed air-path media such as microwave, in that the signals broadcast from the master and remotes can be received by any receiving units in the broadcast area. There are many issues involved in the use of repeaters, especially multiple repeaters, most of which are beyond the scope of this report. For now it is assumed that the central transmitter can reach all remotes, and all remotes can reach the central receiver without repeaters. In this case, the maximum range of radio communications in the 928/952 MHz band is on the order of 15 to 30 miles, subject to any obstacles to the line-of-sight transmission paths. It should be noted, however, that repeaters are widely used in radio, and can be designed into a network to significantly extend its area of coverage.

Radio systems must be carefully designed because the system cannot be isolated from sources which produce noise in the atmosphere. While some constant noise sources can be taken into consideration, impulse noise and some noise from atmospheric phenomena cannot. In addition, the radio network is subject to interference from any out-of-band signals generated by other systems in the area. There are, however, many different types of error control which can be and are implemented in radio based systems. Some of these are implemented in the radios themselves, while others are implemented in the CCU and RCU's. A radio based system can be made as error free as desired, but at the cost of throughput, delay, and overall efficiency.

Current and Potential Applications

Current applications of the 928/952 MHz radio based systems center around the use of a 25 kHz channel as a direct replacement for a voice grade channel. This technology is well supported by multiple vendors. Such an application could include the transmission of low speed data, telemetry, and any other type of information typically transmitted over a voice-grade line.

The major drawback at this time is the limited availability of channels. Because so few channels are available, the only applications for radio at this point would be in a few isolated areas, with communications for the majority of the system implemented over a different medium.

As an example, in one small urban area, there are a total of 20 each 25 kHz channels available for government access (including State, county, and city). These channels have been further allocated by agency function (law enforcement, utility, etc.) such that only three channels could be obtained for a traffic control system. A quick calculation shows that if the typical centralized traffic signal system used these three channels as a direct substitute for a twisted-pair circuit (with eight controllers per circuit), a total of only 24 controllers could be supported over radio in this area. As almost all systems have more than 24 controllers -- the city in this example has around 700 -- either the radio channels must be used more efficiently, or they must be used only for isolated intersections and special circumstances.

Fortunately, there are a number of techniques which can increase the efficiency of available radio channels, each technique varying in efficiency and complexity. Perhaps the simplest technique is to increase the bit rate. As previously mentioned, data rates of up to 9600 bps can be accommodated over the 25 kHz channels. The above calculation assumed a 1200 bps data rate with a maximum of 8 controllers per channel. At 9600 bps, some 35 to 40 controllers could be accommodated per channel. This would increase the total capacity of the three available radio channels in the example to between 105 and 120 controllers. While this is much better, it still does not fulfill the total capacity requirements of many systems. Other techniques can increase channel efficiency even further. One of the more promising of these techniques lies in the area of alternative protocols. These protocols are discussed under the section entitled Alternative Channel Access Techniques.

The future hold promise for radio communications in traffic control systems. However, radio is and will continue to be limited in its application to traffic control communications -- particularly where frequent (e.g., once-per-second) communications are necessary -- by the availability of an adequate number of channels, the ability to make efficient use of these available resources, or a combination of the two.

CELLULAR RADIO

Characteristics and Data Transmission Techniques

Cellular radio is a technique for efficiently sharing limited radio channel resources among a large population. Instead of allocating a channel for a single user over an entire area, a large group of frequencies is defined as a system which affords access by all users to the entire area. The cellular concept divides up the large group of frequencies among small areas or "cells". By limiting the size of the cells, frequencies can be reused over the area. In addition, by dynamically allocating each cell's frequency resources, the limited pool of frequencies can be used very efficiently. The term "cellular" refers to any network utilizing this basic concept.

The term "cellular radio" or "cellular telephone" is most commonly used to refer to those frequencies in the 825 MHz to 890 MHz band which are dedicated to radio telephone using a cellular network in the United States. These systems utilize radio links between cellular radio transceivers to access the telephone system for voice communications. This specific system will be referred to as cellular radio for the remainder of this discussion.

As mentioned above, cellular radio uses frequencies between 825 and 890 MHz. As with the 928/952 MHz band discussed above, propagation is primarily line-of-sight. However, reflections from buildings and hills do occur and can cause destructive interference in the received signal.

Channel assignments are currently based on 30 kHz wide channels. In each city, two operationally identical systems can be used. Each system has 333 channels allocated for it. Of these, 21 channels are used for control purposes, with the remaining 312 used for actual subscriber communications (voice and data). These 312 channels are divided into either seven sets of 44 to 45 channels each; or four sets of 78 channels each. Each cell uses one set of frequencies with adjacent cells using different frequencies as shown in figure 22.

Figure 22. Cell geometrics and frequency subsets.

The available bandwidth in cellular radio is limited by the channel width of 30 kHz and the number of channels available. The data rates achievable over a cellular radio channel are fairly low because the adaptive equalization techniques used to achieve higher bit rates over voice-grade wire lines cannot be used over cellular radio -- the result of the rapidly changing received signal in a mobile environment.

Because of the narrow channel width, radio channels in this band are not usually multiplexed beyond simple polling or other multiple access techniques. Repeatering is not used in cellular radio. By definition the central transmitter for each cell can reach every location within its cell, and there is no need for repeaters.

Radio transmissions of data, especially at low power levels, are very susceptible to noise. Cellular radio is able to minimize the impacts of noise by transmitting over a small, controlled area. Even so, impulse noise can be a problem in data communications. While voice transmissions are not severely affected by impulse noise, data transmissions can be corrupted by a single "hit". Most data transmissions carried over traditional radio links have provisions for re-transmission if the messages are not received properly. These systems use positive acknowledgment and parity/checksum among other techniques for error detection. As most cellular radio transceivers do not have any such error control provisions, error control must be implemented by the end equipment.

Data transmission over the cellular radio frequencies is not as well supported as data transmission on some other media. The cellular radio industry is just starting to realize some of its potential for data communications. As a result, only a small amount of support for some low-speed data communications is available at this time. However, it is very likely support will increase greatly in the near future.

Current and Potential Applications

Cellular radio has one very attractive attribute. It can provide voice-grade communications links over an entire city via a network already in place and without a single physical connection. While this sounds like an attractive proposition, its drawbacks more than outweigh its assets.

As discussed earlier, cellular radio is a technique to use limited radio channel resources with maximum efficiency. This is accomplished through frequency reuse and dynamic re-allocation of resources. Since communications in centralized traffic control systems and in distributed systems between field masters and intersections, are more or less continuous, there could be no dynamic re-allocation of the channels to other subscribers, thereby eliminating cellular radio as a viable alternative.

In addition, cellular radio provides only a link from the remote unit to the cell transmitter. The remainder of the transmission path (e.g., transmitter to central) is provided over wire lines. As typical drops in a traffic control system are (hopefully) not mobile, these points could be equally well served by leased wire circuits. Finally, cellular networks have a rate structure which would make continuous connection of the type required in a traffic control system prohibitively expensive -- far greater than even the cost of leased Telco facilities.

Three applications of cellular radio do appear viable for traffic control systems:

- Communications between a portable remote terminal (e.g., a crew responding to a trouble call) and the central computer.
- A dial-up connection between the central microcomputer and the on-street master in a distributed system, although a dial-up wire line is usually quite economical for such applications.
- In-vehicle navigation information.

450/512 MHZ RADIO

Characteristics

The 450/512 MHz frequency bands are allocated for public safety and municipal use. Unlike the 928/952 MHz bands, these frequencies are not dependent on line-of-site; but there are power restrictions which limit the transmitter output to 10 watts -- approximately 10 miles.

One manufacturer has recently developed a device consisting of receiver, transmitter, and microprocessor-based modem and protocol controller. The device operates in the 450/512 MHz band and has the following features:

- Half-duplex, 1200 baud.
- TDM/FSK communications.
- EIA RS-232 port and DB-25p connector.

Current and Potential Applications

This radio data communications system was designed as a direct replacement for the physical medium data links (i.e., twisted-pair and/or leased Telco) in most distributed closed-loop traffic signal systems as shown in figure 23. The system is scheduled to be installed in a few cities along the eastern seaboard before the end of 1988.

This radio-based communication system offers much promise. It is an ideal first (contemporary) application of radio to computer-based traffic control. Given the relatively infrequent communications in a distributed system, many of the technical complexities of using radio in a traditional centralized system have been avoided. Furthermore, the system is not constrained by line-of-site restrictions. The hardware also appears to be cost competitive.

A major drawback with this radio system (at the time of this report) is that it has not yet been thoroughly tested in an operational setting. The reliability and capacity (i.e., number of field masters, number of controllers) of the communications system needs to be determined. However, there appear to be no technical reasons why these and similar concerns won't be adequately resolved in time.

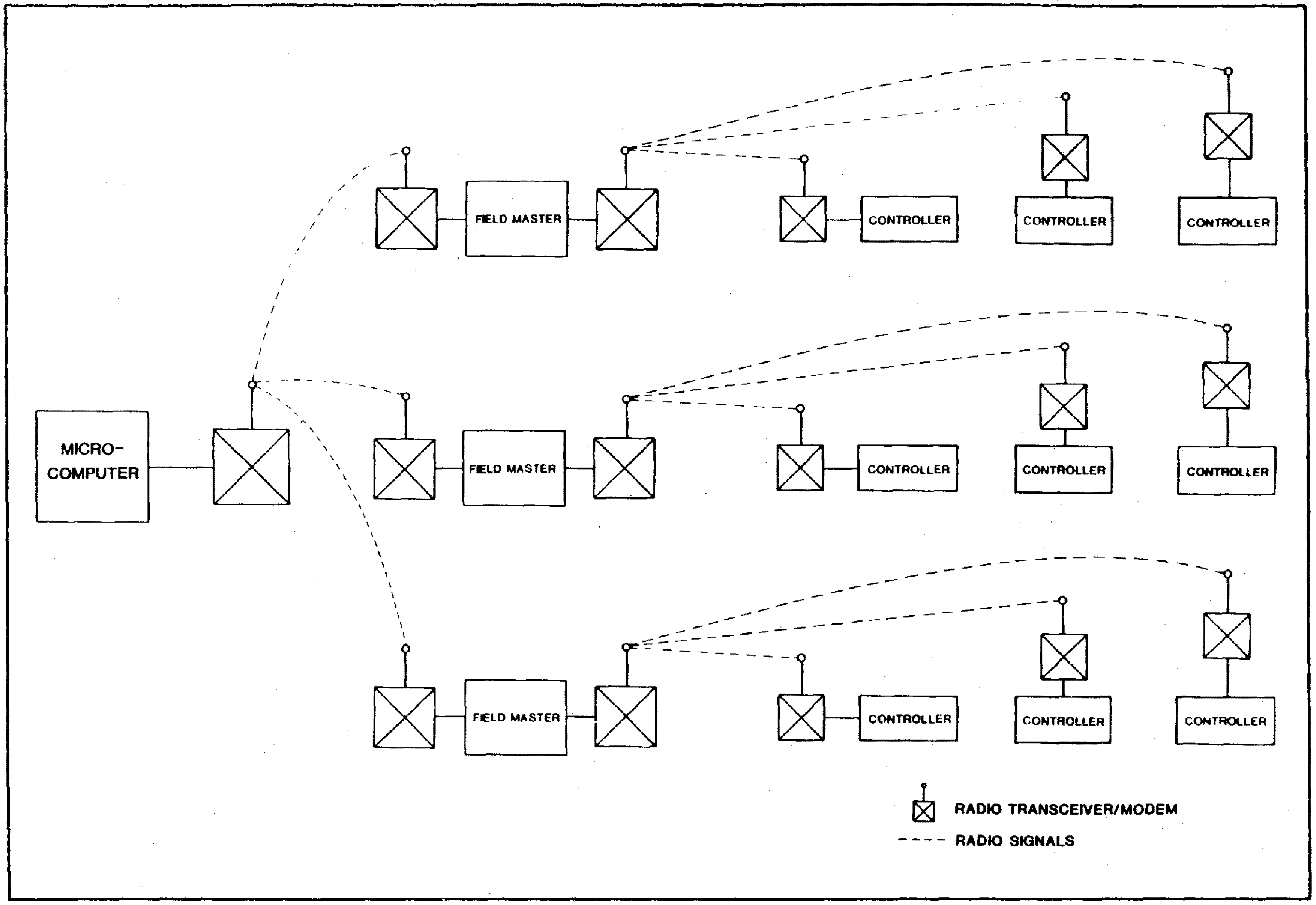


Figure 23. Radio-based communications for distributed signal systems.

Design requirements include housing the radio device, and the height of the directional antennae. Additionally, as with all radio communication systems, availability of channels (i.e., frequencies) and FCC regulations are a significant issue.

ALTERNATIVE CHANNEL ACCESS TECHNIQUES

General

The vast majority of all traffic control system communications are based on some type of polling technique. When information is needed from one field drop or another, the central requests the information from the remote drop by a "poll". The poll consists of a message from the central to the remote containing the remote's address, the type of data to be sent or received, and any actual data required. All coordination of responses is provided by the master, and no remote can initiate a transmission unless at the specific request of the master. In this way, multiple crops can share a channel, without coordinating between themselves. (Refer to discussion of TDM in chapter 2).

In most systems to date, this scheme has worked quite well for a number of reasons. First of all, in second-by-second control systems such as UTCS, a central-to-remote transmission is required every second. Any information requests can be incorporated into that transmission such that no additional overhead is required to initiate a transmission from the remote to the master. Secondly, in the most common case of voice-grade channels over hardwire interconnect (including leased Telco), a system can operate eight controllers on a single circuit, and as many circuits as required can be installed or leased.

Now, however, there is an ongoing evolution in the system configurations and architectures as a result of advances in microprocessor technology. Systems are utilizing more and more intelligence at the local controllers and other field devices. These devices are capable of processing system detector data, and even using it to make decisions. In addition, using common time-base references, microprocessor-based controllers can coordinate their local cycles with those of other controllers in a group.

All of these changes have caused a shift in the communications dependencies of contemporary systems. Second-by-second control is less critical. Instead, the central facility can download timing plans in advance and simply implement a timing plan number only 4 to 8 times per day. In some cases, even the schedule can be downloaded in advance so that ordinary TOD/DOW operation can be achieved with almost no regular central-to-remote command communications.

While the communications scheme described above requires far fewer transmissions than once-per-second centralized control, it is still necessary to get data back from the field locations for detector data collection, failure reporting, data base upload, etc. Additionally, monitor data (e.g., phase green) must be requested more frequently than the on-street changes -- usually once-per-second for real-time monitor data -- so that no changes of state are missed between transmissions. This can be accomplished within the standard polling scheme; but since the central must initiate all return transmissions (i.e., poll the field drops), the majority of the central-to-remote transmissions are now purely overhead. Thus, there is no increase in the number of controllers which can share a channel.

If all remotes could initiate channel access as needed -- with some type of coordination between them so that no intervention would be required by central --then return communications (i.e., monitor messages) would only be necessary when there was a change of state in the local controller, (e.g. a phase change, new detector data, power outage, etc.), and the number of controllers per channel could be increased. This type of communications scheme can be achieved, using a **contention** channel access technique.

A contention system is defined as a system in which multiple users share a common channel in a manner that can lead to conflicts. Two contention techniques will be discussed: ALOHA and Carrier Sense Multiple Access (CSMA). Both of these protocols allow for access to a channel by all remotes (and the central) with provisions for coordinating the accesses and resolving any conflicts (collisions).

ALOHA

The ALOHA system was first developed at the University of Hawaii to allow various facilities on the islands to access the main computers over a common channel resource. There has been much research on ALOHA, and quite a number of variations exist. In its basic form, ALOHA is based on a very simple premise -- whenever there is data to transmit, the user proceeds without delay and sends the information.

Obviously, this is going to cause a fairly high number of collisions between users accessing the channel simultaneously. On the other hand, some messages will be transmitted without conflict (based on a probabilistic model), and those experiencing conflicts can retransmit their messages. Because pure ALOHA does not impose any restrictions on when units can transmit, its maximum theoretical throughput is only around 18 percent of the total channel capacity. A variation on pure ALOHA, called slotted ALOHA, allows transmissions to begin only on specific boundaries, and therefore achieves a slightly more attractive 37 percent maximum theoretical throughput.

Without doing any detailed analyses or modeling on the generation of monitor data transmissions in a typical traffic control system, it is difficult to precisely estimate the efficiency of an ALOHA system. However, to get a very rough idea of the kind of efficiency that is achievable with ALOHA contention as compared to a polling technique (and making some gross assumptions), up to 50 controllers could be accommodated using conventional polling techniques over a 9600 bps radio channel, while approximately 85 controllers could be accommodated over the same channel using a slotted ALOHA system.

There are many variables in an ALOHA system which can only be modeled using very complex mathematical models. As these are well beyond the scope of this discussion, any system designer considering using an ALOHA technique would need to perform a fair amount of research to establish which variation would best suit the needs of the system and what values could be obtained for parameters such as throughput, delay, and stability.

Carrier Sense Multiple Access (CSMA)

Carrier Sense Multiple Access (CSMA) techniques are another form of a contention system. As with ALOHA, CSMA systems allow multiple users to share a common channel in a way in which conflicts can occur. However, CSMA provides a mechanism by which the number and probability of collisions can be significantly reduced. In a CSMA system, whenever there is data to transmit, the user must first listen to the channel to determine if it is currently in use. If it is, the user will defer transmissions until the channel is clear. This is the "carrier sense" part of CSMA.

Collisions can still occur in the case where multiple users are ready to transmit, but defer until the end of a current transmission, at which time more than one user attempts to transmit. Collisions can also occur if multiple users attempt to access an idle channel simultaneously. This **contention interval** is related to the propagation delay through the medium. The contention interval in CSMA systems is much smaller than the contention interval in ALOHA systems. This results in higher throughput and fewer collisions.

CSMA systems can operate at theoretical throughputs of greater than 50 percent, with some systems achieving greater than 90 percent throughput under certain load conditions. For comparison, a throughput of 65 percent is assumed. Performing a very rough calculation as in the previous section, up to 150 controllers could be accommodated over a single 9600 bps duplex radio channel, as compared to the 85 controllers with slotted ALOHA and the 50 controllers with polling techniques.

As was the case with ALOHA, there are many variables in a CSMA system which can only be modeled using complex mathematical models. As these are well beyond the scope of this discussion, any system designer considering using an CSMA technique would need to perform a fair amount of research to establish which variation would best suit the needs of their system and what values could be obtained for parameters such as throughput and delay. Figure 24 shows the relative throughput of various random access protocols versus load conditions.

Current and Potential Applications

The random access protocols discussed in this section currently have limited applications in traffic control. As discussed at the beginning of this section, all once-per-second control strategies require central-initiated communications every second with a constant, minimal delay. Accordingly, once-per-second based control systems cannot use these random access protocols since delay cannot be held constant. This includes a great many of the centralized systems in operation at this time.

With physical media such as twisted pair, coax, and fiber, these protocols will be of limited use. In twisted pair, the data rate is so low that only a small measure of efficiency could be gained. Coax and fiber media typically have ample capacity for traffic control communications using the simpler polling technique, so that a random access protocol would be of little benefit.

However, in a radio-based traffic control system which does not require once-per-second control commands nor monitor messages, and where available radio channels are limited, these protocols can significantly increase the efficiency of the medium. Referencing the example begun in the previous section on radio, where only three radio channels were available in an urban area for traffic control communications, the channel efficiency could be increased as shown in table 13.

In this example, where channel availability limited the total number of controllers which could be supported using conventional techniques, applying a higher bit rate along with a more efficient protocol resulted in a 1,800 percent increase in the number of controllers which could be included in the radio-based system.

At this time, there is no support for the application of these random access protocols in the traffic control systems industry. However, there is some support from the radio industry. At least two radio manufacturers produce data radios which incorporate some type of random access protocol into the radio itself. One has implemented a variation of slotted ALOHA and the other has implemented a type of CSMA. With the appropriate development effort, this existing hardware could be transferred to traffic control applications.

Table 13. Channel efficiency for various channel protocols.

Protocol	Bit Rate	Number of Controllers (3 Channels)
Polling	1200 bps	24
Polling	9600 bps	110
ALOHA	9600 bps	255
CSMA	9600 bps	450

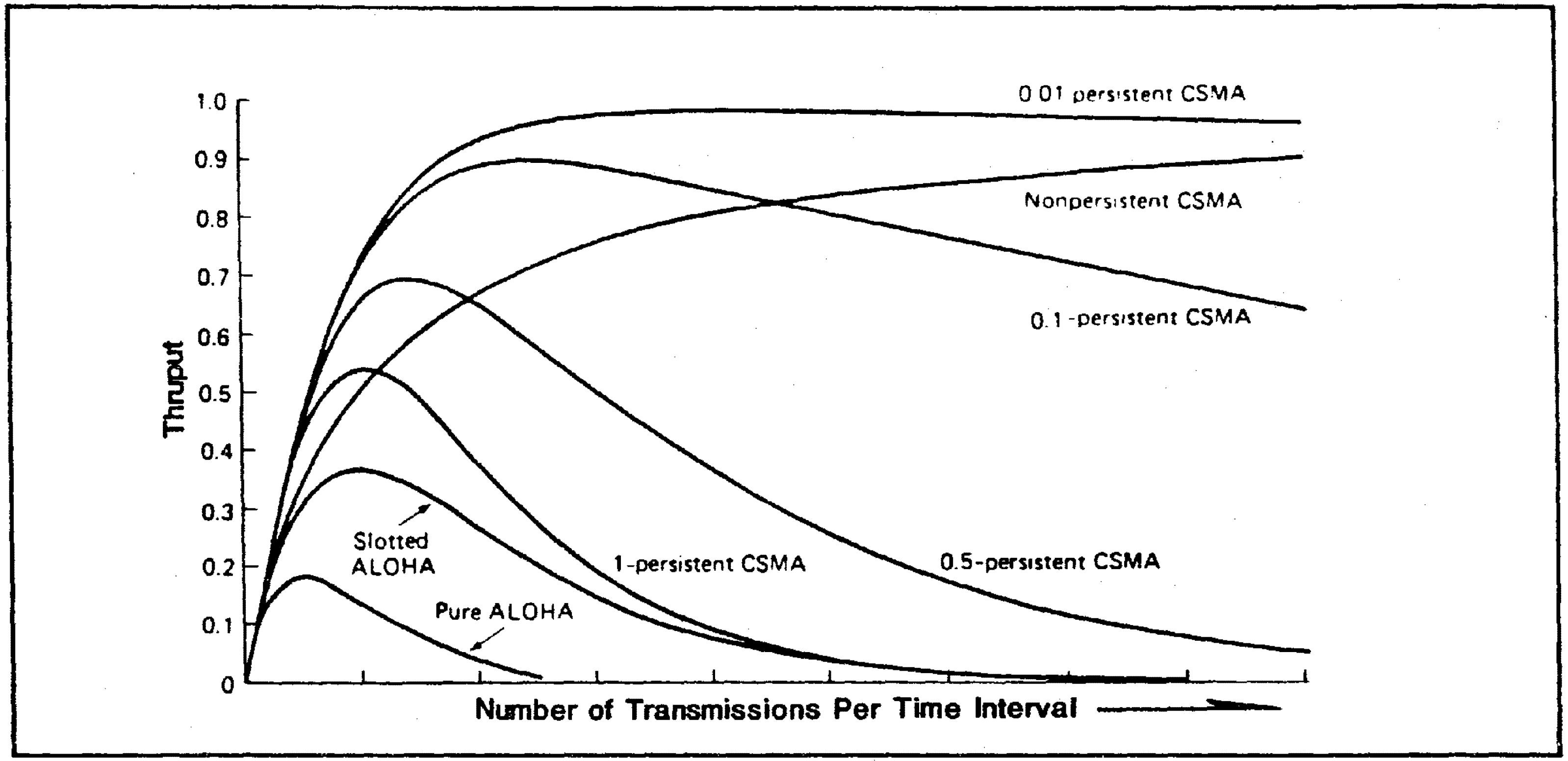


Figure 24. Comparison of the channel utilization versus load for various random access protocols - reference 6.

6. THE FUTURE

The information and discussions presented in this report have covered many different facets of communications in traffic control systems; from the fundamentals of communications theory and terminology, to the applications of various communications technologies in contemporary systems. At this point, an appropriate question is "Where do we go from here?" This chapter attempts to answer that question. It summarizes potential research and development activities for improving the performance of existing communications media, and for making the emerging technologies suitable for widespread application in traffic control systems.

OVERVIEW

As discussed early in the report, information requirements can vary significantly between traffic control systems. Differences exist in the type of information to be transmitted (data, voice, video); the quantity of information; the rate at which information needs to be transferred (e.g., once-per-second or on an as-needed basis); and the path of the information (point-to-multipoint or point-to-point). Such distinctions are essential whenever discussing the application of communication technologies to traffic control. For example, it is generally agreed that twisted-pair cable is a reliable and cost-effective medium for a traffic control system. But in reality, this is true only for point-to-multipoint networks involving low-speed (i.e., 1200 baud) data transmissions. Such an application does pertain to the vast majority of today's traffic control systems; but for a system requiring trunking capabilities or full-motion video over a large area, twisted-pair cable would not fulfill all the system's communication requirements.

As just noted, a characteristic common to most traffic control systems is the relatively low data volume per control location when compared to other types of data communications (e.g., bank and airline reservation transactions). This is a particularly interesting characteristic in light of some of the recent advances in data communications. As the need to transfer large amounts of data between powerful computers has grown, the need to increase the capacity and speed of data communications devices has grown accordingly. Thus, considerable development has been centered on transferring data at very high speeds from one point to another point for applications such as local area computer networks.

Traffic control systems are at the opposite extreme of the focus of this development activity in that they typically require transferring very little data to each field device, using a simple polling technique at low speeds, and communicating over a network that encompasses many square miles. As a result, many of the communications techniques used in traffic control systems are based on technology developed over 10 years ago. Fortunately, for the current generation of traffic control systems, this technology is still adequate.

It must be recognized that traffic control communications comprise only a very small part of the overall picture. Advancements in communication technology have been, and will likely continue to be, driven by needs outside the traffic control industry. It will be possible to transfer some of these new/improved technologies directly to traffic control. In other instances, significant changes to certain traffic control and monitoring concepts will be necessary to take full advantage of an advancement in communications. Finally, the nature of several communications media is such that, regardless of any enhancements which might occur, their potential use in traffic control systems will be limited to special and unique situations.

EXISTING COMMUNICATION TECHNOLOGIES

In general, the communications technologies currently available will continue to be adequate for today's traffic control systems for some time. There are, however, some changes and advancements which could impact these existing media.

Twisted-Pair/Leased Telco

Copper cable "technology" is well established, and should continue to meet the majority of the needs in traffic control for some time. By following the guidelines presented in chapter 3, the design, installation, and maintenance of twisted-pair and leased Telco networks can prove very successful.

Advancements in voice-grade data communications will focus on increases in information throughput. For example, 2400 bps modems and 9600 bps modems are currently available. The 2400 baud modern may have applications in current traffic control systems; but it must first be tested in a multipoint environment. This also holds true for the 9600 baud modem. Additionally, the turn-around overhead associated with a 9600 baud modem may dictate that data communications in centralized systems occur less frequently than once-per-second; which, in turn, would require the development of new communications hardware (e.g., CCU) and associated software.

The potential for increased throughput translates into more field drops (e.g., controllers) per full-duplex channel. In a twisted-pair network, this means fewer cable pairs. Smaller cables will reduce installation costs slightly. They may also enhance the usability of some existing conduit networks (e.g., available conduit space, cable bends in handholes, etc.), particularly for the installation of trunk cables.

In a leased network -- assuming that the Telco lines are capable of handling the increased baud rate -- increasing the number of drops per channel will obviously reduce the total number of Telco channels required. Depending on the tariff of the local telephone company, the cost savings could be significant.

Another area of development for twisted-pair communications is the application of video. As previously discussed in chapter 3, slow-scan technology is currently available, and can be used in traffic surveillance applications where full-motion video is not required. Additional video techniques are also being developed, including one that uses pre-emphasis techniques to compensate for extremely high cable losses at the higher frequencies. This technology can achieve unrepeatered transmission distances of approximately 1 mile. Additional testing is required to measure the performance of this video technique in multipair cables and in repeatered networks.

Coaxial/CATV

Coaxial technology is well developed, and no new major advances are foreseen. If anything, the use of coax cable for traffic control data and video communications may even decrease if fiber optics becomes more suitable for multipoint applications. Using slotted coaxial cable as an antenna for low-power radio voice transmissions has met with great success, and should continue to be a viable alternative for HAR and related applications.

NEW AND EMERGING TECHNOLOGIES

As discussed in chapter 5, the new and emerging communication technologies have generally been used in traffic control systems for special and unique circumstances. Traffic control systems are evolving. They are increasingly using the capabilities of low-cost microprocessors to distribute processing from the central computer to the local devices (controllers, ramp meters), and changing the nature of the communications between them. This evolution, coupled with continuing advancements in the communications field, will make some of the new and emerging technologies more applicable to traffic control systems.

Fiber Optics

The future potential for fiber in traffic control is great. As discussed in chapter 5, fiber is already being used in a number of systems, including data trunking between a central computer and an area computer, closed-circuit television along a freeway, and to connect data hubs and video hubs to a central computer.

One current drawback to fiber is its cost. Fortunately, the relative cost of fiber and its associated electronics is decreasing -- the result of widespread interest and applications throughout the telecommunications industry and other markets. Because of this great interest in fiber, these cost reductions will continue without any action or reaction within the traffic control industry.

Developments in fiber technology are necessary to expand its potential for point-to-multipoint applications. Practical technology at this point dictates some form of electro-optical conversion/reconversion at each control location which causes inefficiency and reduces the reliability of the network -- a single failure disrupts all transmissions beyond the failure point. Fiber can and is being used in some multipoint systems; but these networks really consist of a series of separate point-to-point links using either a daisy-chain configuration (e.g., signals along an arterial), or using a separate fiber for each field drop and running these fibers directly back to the control point.

A cost-effective fiber transceiver, which could receive from and transmit onto a fiber without "breaking" the entire light signal and then regenerating it, would allow fiber optics to perform more effectively in a multipoint environment. In essence, such a device would function like the passive taps used in coaxial systems.

Perhaps an intermediate step between current practical technology and the concept discussed above is a "passive-fail" modem. This modem in normal operation would function just as current drop and insert modems (i.e., convert all incoming information to an electrical signal, check to see if it is intended for its location, act on it as required, and reconvert it to an optical signal and transmit it down the line). However, in the event of a failure, the modem would optically connect the incoming and outgoing fibers. Instead of causing a loss of communications to all succeeding drops, it would function as a passive connection in the cable network and not impact any other communications. This type of modem is in the process of being designed and manufactured at the time of the publication of this report. The status of this passive-fail modem should be investigated whenever considering a fiber solution to a system's communications needs.

Finally, many fiber optic devices are not designed to environmental specifications suitable for operation in traffic control cabinets. This can be a limitation in the design and/or reliability of a fiber-based system. Therefore, there is a need for a greater number and variety of fiber optic electronics which are certified to operate over the entire range of temperature and humidity specified for NEMA controllers.

Micrcowave

Terrestrial microwave is currently well supported due to its application in many other industries. As discussed in chapter 5, microwave currently has applications (albeit limited) for traffic control systems, including point-to-point trunking and point-to-point transmission of video signals where the density of cameras is low and/or a physical connection is impossible or too costly. There are, however, no foreseeable developments which could specifically enhance its use in point-to-multipoint, duplex networks such as required in most traffic control systems.

Leased Telco Digital Data Channels

One development that offers great promise is the offering of expanded digital services, both high and low speed. At the time of publication of this report, Pacific Bell is attempting to get approval on a tariff revision which would offer new, end-to-end digital services at lower rates than those currently offered on DDS services. These new services would provide offerings from 1200 bps to 64 kbps (as opposed to the current 56kbps for DDS). The 1.544 Mbps T-1 may also be affected (in the form of lower rates) by these new offerings.

Because the tariff is subject to change prior to the Public Utilities Commission approval, quantitative information on rates and performance is not available at this time. Additionally, tariffs and offerings vary between the regional operating companies. Nevertheless, when designing a traffic control system, it would be worthwhile to check with the local telephone company to ascertain what offerings are currently available.

Optical Infrared Atmospheric Transmission

Except for a limited experiment in the late 1970's, this technology has not been applied to traffic control. Atmospheric infrared communications are similar to microwave in that both can support large bandwidth signals, transmit along a line-of-sight path, and are point-to-point in nature. An infrared atmospheric communications link could conceivably be used for short-distance broadband applications (e.g., trunking and video transmissions of 1 mile or less) where a physical connection is impossible, too costly, or where microwave channels are unavailable. (Note: As previously discussed, optical infrared atmospheric transmission is not regulated by the FCC). Equipment is currently available for these applications.

The use of atmospheric infrared transmissions in point-to-multipoint traffic control systems would prove very difficult. Being a point-to-point medium, a laser-based communications network would have to be arranged in a daisy-chain configuration. Thus, a failure at any control point (e.g., malfunction of the transceiver itself, or an alignment problem) would disrupt communications on all subsequent links. Furthermore, frequent (i.e., once-per-second) polling cannot be used with currently available hardware. At this point in time, it is doubtful that optical infrared atmospheric technology will experience any new developments to resolve these problems, thereby preventing airborne laser from becoming a more attractive communications alternative for the majority of traffic control systems.

Radio

For a few years during the 1960's, radio transmission was used for traffic control. The transmissions were limited to low-volume applications, and did not involve any applications in medium-speed time divisions. In recent years, radio technology has been applied only on a limited basis -- applications where the transmission volumes are relatively low and time is available for multiple retries.

Radio technology is now applicable in a new form. Data radio is a resource that has just begun to be tapped for traffic control communications. As discussed in chapter 5, a radio-based communications system has already been developed for distributed closed-loop traffic control. Thus, the necessary research and development in this particular area involves evaluating the initial applications of the radio-based system in the field; verifying its operation in terms of reliability, capacity (i.e., number of controllers and field masters per radio channel), and compatibility with closed-loop systems of all manufacturers; and making any necessary adjustments and improvements to provide the desired operation. Additional enhancements (e.g., provide data and voice communications simultaneously over the same radio channel) may also prove beneficial.

From a technical viewpoint, it is currently feasible to use radio communications for centralized traffic control system. As discussed in chapter 5, radios which transmit/receive over 25 kHz channels in the 928/952 MHz bands are commercially available. There are, however, significant institutional constraints to radio's widespread application in this manner -- namely, a limited number of available channels. In order to progress from the "special case" application of radio in centralized systems, it will be necessary for the traffic control industry to make significant changes in certain system control and monitoring concepts such that the few available radio channels are used more efficiently. In essence, the number of field drops (i.e., controllers, ramp meters, variable message signs, etc.) per channel must be significantly increased.

There are a number of creative alternatives for achieving this goal. While the specifics are beyond the scope of this report, the necessary development will likely involve some combination of a non-polling channel access protocol (e.g., contention system), a reduction in the frequency of communications (e.g., download timing plans, transmit phase green returns only when they change state, etc.), and an increase in a traffic control system's tolerance to variable throughput delay.

CLOSING

The current state of the art in communications and in traffic control provides a very fertile environment for the development and further enhancement of communications media. Systems with special communications needs, whether due to advanced features or unique constraints, will be the ideal test beds for these new and emerging technologies, and will provide the vehicle for the collection of applications data and for the development of communications hardware and components required for the more general application of these media in traffic control systems.

Existing technology will continue to be used in traffic control systems for some time. New technologies such as fiber optics and, to a lesser extent, radio are emerging as viable alternatives for many traffic control applications. The nature of many communication media -- microwave, atmospheric optical infrared, cellular telephone, and leased Telco digital data channels -- is such that their potential for widespread use in traffic control is limited. But the designer should not simply dismiss these (or any communications technology) from consideration.

Many traffic control systems have unique features, communication requirements, and constraints; and the process of analyzing and selecting the "best" communications media (or combination thereof) must consider all possible technologies.

APPENDIX - EXAMPLE COMMUNICATIONS TRADE-OFF ANALYSIS

This appendix presents a "real-world" example of the recommended procedures for conducting a communications trade-off analysis. A number of simplifying assumptions have been made for the sake of brevity. Nevertheless, the various guidelines presented in chapter 3 have been followed.

BACKGROUND

A centralized traffic signal system (UTCS-based) is being evaluated as part of the overall traffic engineering analysis. The initial implementation area will consist of 75 signalized intersections. No significant special features (e.g., CCTV, 1.5 GC) are being considered; although the system will include permanent count stations and must be compatible with local fire preemption.

TRANSMITTED INFORMATION

The basic communication parameters for the proposed system are summarized in table 14. In order to handle the additional data loading from count stations the detector data will be preprocessed by the RCU's prior to transmission to central.

COMMUNICATION RESOURCES AND CONSTRAINTS

Existing communication resources (e.g., signal locations, existing conduit and pole lines) are shown in figure 25. Other pertinent information is listed below:

- Existing conduit and most of the pole lines contain random-lay cable for AC interconnect (existing system).
- No available conduit in Telco duct network.
- Telco terminations (manhole or pole) are within 80 ft of each controller cabinet.
- No CATV in the area.
- Any new conduit will be installed within existing rights-of-way, and predominately in roadway and sidewalk areas.

Table 14. Example analysis - basic communication parameters.

TYPE OF INFORMATION

- Control Commands.
  - Address
  - HOLD-ON-LINE
  - HOLD
  - FORCE-OFF
  - FLASH
  - Special functions on/off (3 separate functions)

- Monitor Messages.
  - Green phase on
  - Flash on
  - Preempt on
  - Detector volume and summary (8 detectors)

QUANTITY OF INFORMATION

- Once-per-second transmissions, except detector data which are preprocessed and returned once per minute.

- Voice-grade channels, operating at 1200 baud, are required as a minimum.

- TDM/FSK

QUALITY OF INFORMATION

- Standard error checking techniques (e.g., parity) will be appropriate.

NETWORK CONFIGURATION

- Full duplex; point-to-multipoint.

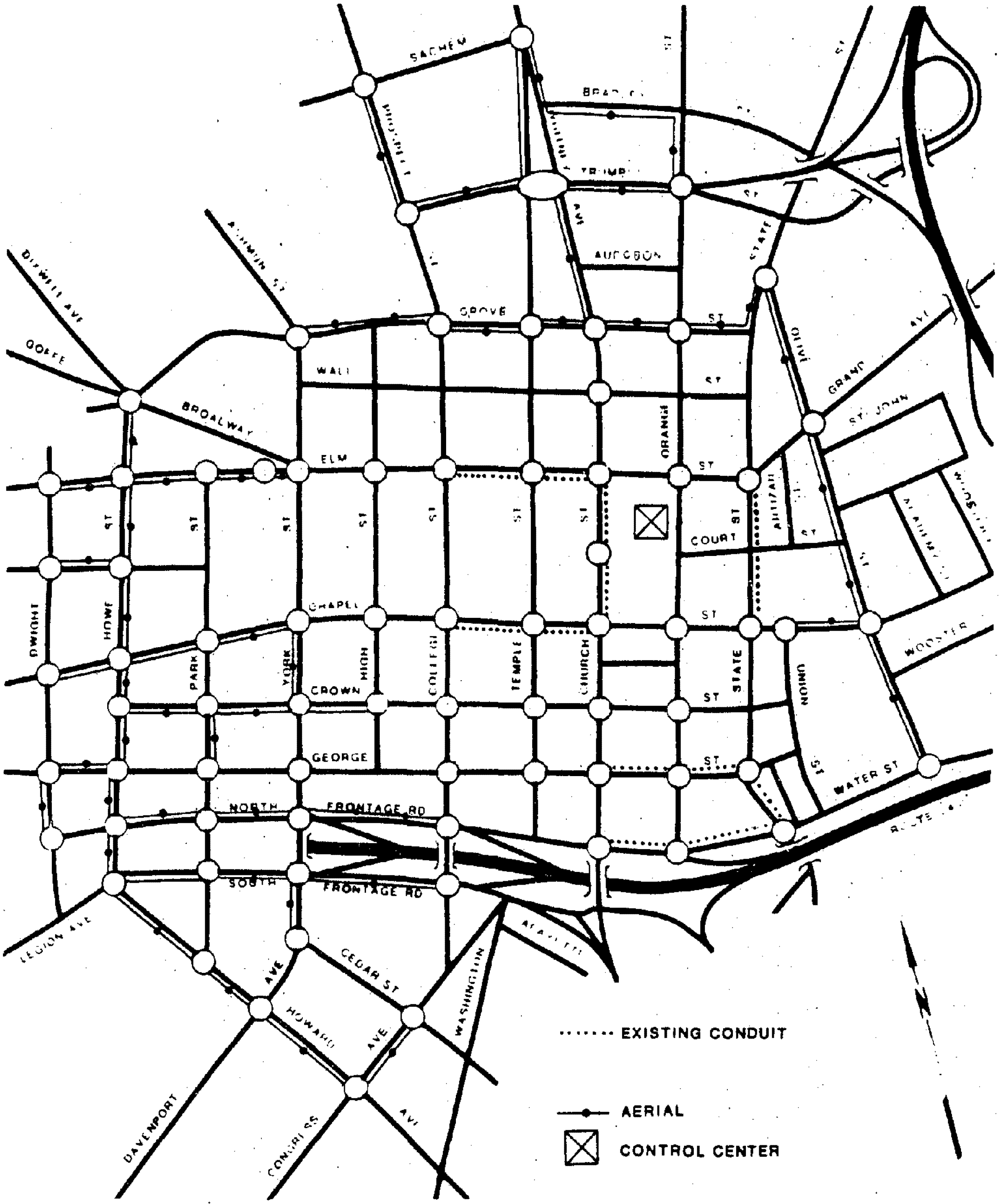


Figure 25. Example analysis - existing communication resources.

- Tariff shown in previous figure 16 is applicable.
- Past Telco rate increases have been uniform and stable.
- Maintenance personnel and existing skills level are adequate for communications hardware in the existing system.

COMMUNICATION ALTERNATIVES

Three media alternatives are selected for further analysis:

- City-owned cable network.
- Leased Telco.
- Combination of city-owned and leased Telco.

Coaxial will not be analyzed in depth because of the increased maintenance requirements. Communications media which are basically point-to-point (e.g., fiber optics, microwave, laser, etc.) are not appropriate for this application. Radio is not feasible for a centralized system. Additionally, an integrated (i.e., shared) communications network is not applicable in this example.

City-Owned Cable

This alternative consists of city-owned cable installed between the master site and each signalized intersection. The communications cable would be twisted-pair conforming to REA Specification PE-22 for telephone-type cables.

The existing conduits are evaluated by tugging on the existing interconnect cables. Most of these cables will not move, implying a constriction or blockage in the conduit. A representative sample of these conduit runs are rodded. It is discovered that several old conduits have collapsed. Furthermore, several runs have sharp bends (i.e., 90° elbows). It is determined very little of the existing conduit can be used, and that new conduit and handholes will have to be installed in those areas where no useable conduit nor pole lines exist.

The pole lines are checked in the field with utility representatives. They are usable, but will require that the existing interconnect cable first be removed --weight, and entry into controller cabinets via existing weatherheads and conduits are the major concerns -- and that utility relocations be made at several locations.

A city-owned communications network is configured using new and some existing conduit, and existing pole lines. The cables serving the initial implementation area are sized for the ultimate system so that future system expansions will involve simply "tapping" into a trunk cable on the periphery of the area. A variety of cable sizes are included in the configuration, with the larger sizes (e.g., 100, 50 pair) utilized as trunk lines, and smaller sizes (e.g., 12, 25 pair) used to interconnect intersections to larger cable runs.

Leased Telco

This alternative consists of analog Type 3002 full-duplex circuits leased from the Telephone Company. The tariff previous (figure 16) offers a prepayment plan which is eligible for Federal-aid funding. It is noted that other computerized signal systems in the State are using leased Telco circuits (from the same Telephone Company), and their reliability and the Telco maintenance response is good.

In addition to the one-time tariff charge, there are also Telco installation charges and related field construction costs. The field construction includes conduit laterals between Telco facilities (manholes or utility poles) and each controller, and the installation of an Auxiliary Termination Cabinet on the outside of each controller cabinet for the Telco terminations.

Combination

This alternative is a hybrid of the first two alternatives. In those areas where there are pole lines, four to six intersections comprising a communications channel would be interconnected with city-owned 6-pair cable. Each channel would then be connected to the computer facility via a leased Telco circuit in accordance with the tariff. Leased lines would also be used to interconnect intersections located in those areas where no pole lines or useable conduit exist. The proposed cable routing for the hybrid network is shown in figure 26.

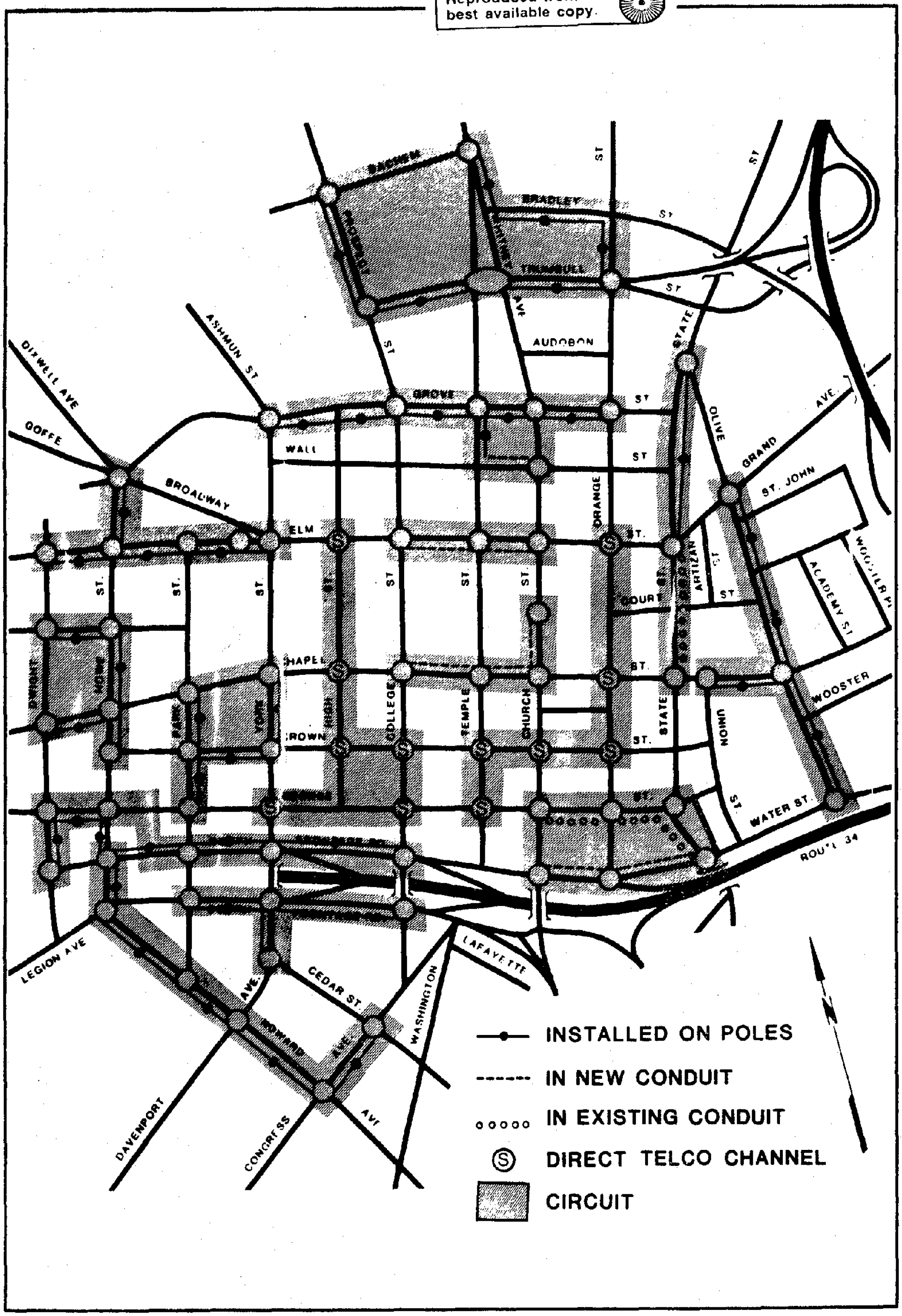


Figure 26. Example analysis - hybrid cable routing.

ALTERNATIVES ANALYSIS

Cost estimates for the city-owned cable network, leased Telco, and the hybrid are shown in tables 15, 16, and 17, respectively. (Note: These estimates do not include the costs of interface hardware (RCU's) and test equipment, as they are the same for each alternative.)

The 10-year life cycle costs are summarized in table 18. The major drawback with the city-owned cable approach is its high cost -- more than twice the other 2 communication media options. Given the fixed project budget and increased maintenance requirements, installation of city-owned cable for system communications is not a viable alternative.

The leased Telco and hybrid alternatives are fairly equivalent in terms of their life-cycle costs. There are, however, a number of intangibles that must be considered, including:

- The hybrid alternative contains potential non-project expenses which were not included in the cost estimate -- specifically, utility adjustments on telephone poles to provide adequate clearance for the city's communications cable.
- All maintenance of the communications cable network will be the responsibility of the telephone company. With the hybrid alternative, maintenance responsibilities would be split between the city (for their cable) and Telco (for their facilities). Isolating problems and identifying who is responsible for correcting the problem could prove troublesome.
- The city's existing signal system will not be affected during construction of the Telco communications network. With the hybrid alternative, the existing interconnect cable would have to be removed to provide space on poles and in existing conduit for the new twisted-pair cable, thereby disrupting system control for some time until the computerized system was turned on.

In consideration of costs, intangibles, and the telephone company's past performance with computerized signal systems, it is judged that the leased Telco alternative is the optimum network for a centralized traffic signal system in this city. It is emphasized that this is just an example. If the city had a large network of usable conduit, the prepayment Telco tariff was not available, or there was potential for integration, then a city-owned cable network may have been better. Each system requires an individual site-specific communications analysis.

Finally, it is emphasized that a communications trade-off analysis is necessary for each traffic control system configuration being considered in the overall traffic engineering analysis. This example addressed only a centralized signal system. Additional communication trade-off analyses would typically be performed for other system alternatives (e.g., distributed system); and the optimum communications network for each alternative system would then be integrated with the overall traffic engineering analyses.

Table 15. Example analysis - estimated cost of city-owned cable network.

ITEM	QUANTITY	UNIT PRICE	INSTALLATION COST	ANNUAL COST
Signal Pole Lateral (new conduit from pole to controller cabinet)	26 ea.	$ 3,000	$ 78,000	$
Conduit-Rdwy (includes handholes)	8,500 ft.	40	340,000	
Conduit-Trench (includes handholes)	4,500 ft.	20	90,000	
Communications Cable (conduit)	17,000 ft.	6	102,000	5,100
Communications Cable (aerial)	34,500 ft.	3	103,500	5,175
Termination Cabinets (trunk cables)	4	3,000	12,000	
Aux. Termination Cabinets	10	1,000	10,000	
Modify Exist Foundation	22	1,000	22,000	
Modify Exist. Pole/Cabinet	46	300	13,800	
		TOTALS	$771,300	$10,275

Note: All costs are shown for example purposes only. Current local costs for these items should be determined and used.

Table 16. Example analysis -- estimated cost of leased Telco.

ITEM	QUANTITY	UNIT PRICE	INSTALLATION COST	ANNUAL COST
Telco Local Channels	90	$624/5.32	$ 56,160	$ 5,746.00
Telco Bridging Arrangements	90	632/4.50	56,880	4,860.00
Telco Installation	90	125	11,250	
Telephone Facility Lateral (from manhole/pole to controller cabinet)	75	1,500	112,500	
Aux. Termination Cabinets	75	1,000	75,000	
		TOTALS	$311,790	$10,606.00

Note: Local channels and bridging arrangements is the sum of the number of intersections (75) plus the number of communication channels (15 - an average of six controllers per channel).

All costs are shown for example purposes only. Current local costs for these items should be determined and used.

Table 17. Example analysis -- estimated cost of hybrid.

ITEM	QUANTITY	UNIT PRICE	INSTALLATION COST	ANNUAL COST
Telco Local Channels	40 ea.	$624/5.32	$ 24,960	$2,553.60
Telco Bridging Arrangements	14 ea.	$632/4.50	8,848	756.00
Telco Installation	40 ea.	125	5,000	
Telephone Facility Lateral	25 ea.	1,500	37,500	
Signal Pole Lateral	12 ea.	3,000	36,000	
Conduit-Rdwy (includes handholes)	300 ft.	40	12,000	
Conduit-Trench (includes handholes)	4,500 ft.	20	90,000	
Communications Cable (conduit)	8,000 ft.	1.00	8,000	400.00
Communications Cable (aerial)	32,000 ft.	2.00	64,000	3,200.00
Telco/City Interface Cabinets	13	3,000	39,000	
Aux. Termination Cabinets (ATC)	12	1,000	12,000	
Modify Exist. Foundation	10	1,000	10,000	
Modify Exist. Pole/Cabinet	46	300	13,800	
		TOTALS	$361,110	$6,910.00

Note: -One bridging arrangement per communications channel (14).
-Local channels equals number of controllers connected directly via leased Telco (12), plus twice the number of communications channels (two "local channels" per communications channel -- one on each side of the demarkation at Telco central office).

All costs are shown for example purposes only. Current local costs for these items should be determined and used.

Table 18. Example analysis -- communications cost summary.

Alternative	Up-Front Cost	Annual Cost	10-year Costs (present worth)
City-Owned Cable	$ 771,300	$ 10,275	$874,050
Leased Telco	311,790	10,606	417,850
Hybrid	361,110	6,910	430,210

Note: Discount rate and inflation rate are assumed to be equal in calculating present worth of annual costs.

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GLOSSARY

Prefixes

T = tera = 10^{12}
G = giga = 10^{9}
M = mega = 10^{6}
k = kilo = 10^{3}
m = milli = 10^{-3}
u = micro = 10^{-6}
n = nano = 10^{-9}
p = pico = 10^{-12}

Addressing - The process of selecting a specific drop on a multiline so that the unit alone will respond to a transmitted message.

Amplitude Modulation (AM) - A method of transmitting information by varying the strength (amplitude) of the carrier wave form.

Amplifier - An electronic device used to increase signal power or amplitude.

Analog - Information represented by continuous and smoothly varying signal amplitude or frequency over a certain range; such as in human speech or music.

Antenna - A device for radiating and receiving electromagnetic waves.

Asynchronous - A mode of transmission in which the time between sequential events (e.g., messages) is unpredictable.

Attenuation - The loss in signal strength (weakening of power) associated with the transmission process. Attenuation is usually expressed as the ratio of received signal strength to transmitted signal strength. This ratio is often expressed in decibels, a logarithmic unit for expressing dimensionless ratios.

Bandwidth - The range of signal frequencies that a medium or network will respond to, or carry without excessive attenuation.

Baud - A unit for expressing the rate at which information is transmitted.

Baud Rate - The transmission speed of a data channel.

Bit - An abbreviation of Binary digit; a single character in a binary number.

Broadband Communications - Transmission of signals with a large bandwidth, a term that is in some ways deliberately vague. Often used to denote video transmission.

bps - Bits per second. The measure of transmission speed in serial systems.

Byte - A group (word) of 8 bits operated on as a unit.

Carrier - A single frequency which is modulated to communicate information.

Channel - A path of communication between two points. Also used at times to refer to particular frequency range or type of transmission over a link, such as a television "channel".

Communication - The transfer of meaningful information from one location to another.

Conditioned Line - A communications cable specially compensated to provide improved transmission characteristics.

Connector - Hardware installed on cable ends to provide physical attachment to a transmitter, receiver, other hardware, or another cable.

Cross Talk - Interference or presence of unwanted signals from one transmission channel, detected on another (usually parallel) channel.

Decibel (dB) - A logarithmic unit used in comparisons of power, which is defined as one tenth of a bel -- although nobody ever measures anything in bels. The difference of the power levels expressed as a ratio of received signal strength to transmitted signal strength.

Demodulation - The process of extracting transmitted information from a carrier signal. The opposite of modulation.

Digital - Information in discrete or quantized form; not continuous.

Drop - Receiver on a transmission line. A drop may also act as a transmitter in a two-way communications network.

Electromagnetic Spectrum - The entire available range of sinusoidal electrical signal frequencies.

FCC (Federal Communications Commission) - A government agency that regulates and monitors the domestic use of the electromagnetic spectrum for communications.

Frequency Division Multiplex (FDM) - A system of transmission in which the available frequency transmission range is divided into narrower bands, so that separate messages (channels) may be transmitted simultaneously on a single line.

Frequency Modulation (FM) - A method of data transmission whereby the frequency of a sinusoidal waveform (carrier) is changed in accordance with the information that is to be transmitted.

Frequency Response - The plot of frequency versus the ratio of output to input signal for a medium.

Frequency Shift Keying (FSK) - The binary form of frequency modulation, in which a "O" is represented by one frequency and a "1" represented by another frequency.

Full Duplex - A transmission link providing simultaneous transmission and reception in both directions.

Guard Band - A region of unused frequencies that separates the different frequency regions within a FDM transmission system. The guard bands facilitate the separation of the signals.

Half Duplex - A transmission link providing both transmission and reception in both directions, but not simultaneously.

Hertz (Hz) - A measure of frequency, defined as one cycle per second.

Medium - The composition of the path along which a communications signal is propagated, such as wire pair, coaxial cable, optical fiber or air-path.

Modem - A device used at both ends of a communication channel to transmit and receive data. Contraction of Modulator Demodulator.

Modulation - The process of controlling and modifying the properties of the carrier signal so that it contains the information to be transmitted. Often digital information is superimposed on a sinusoidal (analog) waveform.

Multipoint Connection - The connection of two or more drops to a single communications channel.

Multiplexing - A communications technique which allows more than one item of information to be transmitted or received over the same channel.

Noise - Any unwanted signal not present in the original transmitted information -- disturbances that tend to interfere with normal operations of the communication system.

Parallel Data - The simultaneous transmission of a group of bits.

Parity - The addition of noninformation bits to a character being transmitted in order to make the number of one bits in each character always be odd or even. At the receiver, the bits in each received character are checked to see that an odd number of one bits per character has been received in order to detect the presence of errors in the received data.

Phase Modulation (PM) - A technique to transmit information using a sine wave carrier. The sine wave has its phase changed in accordance with the information to be transmitted.

Polling - A centrally controlled technique of sequentially calling a number of drops to permit them to sequentially transmit information back to central.

Repeater - A receiver and transmitter combination used to regenerate an attenuated signal.

Radio Frequency (RF) - As opposed to sound, light, infrared, or ultraviolet frequencies.

Serial Data - The transmission of digital data in a sequential pattern -- one bit at a time.

Simplex - A ransmission link capable of transmission and reception in one direction only.

Time Division Multiplexing - A technique for transmitting several different messages over a single channel by dividing a fixed interval of time into several time slots into which a discrete message is sent in each time slot.

Transmission Link - The path over which information flows from sender to receiver.

Trunk - A transmission link joining two points. It is distinguished by its large information carrying capacity and by the fact that all signals go from point-to-point without branching off to any separate drops except at the end points.

Video Signal - The electrical signal containing the picture content information in a television system.

Waveguide - A specially constructed structure (e.g., conductor) for contained transmission of electromagnetic radiation.

Wideband Channel - A channel broader in bandwidth than a voice grade channel.