Communications Handbook for Traffic Control Systems

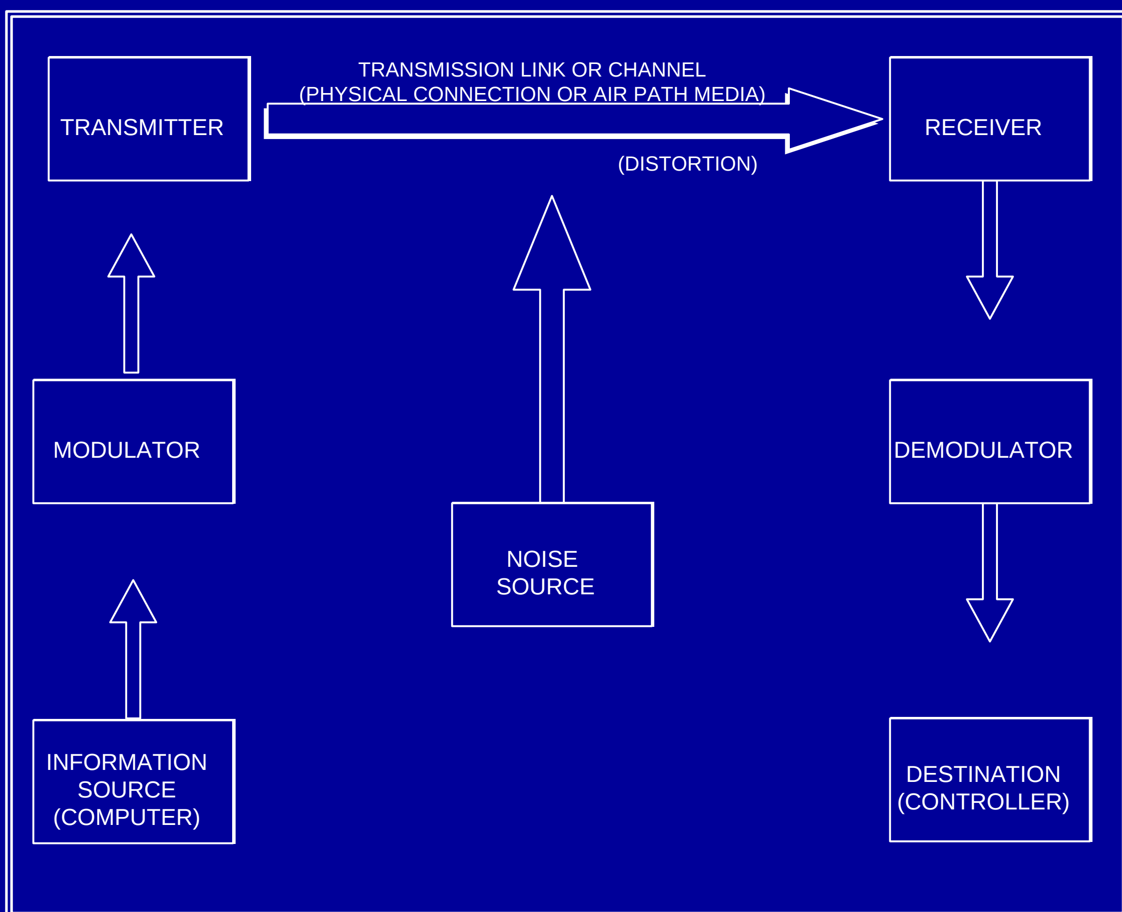
NOTE TO READER:

THIS IS A LARGE DOCUMENT

Due to its large size, this document has been segmented into multiple files. All files separate from this main document file are accessible from links (blue type) in the table of contents or the body of the document.

U.S Department
of Transportation
**Federal Highway
Administration**

Communications Handbook for Traffic Control Systems



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16. Abstract

This handbook was written to enable transprotation engineers to plan, select,design, implement, operate maintain communication systems for traffic control.

It has been designed to aid:

- Transportation officials overseeing traffic control systems;
- Communications engineers; and
- Traffic control systems engineers.

The handbook provides information on communications media, system architectures, decision-making processes, and trade-off analyses.

The handbook will serve as a guide for agencies wiching to:

- Initiate a traffic control system that incorporates functional, effective, realiable and economical communications.
- Update and modemize an existing communications system for traffic control.

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FOREWORD

This handbook provides an easy-to-use reference on communications for traffic control system applications. It compares various communications media, technologies, architectures, and options and presents techniques to guide the user through a communication system design.

The handbook should prove useful to agencies considering the implementation, upgrading, or expansion of a traffic control system, as well as by system designers responsible for making decisions on the various features of the communications system. The cost data provided generally represent the state-of-the-practice at the of handbook preparation; however, handbook users should develop their own cost data for analysis of specific projects.

NOTICE

CHAPTER 1 - INTRODUCTION

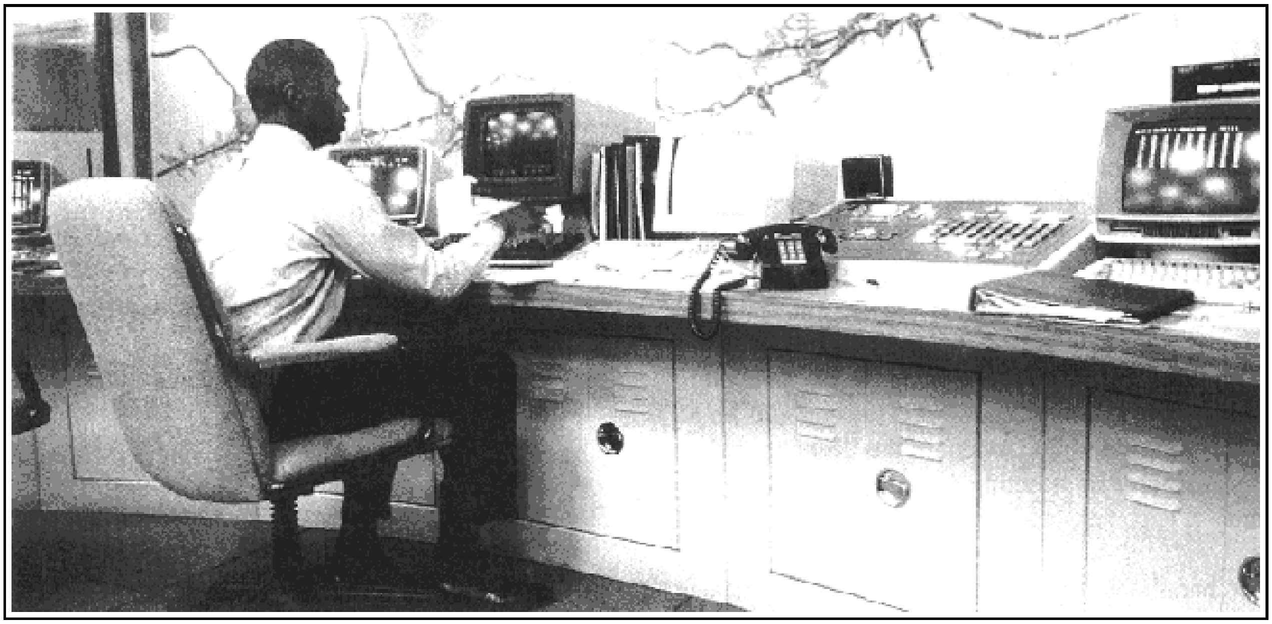


Figure 1-1 Traffic Operations Center

Communications

To better manage and enhance the efficiency of traffic flow on streets and highways, transportation agencies increasingly rely on computerized traffic control systems. These advanced traffic management systems also form the infrastructure for future Intelligent Vehicle Highway Systems (IVHS) which promise to greatly increase roadway capacity and improve safety.

The communications system functions as the traffic control system's backbone to transfer information among system components in the form of:

- Commands to the various field components
- Data from system sensors, and
- Status checks of field equipment to detect malfunctions and effect faster repairs.

Need for Handbook

The communications system generally proves the most critical and expensive element of a traffic control system/IVHS. Therefore the successful design, implementation, and operation of the communications system become key to the effectiveness of the overall traffic control system.

Transportation engineers must be able to plan, select, design, implement, operate, and maintain the communications system. The practicing transportation professional must be familiar with existing communications technologies and system architectures, as well as technological advances and emerging technology.

This handbook will help the transportation professional operate and maintain a cost effective and efficient traffic control communications system. It will assist the user in understanding communications principles, and serve as a guide to decision making processes for selecting the communications system.

Purpose of Handbook

This handbook will assist engineers in specifying traffic control system communications media, technologies and architectures which are both compatible and effective.

The handbook presents a general tutorial on communications related issues in traffic control to familiarize handbook users with fundamental communications concepts. This will help users understand and evaluate the decision making processes in selecting a communications system.

The handbook will serve as a guide for agencies wishing to:

- Initiate a traffic control system that incorporates an effective, reliable, economical, and functional communications system.
- Update and modernize an existing traffic control communications system.
- Expand an existing communications system.
- Review, evaluate, and select new and emerging technologies for the communications system.

Organization of Handbook

The handbook contains four major subject groups:

- Communications fundamentals
- Traffic control communications requirements
- Traffic control systems communications technology
- Selection considerations and selection methodology

Table 1-1 summarizes the subject groups with corresponding chapters, purposes, and topics. This table serves as a menu to allow the reader to focus on those chapters of most relevance.

While the handbook provides examples of equipment and installation costs, these vary with location, supplier and time. The handbook user should therefore use his or her own cost assessment in design studies.

Chapter Number	Title	Purpose	Topics
2	Fundamentals	Tutorial Background on communications systems Historical perspectives	Information Signals Modulation Bandwidth Attenuation Multiplexing Noise and Interference Error detection and control Data transmission and link control Historical perspective
3 and 4	Field Equipment Interfaces Communications Requirements	Traffic control data communications requirements CCTV communications requirements	Physical and functional interfaces with field equipment Controllers Changeable Message Signal Detection devices Highway Advisory Radio Data rate Polling Distribution systems Full motion video, freeze frame, and coded TV transmission
5 - 7	Communications Architectures Land Line Alternatives Wireless Alternatives	Traffic control systems communications technology	Central, distributed, and hybrid architectures Twisted wire pairs, coaxial cable, fiber optics, and leased channel alternatives Wireless alternatives or area radio networks, terrestial microwave links, spread spectrum radio

Chapter Number	Title	Purpose	Topics
	Reliability, Maintainability and Expandability Standards Institutional and Local Issues Selection Techniques	Selection considerations Selection methodology	Communications failure Design techniques to enhance reliability Improved installation and testing techniques Techniques for improving maintainability Advantages and disadvatages of inforporation of standards into system design User preferences Utilities CATV facilities Maintenance capability Equipment standardization Risk versus new technology Generic data communication links Selection techniques and tradeoffs Selection approaches and procedures Examples of technology selection

Table 1-1. Organization of Handbook Chapters

CHAPTER 2 - FUNDAMENTALS

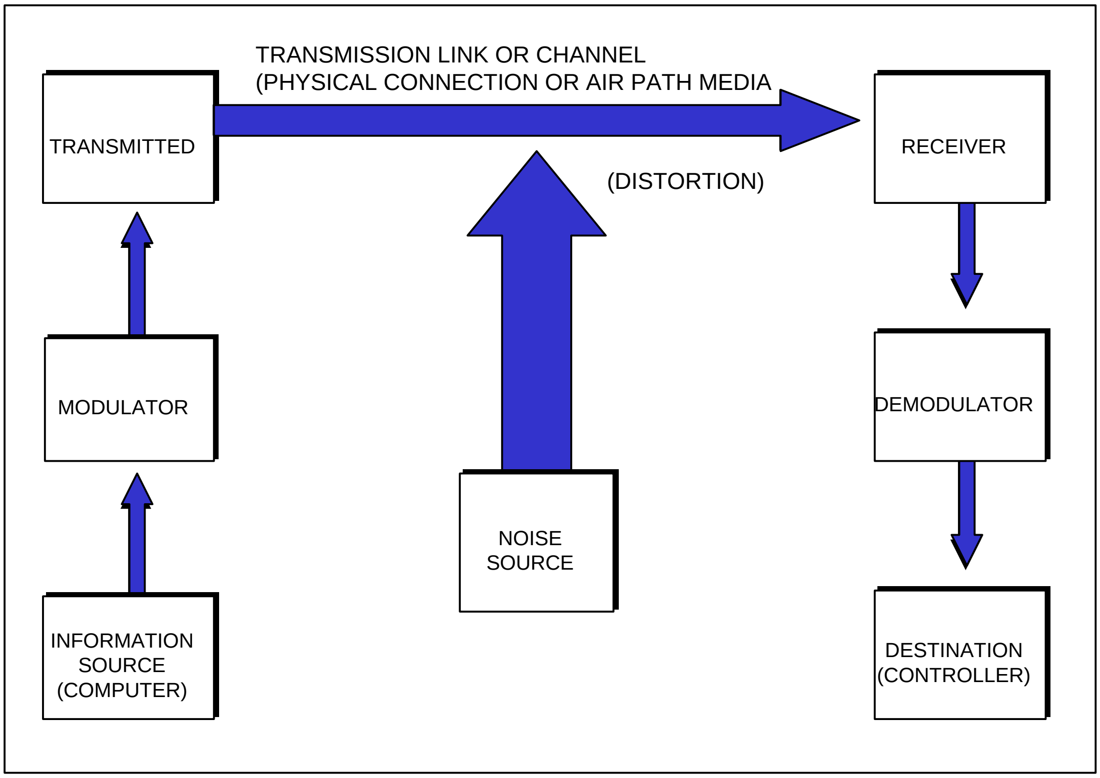


Figure 2-1 Basic Communications Systems

Introduction

Effective traffic control requires the coordination of widely dispersed system elements. To provide effective coordination, a communications system must:

- Transfer information from field components to the traffic operations center, and
- Transmit responses and commands to various field components.

To the non-specialist, communication systems may appear sophisticated and complex. However, understanding basic fundamentals will enable the transportation professional to use the decision-making processes described later in this handbook. In turn, this will lead to the design and acquisition of reliable, cost-effective data communications systems for traffic control.

Need

Communications, like other disciplines, has its own language, terminology and jargon. The transportation professional must acquire some fluency in this language before entering into trade-off analyses and decision-making methodologies. He or she must understand at least the following concepts:

- Communications system
- Information
- Modulation
- Transmission link or channel
- Error detection and control
- Data transmission and link control

Purpose

This chapter identifies and explains fundamental communication concepts and associated terminology commonly used in traffic control systems.

These fundamentals allow the reader to understand and use the techniques described in the remainder of this handbook.

Organization

Chapter sections as summarized in Table 2-1 correspond to fundamental concepts of communication systems.

Elements

Communication refers to the transfer of information between locations. To communicate in a traffic control system requires these elements:

- An information source or transmitter
- A destination or receiver
- A path called a transmission link or channel
- A communications medium to provide the path

Figure 2-1 illustrates the basic elements of a communication system for traffic control. For simplicity, the figure shows only a one-way information flow from source to destination.

In traffic control systems, the traffic operations center computer represents a source, transmitting information to a field device, such as a field master controller, detector, intersection controller, or changeable message sign. The destination can also represent a source in a two-way communications system, transmitting information or data back to a destination, such as the traffic operations center computer.

Information travels from a source to a destination via a *link or channel*, through a *medium* such as:

- Land line cable/wire or
- A wireless air-path

To efficiently transmit information over a channel, most communication systems use some form of *modulation.* A modulator converts information into a *signal* while a demodulator converts the received signal back into a form suitable for use at the destination.

Signals deteriorate during transmission. This results from:

- Signal *attenuation* (weakening) over the transmission path,
- Distortion in the communication system, and/or,
- Ingress of unwanted signals (noise) from an external source. *Noise* and *distortion* may introduce errors into the transmitted information or even destroy it.

The remainder of this chapter treats in more detail each of these terms and other needed fundamentals. Chapter organization follows the basic information flow depicted in Figure 2-1.

Information Source

Information

In simple terms, information refers to content which would remain unknown at the destination, if not for a message transmitted by the source. If the text (the message) in this handbook were transmitted electronically, not all of the message would constitute information! For example, Figure 2-2 shows a garbled message which the reader may readily interpret. This message highlights the great deal of redundancy in the English language, about 50% in fact. In other words, 50% of the letters in an English message do *not* convey information.

Section Title	Purpose	Topics
Elements	Overal definition of a communications systems	• Communications - Source/transmitter - Destination/receptor - Media.links/channels
Information Source	Defines information and its conversion to electrical signals	• Information
Signals	Describes the character of signals	• Frequency, period, amplitude
Modulation	Explains the reasons for modulating a signal and describes te types of modulation used in traffic control systems	• Amplitude modulation • Frequency modulation • Phase modulation
Transmission Link or Channel	Describes the characteristics of a communications channel	• Bandwidth/attenuation • Power Budget
Multiplexing	Describes multiplexing techniques	• Frequency/division multiplexing • Time division multiplexing • Code divisin multiplexing
Noise and Interference	Describes the relationship of noise and interference to communication errors	• Noise • Interference • Signal to noise ratio and bit error rate
Error Detection and Control	Describes techniques to mitigate transmission	• Automatic Repeat Request • Forward Error Control
Data Transmission and Link Control	Describes common transmission modes and techniques	• Modes • Techniques • Link Control
Historical Perspective	Describes evaluation of traffic control techniques	• Dominant techniques of each decade

Table 2-1 Organization of Chapter 2

To quantify information, Claude Shannon formulated an entire technical discipline, *information theory*. This discipline proves quite theoretically complex and lies beyond this handbook's scope. Refer to Reference 1 for material in this area.

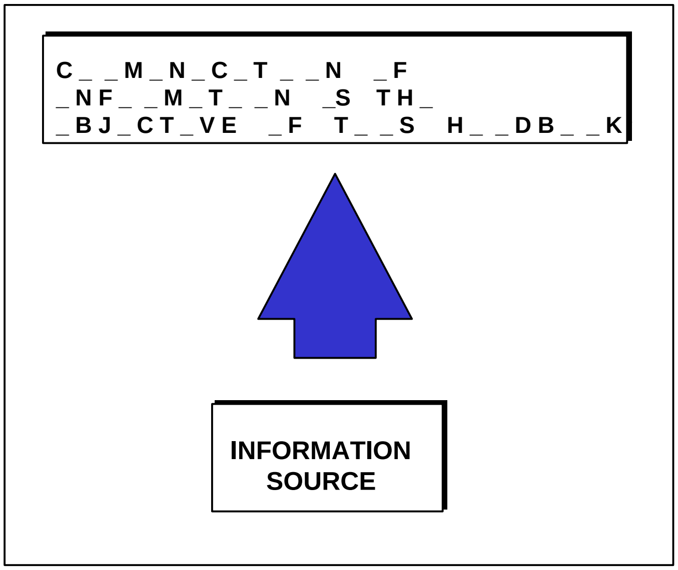


Figure 2-2 Information Content

A bit (binary digit) represents the basic unit of information and takes a value of 0 or 1. The binary system counts in base 2 just as our familiar decimal system uses base 10. Figure 2-3 shows the equivalence of 10111_2 to 23_{10}.

BINARY SYSTEM

Base 2	**2^4**		**2^3**		**2^2**		**2^1**		**2^0**		
Binary Digit	**1**		**0**		**1**		**1**		**1**		
Decimal Equivalent	**$1x2^4$**	**+**	**$0x2^3$**	**+**	**$1x2^2$**	**+**	**$1x2^1$**	**+**	**$1x2^0$**	**=**	**23**

NOTES: **8 Binary Digits (Bits) = Byte**
8 Binary Digits Can Represent 0-255_{10}

Figure 2-3 Binary System

Information to and from traffic control devices generally takes digital form. The source converts data to *signals* at discrete amplitude levels, in contrast to the *analog* or continuous signal of Figure 2-4. (Ref. 2) Figure 2-5 shows a series of signals (pulses) representing a sequence of bits. An eight (8) bit group equals a byte and can represent a letter, numeral, or other keyboard character. It can also represent numbers from 0 to 255 (or 2^8 -1).

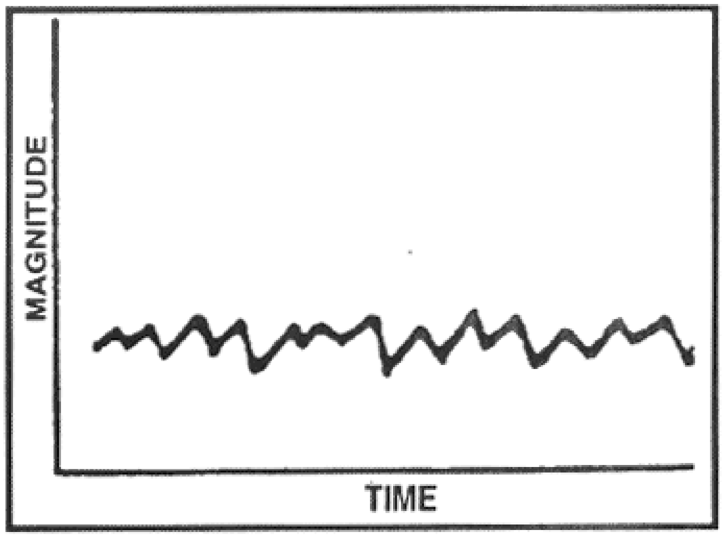


Figure 2-4 Continuous Signal

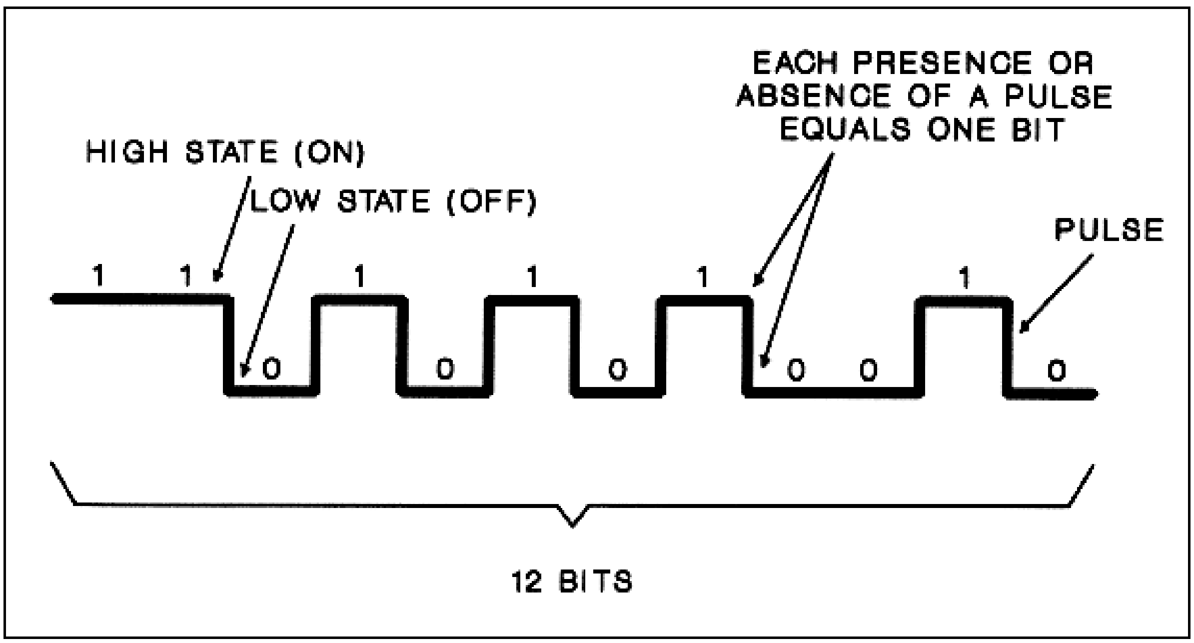


Figure 2-5 Ideal Pulse Train

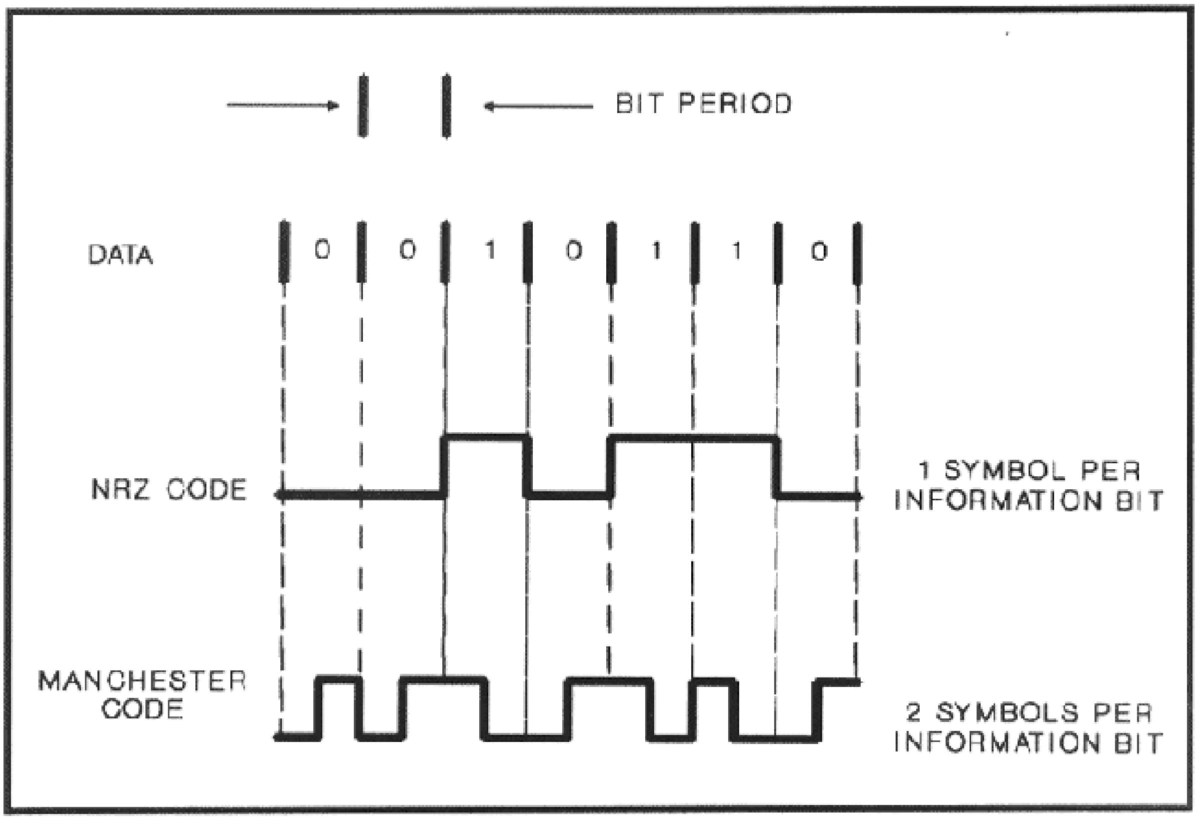


Figure 2-6 Relationship of Code Symbols to Information Bits

The information source must use a coding scheme to send a stream of information bits over a transmission system. Figure 2-6 shows the signal profile for non-return-to-zero (NRZ), a common coding scheme similar to the bit pattern and requiring one symbol per bit of information. Other codes sometimes prove more suitable such as the Manchester code also shown in Figure 2-6. Note that the Manchester code requires two symbols per information bit.

Signals

The prior section showed how the information source must convert a series of bits to a signal for transmission. Signals have characteristics which affect how accurately they arrive at the destination.

Signals can be represented by waveforms which represent the time variation of the amplitude (intensity).

The sum of a set of sine waves of certain frequencies and amplitudes can represent any signal, analog or digital.

The period of a sine wave (see Figure 2-7) is measured in seconds or fractions of a second. A sine wave's frequency (f) (reciprocal of the period) is measured in cycles per second or hertz. The more quickly a wave varies, the shorter its period and greater its frequency.

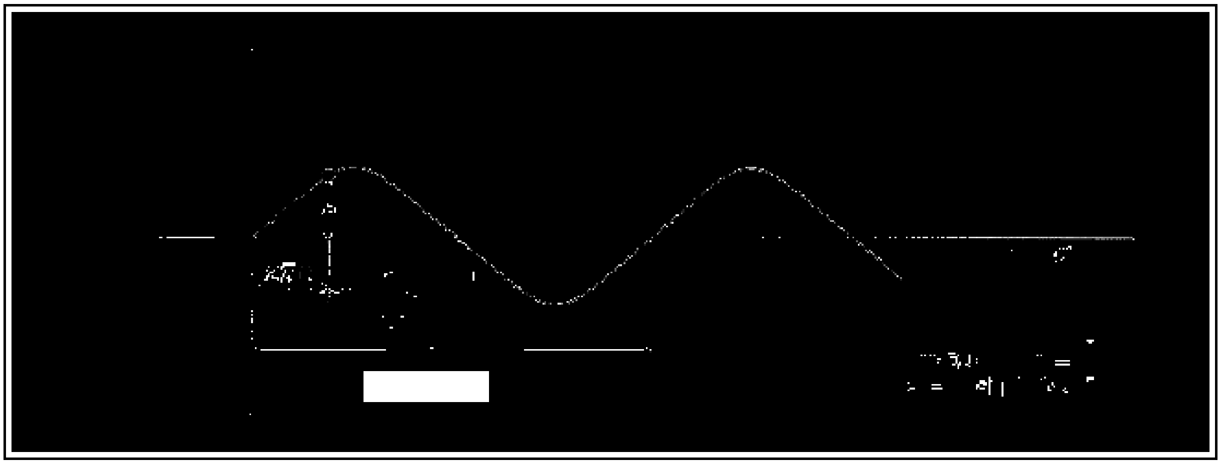


Figure 2-7 Sine Wave

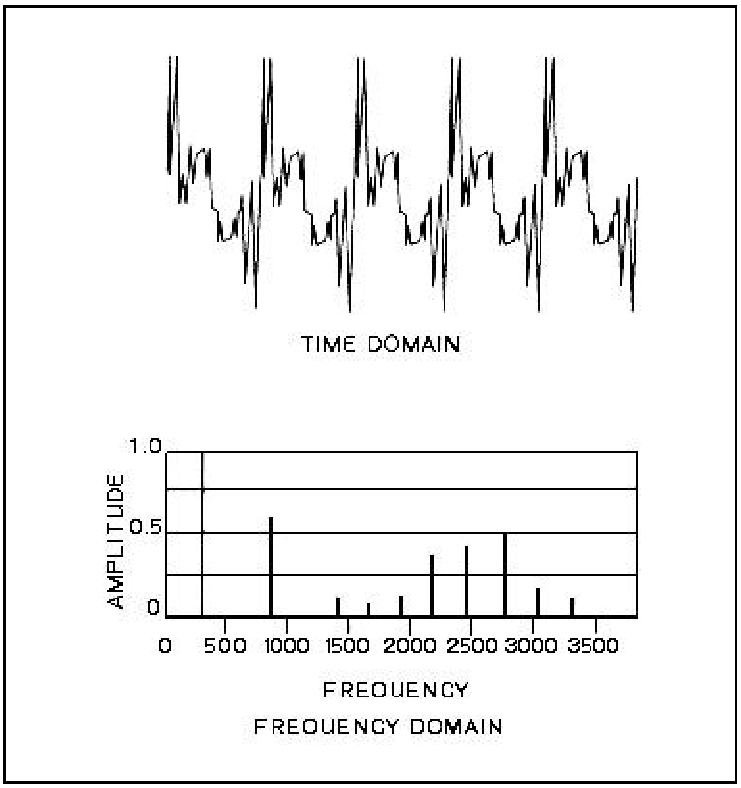
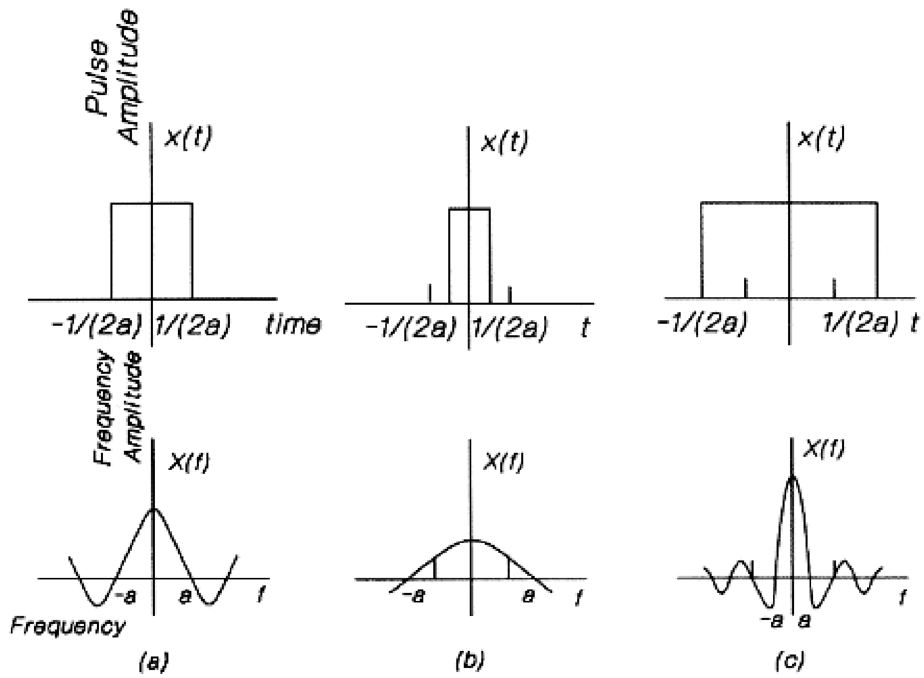


Figure 2-8 Decomposition of Retitive Waveform into Sinusoidal Components

An infinite series of discrete sine waves of varying amplitudes can represent a repetitive waveform as shown in Figure 2-8. A continuous distribution of sine waves, however, is required to represent a non-repetitive waveform. Figure 2-9 illustrates this dual representation of a signal, one in the time domain and one in the frequency domain (Ref 3). Figure 2-9 also shows that when pulses represent signals, the shorter the pulse duration, the wider the signal bandwidth spectrum.



Relation between time and frequency: (a) medium-length pulse, medium-width spectrum; (b) short pulse, wide spectrum; (c) long pulse, narrow spectrum.

Figure 2-9 Relationship Between Time and Frequency

Digital communication channels are measured by the number of symbols transmitted per second (signal rate) or the baud rate. For example, transmitting 1200 bits of information per second by an NRZ code (Figure 2-6) requires a 1200 baud channel. Using a Manchester code requires a 2400 baud channel.

Modulation

Modulation refers to a process which transforms the encoded signal into a suitable or desirable form for the transmission system (see Figure 2-10). Information rates usually prove quite different from the frequencies best supported (have the lowest losses and distortion) by particular transmission media. Modulation consists of transforming a sine wave (Figure 2-7) at an appropriate frequency (called a *carrier*) by the binary signals. Figure 2-11 represents the range of frequencies available for carriers, otherwise known as the electromagnetic spectrum. A modulator - demodulator or *modem* performs the modulation process and transmits the signal at an appropriate power level.

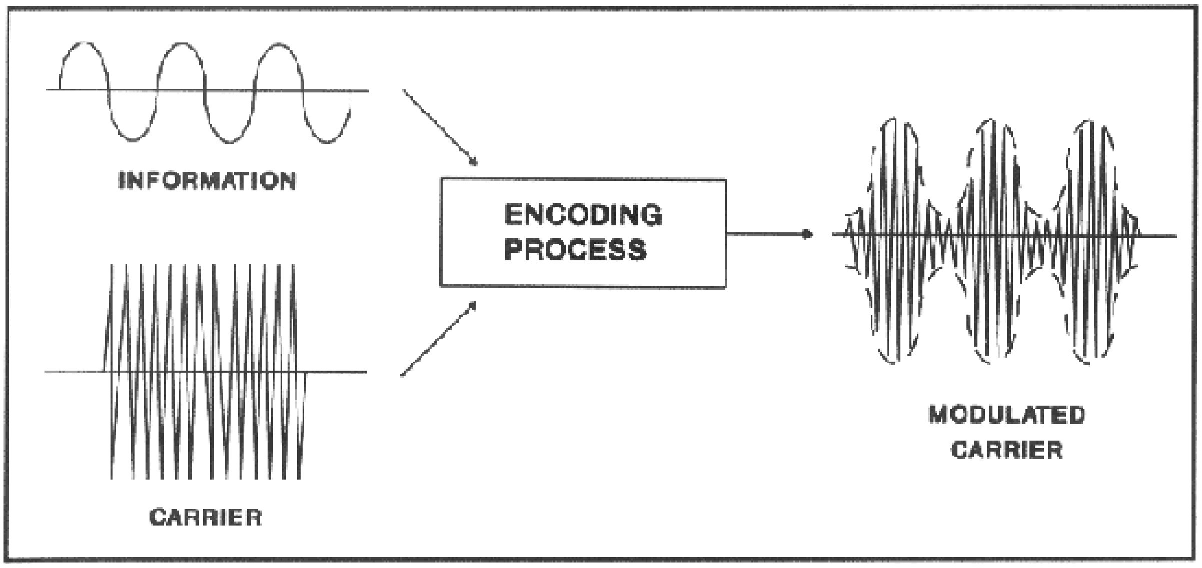


Figure 2-10 Modulation

Modulation techniques include:

- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

Amplitude Modulation

Amplitude Modulation (AM) makes use of the signal amplitude to transmit digital information. Since digital information assumes two binary states, two amplitudes are defined: zero and one, and an amplitude detector decodes this information.

A common form of AM is Amplitude Shift Keying (ASK) where the presence or absence of a carrier represents the binary state as shown in Figure 2-12. This technique, while simple to implement, generally proves more susceptible to errors than other techniques and does not commonly find use in traffic control applications.

Frequency Modulation

When applied to digital signals, frequency modulation is also known as frequency shift keying (FSK), often used in traffic control system communications. One signal state shifts the carrier to a higher frequency and the other to a lower frequency (Figure 2-13). Because of its relative simplicity and noise immunity, it has found widespread application in traffic control systems.

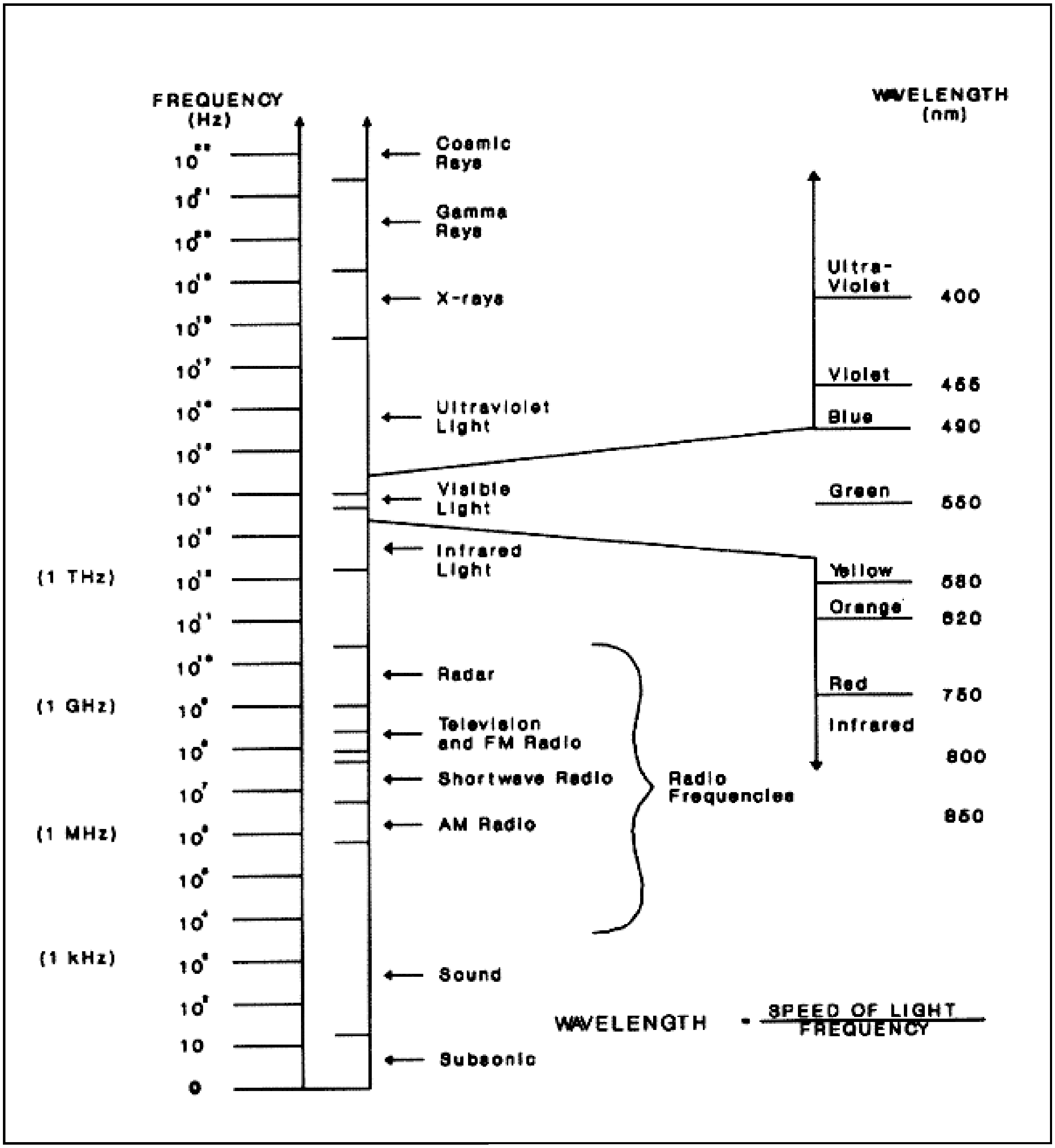


Figure 2-11 The Electromagnetic Spectrum

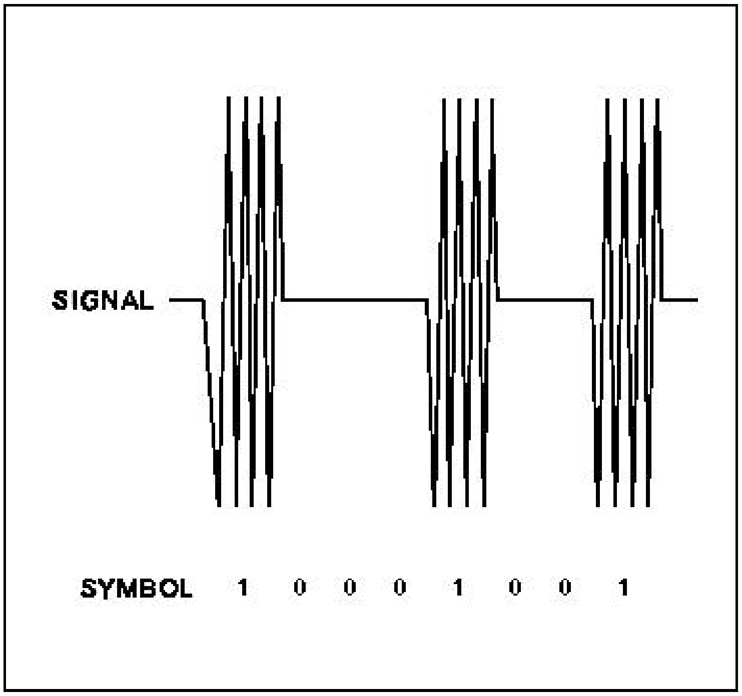


Figure 2-12 Amplitude Modulation, Amplitude Shift Keying

Phase Modulation

With phase modulation, the signal shifts in time to account for variations in the binary signal. This type of modulation requires transmission of a reference signal to allow the phase comparison. Phase modulation varies the phase of the carrier relative to the reference signal to convey changes in signal value, and is sometimes used with other forms of modulation. Although used extensively for data transmission on telephone lines and other media, it has found less frequent application for traffic control systems.

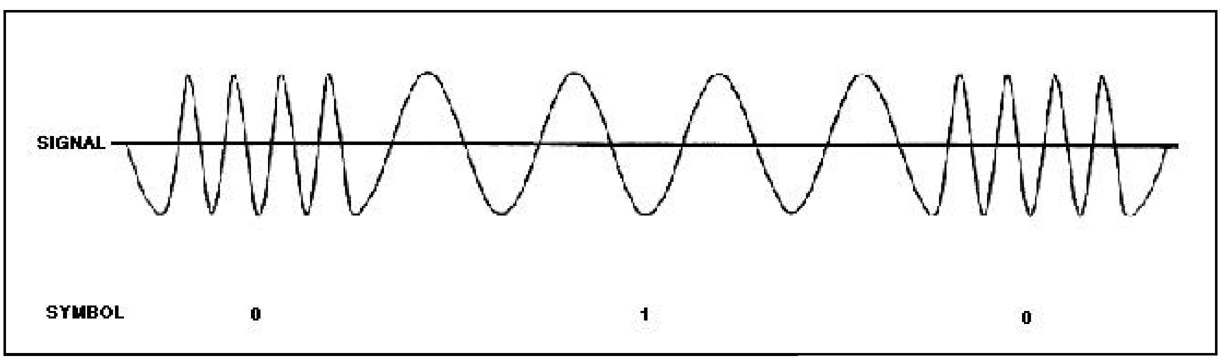


Figure 2-13 Frequency Modulation, Frequency Shift Keying

Transmission Link or Channel

A transmission link or channel provides the path for the modulated signal. To design a communications system, the designer must understand important characteristics of the channel, namely:

- Bandwidth, Attenuation and Power Budget
- Multiplexing

- Noise

Bandwidth, Attenuation and Power Budget

As indicated previously, the channel bandwidth determines how faithfully the destination receives the signal.

Bandwidth refers to the range of frequencies which the channel will pass without significant "attenuation" (loss in relative amplitude). The physical and electrical properties of the medium determine bandwidth. For example, Figure 2-14 shows the relative amplitude response of a voice grade channel using the medium of twisted wire pairs.

Attenuation is measured in units called decibels. For example, the loss of a communication transmission system measured in decibels between the transmitter (tr) and receiver (r) is :

$$dB = 10log_{10} \frac{(Pr)}{(Pt\,r)}$$

A value of -3dB corresponds to a 50% loss in power between these points.

A common measure of signal level is the dB level of the signal relative to one milliwatt of power (dBm).

$$dBm = 10log_{10} \frac{(Pr)}{(1\ mw)}$$

Type of Medium	Source of Attenuation	Value of Attenuation (dB)
LANDLINE		
Copper cable	Electrical resistance	K1* length
Glass fiber	Optical scattering and absorption	K2* length
Leased voice grade line	N.A	See Note 2
WIRELESS		
Microwave radio in free space	Power reduction due to geometrics	38.58 + 20 log D + 20 log f See Note 1 (Ref 24)
Microwave radio	Power reduction de to fading	Complex relationships

Table 2-2 Signal Attenuation in Channel Media

Definitions and Notes(1)

The bandwidth of a channel is commonly measured between the low frequency -3dB (half power) point and the high frequency half power point (Figure 2-15). The bandwidth limits the baud rate (see definition on page 2-12) which the channel can support. The theoretical relationship between bandwidth and maximum baud rate is:

$$B = 2W$$

where B is the maximum baud rate for a channel with a bandwidth of W Hertz (cycles/second).

Actual physical channels require a somewhat higher bandwidth than the above equation shows.

Table 2-2 shows the attenuation properties for representative channel media. The designer can readily calculate attenuation for land line systems based on the formulas provided. Signal losses also accrue in a land line system due to discrete components. For example, fiber optics or coaxial cable connectors and taps (to enable controllers at intermediate points to access the line) cause a loss in signal level. Attenuation for wireless communications systems proves more difficult to estimate due to fading (variation in receiver level power due to refraction, reflection, scattering and rainfall above 10 Ghz).

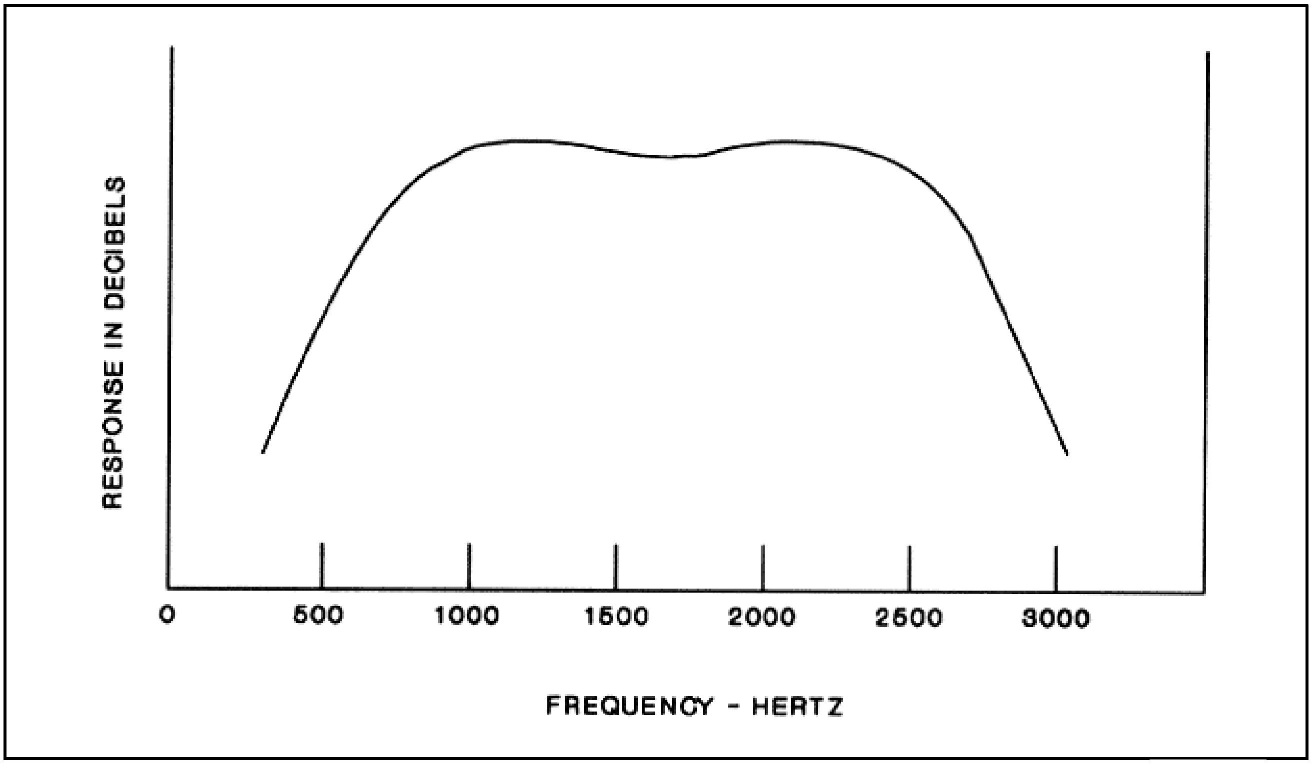


Figure 2-14 Frequency Response of a Typical Twisted Wire Pair Voice-Grade Channel

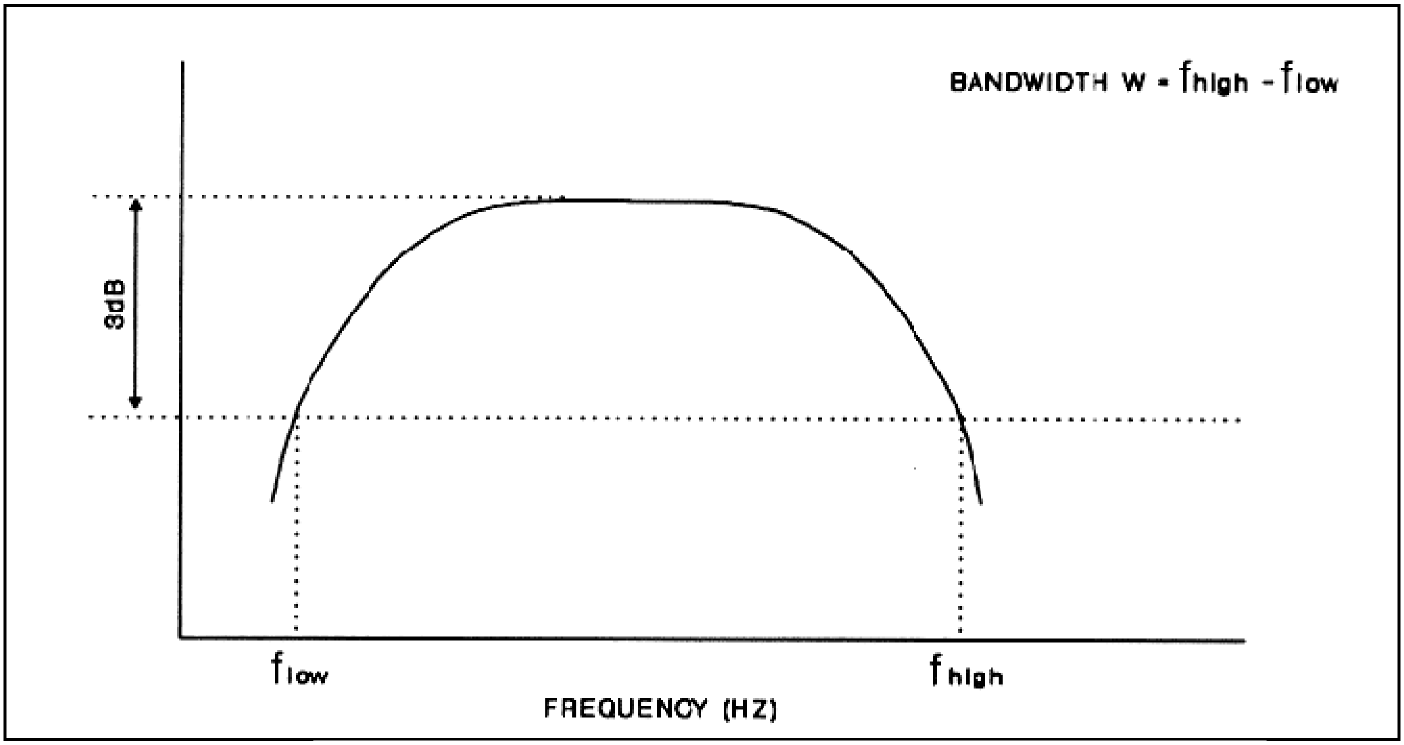


Figure 2-15 Bandwidth

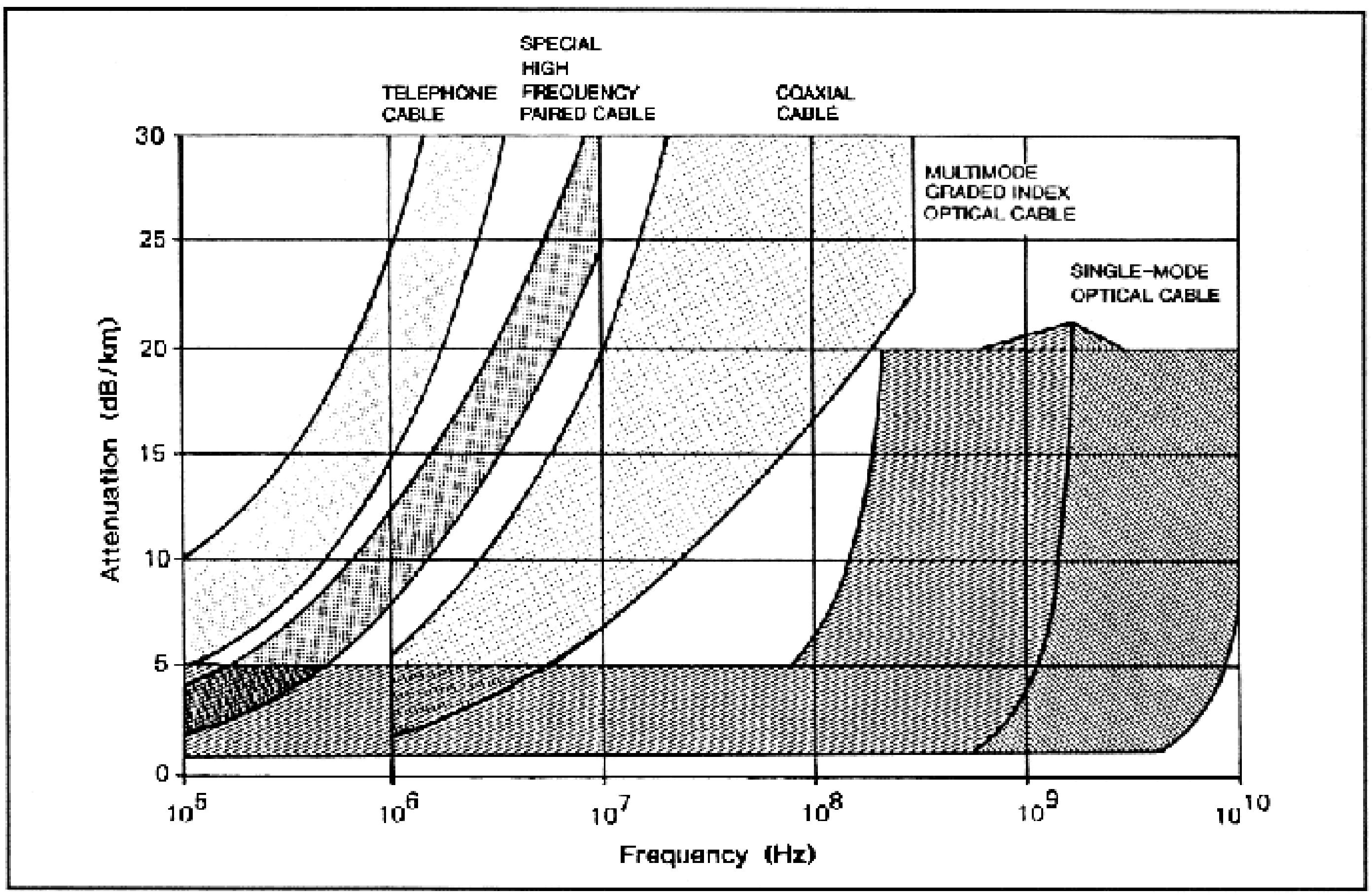


Figure 2-16 Attenuation Versus Frequency

Figure 2-16 shows the attenuation relationship with frequency for different media (Ref. 4).

Communication receivers have a maximum acceptable input level. Power levels greater than this value either saturate or distort the signal. Input power levels less than the minimum acceptable power level will result in an increase in the bit error rate. The difference between the maximum acceptable power level and the minimum is the dynamic range of the receiver. Under certain conditions the power level in the communication channel requires reduction (attenuation) to remain within the dynamic range of the receiver.

Communications system designers use power budgets to estimate attenuation in a communication system. Figure 2-17 shows an example of a power budget calculation.

Multiplexing

Multiplexing refers to sharing a channel's information-carrying capacity by enabling transmission of two or more signals over a single communication channel (Figure 2-18). Traffic control systems can use frequency-division multiplexing (FDM), time-division multiplexing (TDM), code division multiplexing (CDM) or some combination of these. Table 2-3 summarizes key properties of multiplexing.

Frequency Division

Frequency division multiplexing divides the total channel bandwidth into a series of subchannels, each of which occupy a subband of frequencies. Early computer traffic systems used twisted wire pairs with this form of multiplexing illustrated in Figure 2-19 (Ref. 5). The figure shows provision of sufficient attenuation between subbands (a guard band) to prevent interference between channels. Mark and space represent the binary "one" and "zero" states, respectively.

Frequency division multiplexing has, in the past, been used extensively to carry multiple signals on a single coaxial cable in freeway surveillance systems and some signal systems. Some channels typically carry closed circuit television signals while others carry data. The channel usually carries data via a TDM/FSK signal. Coaxial cable channels divide into groups which carry information to the field and other groups which carry information to the traffic operations center.

- Combines a number of daa sources into one communications transmission facility (e.g., wire pair)

- Frequency division multiplexing (FDM)
  - Provides a seperate frequency band for each signal.

- Time division multiplexing (TDM)
  - Provides a seperate time period in a polling cycle for each signal and field location.

- FDM/TDM
  - Provides time division multiplexed channels which have seperate frequency band assignments on a medium.

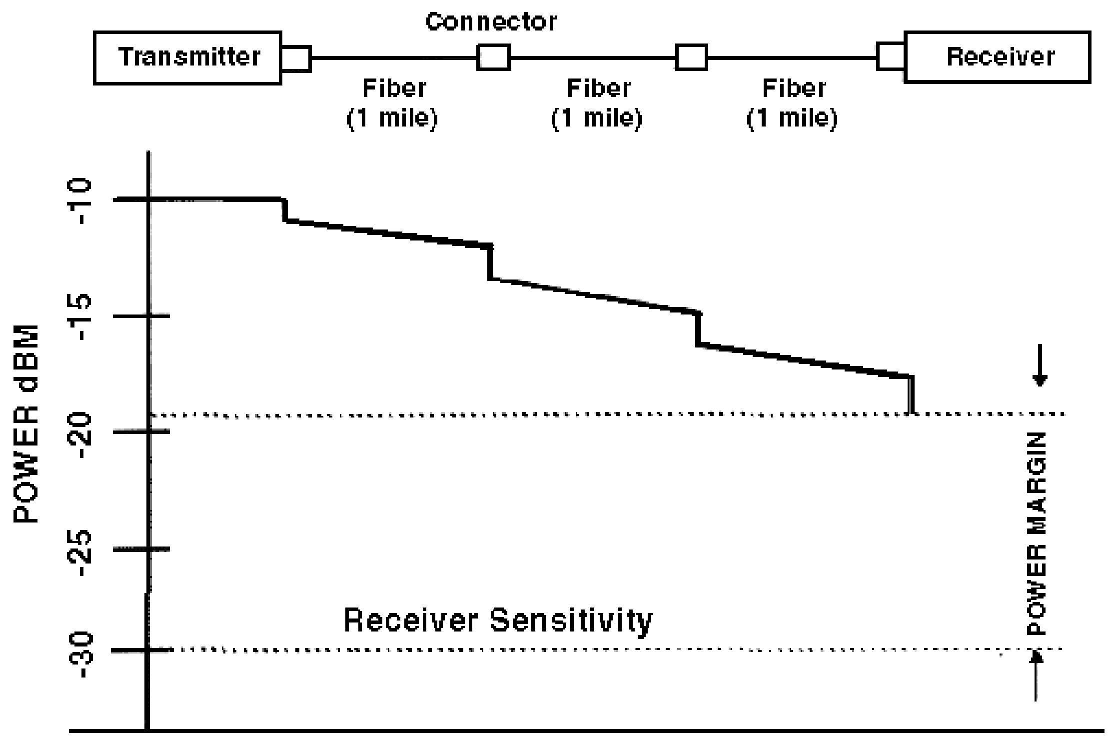
- Code division multiplexing (CDM)

- Uses a specified but different binary sequence for each channel.

Table 2-3 Key Properties of Multiplexing

Time Division

Time-division multiplexing shares time on a channel and enables a traffic operations center or field master to communicate *at different times* with each controller on a communication channel. Figure 2-20 schematically shows how eight signals can be sequentially *sampled* and serially transmitted on one channel. A separate address or designation identifies the target controller so that only it will respond to the message. Figure 2-21 shows how a period of time (polling period) divides to furnish a time interval for each of the eight local controllers on the channel to communication with the traffic operations center.



CHARACTERISTICS

Transmitter Power -10 dBm
(100 microwatts)
Receiver sensitivity -30 dBm
Maximum power at receiver input -6 dBm
Fiber attentuation -1.5 dB/mile
End point connector loss -1 dB each
Midpoint connector loss -1.5 dB each

POWER BUDGET CALCULATIONS

Transmitter Power	-10 dBm
Receiver Sensitivity with bit error rate (BER) = 10^{-12}	-30 dBm
Power Budget	20dB
Fiber loss	-4.5 dB
End connector loss	-2.0 dB
Mid link connector loss	-3.0 dB
Total loss	9.5 dB
Power Margin	10.5 dB

Figure 2-17 Power Budget for Simple Fiber Optics System

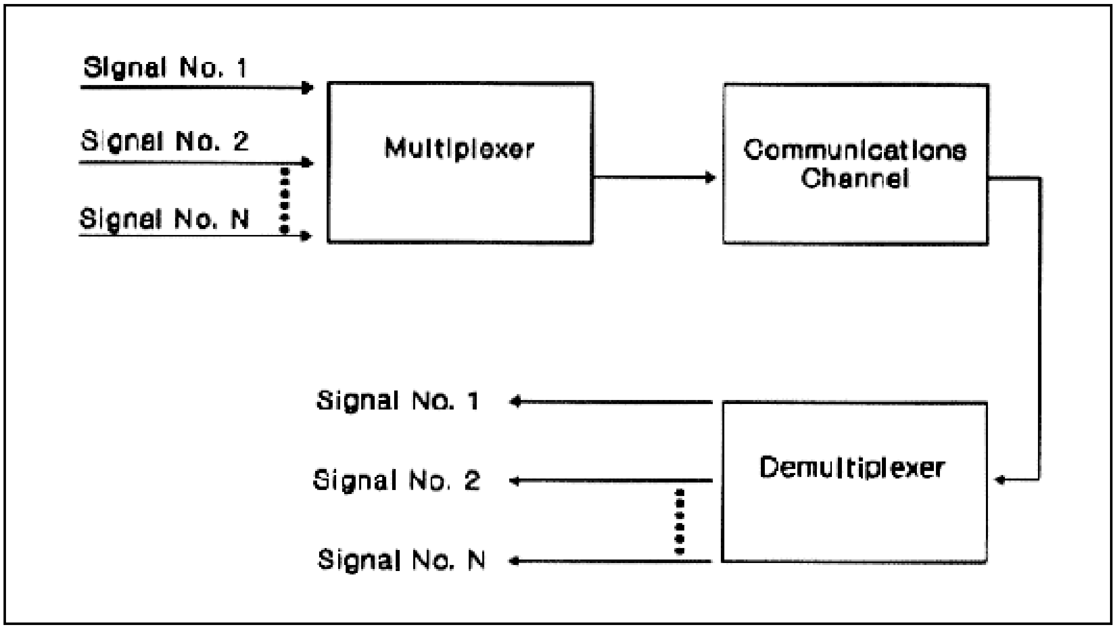
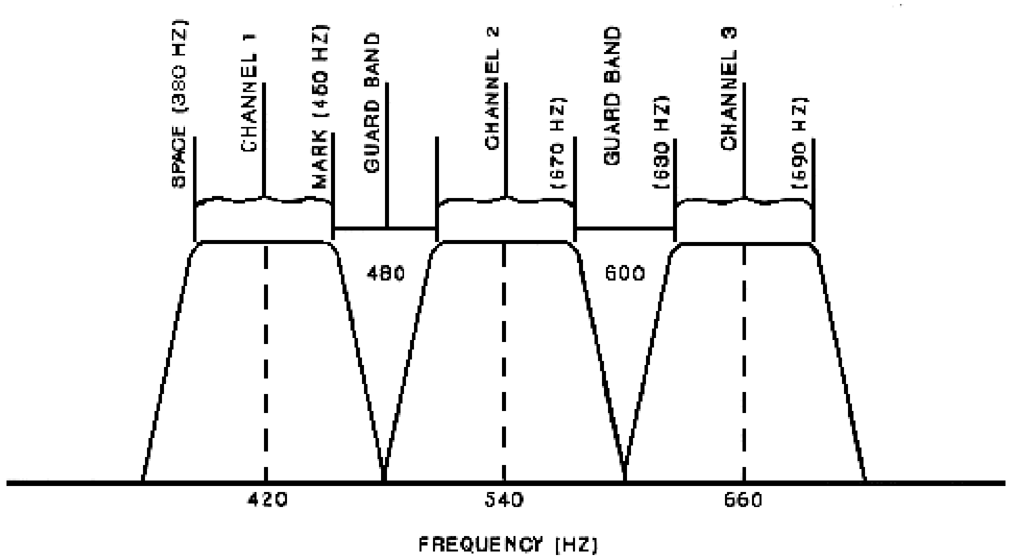


Figure 2-18 Multiplexed Signals on a Single Communication Channel



Channels and guard bands used in frequency division multiplexing (FDM) with frequency-shift keying.

Figure 2-19 FDM Multiplexing Technique

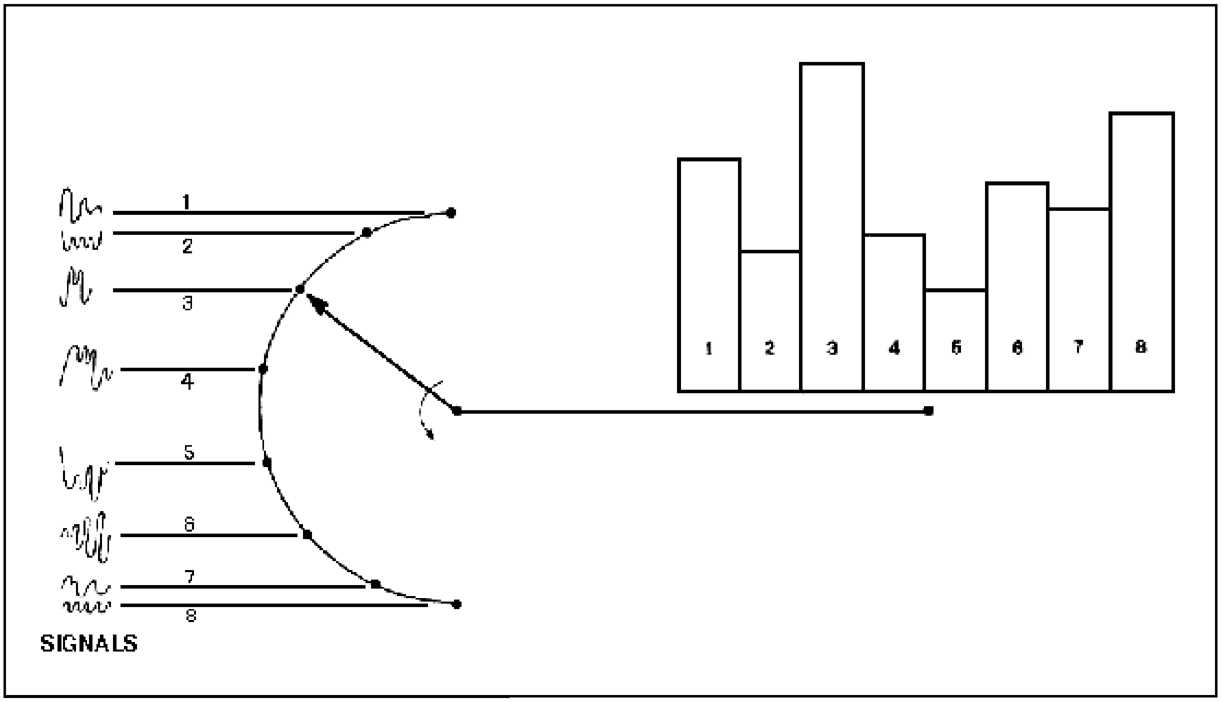


Figure 2-20 TDM Multiplex Technique

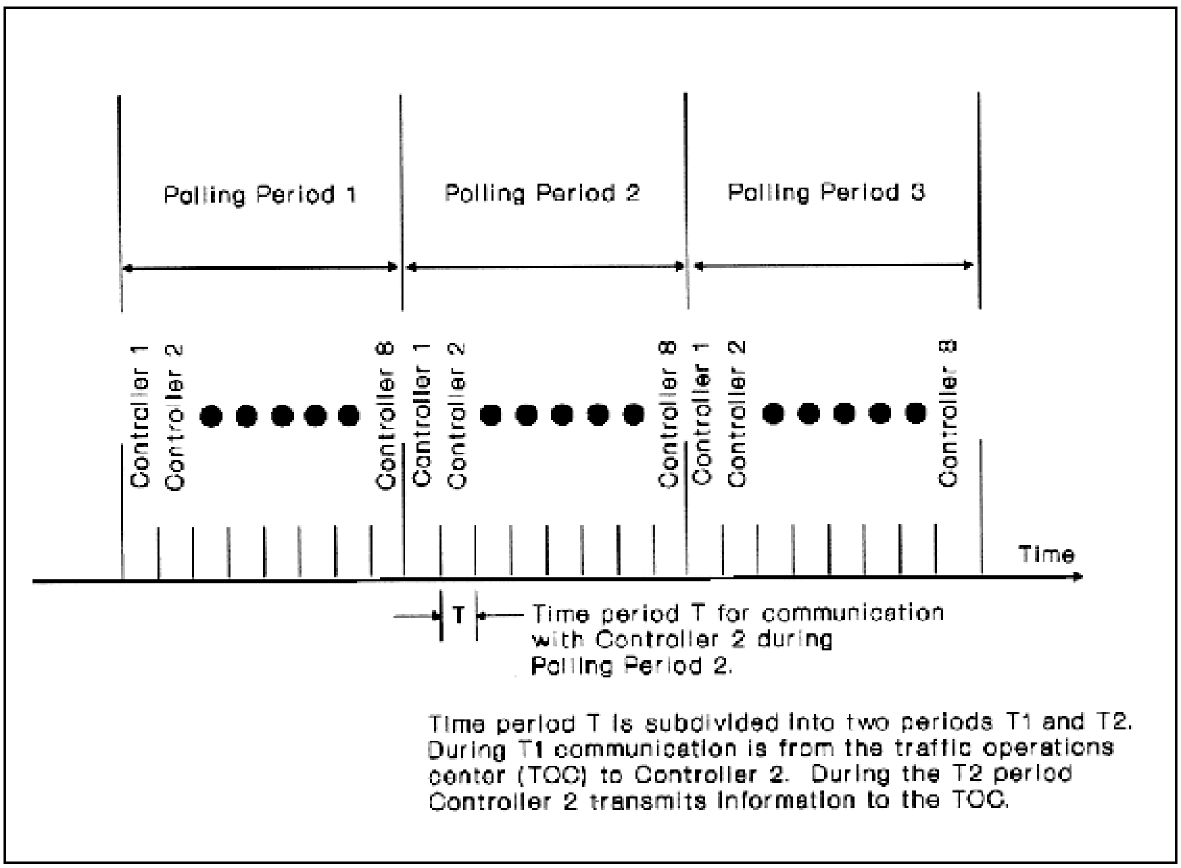


Figure 2-21 Time Relationship in Time Division Multiplexing

Code Division

Code division multiplexing (CDM) encodes data by using a specified but different binary sequence for each channel. All channels share the same frequency band. Spread spectrum radio systems typically use CDM (Chapter 7).

Noise and Interference

Noise

As shown in Figure 2-22, noise results from fluctuations in the signal caused by sources other than the signal. Noise sources can originate in the communication channel, transmitter or receiver, and include natural and human-made electrical interference.

Table 2-4 summarizes key noise properties.

Noise results in the receiver's producing incorrect outputs or errors.

- Result
  - Variation in the signal due to extraneous factors.
- Causes
  - **Thermal Noise** - Thermal agitation of electrons in the load resistance of the receiver.
  - **Radio Noise**
    Atmospheric - lightning, Cosmic and Solar
  - **Human-Made Noise** - Motors, car ignition, power lines, etc.
  - **Noise Peculiar to Media Use** - Crosstalk in twisted wire pair cable.

Table 2-4 Key Noise Properties

Interference

Interference refers to signal disturbance caused by:

- Signals from another communication channel in the same network (e.g., crosstalk originating from multiple twisted wire pair circuits in the same cable).
- Interference from an unrelated channel (e.g., interference on an assigned radio frequency channel from other transmitters).
- Interference induced within the channel itself (e.g., echo due to impedance mismatches in a leased line).

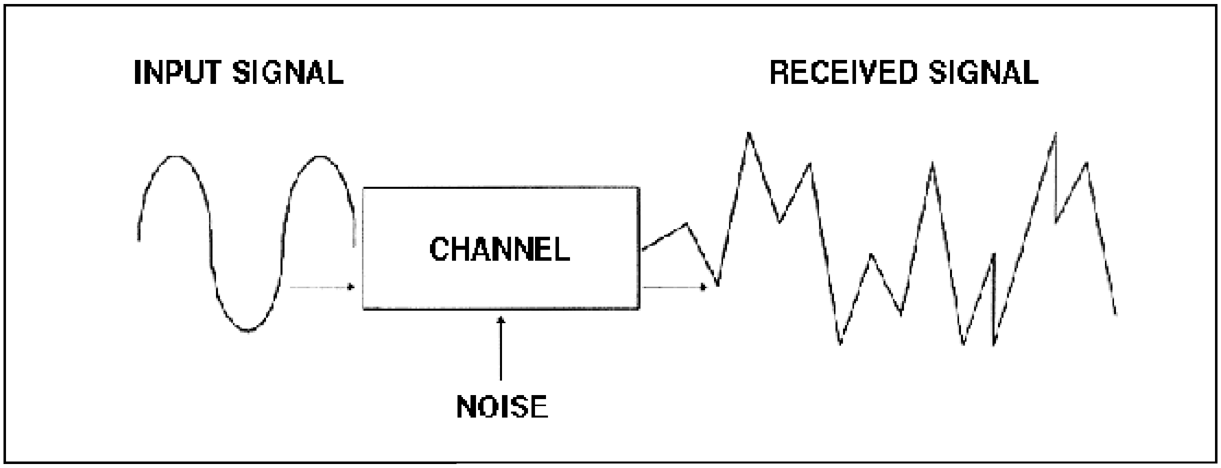


Figure 2-22 Noise Input on Signal

Signal to Noise Ratio and Bit Error Rate

The quality or fidelity of the detected signal depends on the signal to noise ratio (S/N), the magnitude of the signal relative to the noise, expressed in decibels (dB). For digital systems, bit error rate (BER) represents a quality measure. BER values of 10^{-6} end-to-end or better represent the performance values required for the transmission of both computer and traffic systems data. The S/N and BER required at the receiver depend on the type of modulation used and the performance required. As described in the following section, error detecting and control techniques enable the system to manage received digital errors. Shannon's law best describes the relationship between S/N, channel capacity and bandwidth (Ref. 1), i.e., if signals are sent with a signal power S Watts over a channel disturbed by white noise (random noise with a constant amplitude over the entire frequency range) of power N Watts, then the following equation yields the capacity C of the channel in bits per second:

$$C = W\log 2\left(1 + \frac{S}{N}\right)$$

where W is the bandwidth of the channel.

Applying Shannon's formula to some everyday voice channel criteria, W = 3000 Hz and S/N = 10, then

$$C = 30{,}000 \text{ bps}$$

This represents an upper theoretical value, not necessarily achievable by practical implementation. Systems used in practice on voice lines work at speeds very much lower than those above. One technique for obtaining higher data rates than possible with amplitude, frequency and phase shift keying (see page 2-17) modifies the modulation technique to obtain more than just two states. This technique is termed M-ary modulation (M = 2 represents binary). Although not common in traffic control systems, the technique finds extensive use for other applications. Table 2-5 shows comparative signal to noise ratios required at the receiver to obtain the same bit error rate on the same channel using different forms of modulation.

Modulation	S/N (dB)
Binary Phase Shift Keying (BPSK)	10.5
M-ary Frequency Shift Keying (M-ary FSK)	
M = 2 Binary Frequency Shift Keying	14.0
(BFSK)	11.0
M = 4	9.5
M = 8	8.5
M = 16	7.5
M = 32	

Table 2-5 Comparative S/N Rations for Different Forms of Modulation

Error Detection and Control

The previous section discussed the relationship of communication receiver sensitivity and bit error rate (BER). In traffic control systems, errors generally result from impulse noise which may cause bursts of errors (where contiguous bits have many errors). Error detection techniques include extra signal elements that permit the identification of certain classes of errors in the received data.

Technician	Description
Parity - also known as vertical parity	An additional bitis added to each data byte or character. The sum of 1's (ones) in the byte and the additional bit must be an off or even number as specified. This technique detects an odd number of bit errors in the byte. See Table 2-7 for example.
Longitudinal Redundancy Check	An additional byte is provided after an entire message or portion of a message (block). A bit in the new byte is computed from the corresponding bit in each data byte in a way similar to the parity check. An odd number of bit errors is again detected. When used in conjunction with parity this is a powerful tech-que. See Table 2-7 for example
Check sum	An additional byte or character is added to the end of the message or block. An algorithm is used which computes the checksum byte as a function of the message bytes. The receiving station performs a similar computation and de-termines wheather the checksum byte is consistent with the received data.
Cyclic Redundancy Code (CRC)	An additional two or more bytes are added to the message or block. Algor-ithms ar used to compute these bytes whih provide protection, particulary against bursts of errors.
Repeat Transmission	The entire message is revealed. All the receiving station the messages are compared and an error is detected if they are not identical.

Table 2-6 Commonly User Error Detection Techniques

Odd Parity

Data byte 1 0 1 0 1 1 1 1 1
Sum of 1s in data byte equals 6
Total sum including parity bit must be odd; therefore the parity bit is a 1 (see Byte 1 below)

	Parity	Data Byte							
Byte 1	1	1	0	1	0	1	1	1	1
Byte 2	1	0	1	1	1	0	0	1	0
Byte 3	1	0	1	0	0	1	1	1	0
Byte 4	0	0	1	0	0	0	1	0	1
	Total by Columns	1	3	2	1	2	3	3	2

Sum the corresponding columns in the data byte as shown. With the check character each column must result in an odd number. For ex-ample, the right most bit of the check byte must be a 1 to satisfy this requirement. The check byte therefore is

0 0 1 0 1 0 0 1

The parity bit for this byte is computed from the check byte by the parity rules and is a 0.

Table 2-7 Examples of Parity and Longitudinal Redundancy Check

Automatic Repeat Request

The automatic repeat request (ARQ) represents one general approach to overcome the problem of errors. Errors are detected using one or more of the techniques described in Table 2-6. Table 2-7 provides examples of two techniques. If no error is detected the data is accepted; otherwise, traffic systems handle the error in two different ways:

- Ignore all data associated with the transmission and retain the current data until the next polling cycle. The earlier traffic control systems which used rapid, highly structured polling cycles (same variables repeated in each polling cycle) generally used this approach.
- Request that the message be repeated. Since many current designs transmit parameters and variables at intervals not necessarily identical with each polling cycle, traffic control systems currently use this approach more frequently.

Use of error detection techniques plays a key role in assuring reliable data transmission. Transmission of the additional codes which implement the techniques require a corresponding increase in the channel data rate. This becomes a component of the communication overhead burdens discussed further in Chapter 4.

Forward Error Control

Forward error control (FEC) represents the second basic approach which includes error correcting codes with the message to correct a limited number of errors. Table 2-8 summarizes key features of forward error control.

To date, traffic control systems have not used FEC because of its susceptibility to burst noise (noise which lasts longer than the "redundancy time" of the correction technique). Although conventional forms of FEC do not prove effective in such an environment, the use of code interleaving with FEC works well to resolve this situation. Interleavers break up a digital bit stream by the use of a code which rearranges the order of the message symbols so that errors due to the noise burst appear to the decoder as random errors (which FEC schemes can handle). The interleaving intervals or span lengths must significantly exceed the burst period expected.

Disadvantages of FEC with interleaving include the significant symbol overhead required by the correction codes and interleaving and the additional circuitry required by the coder and decoder.

• Bit error rate function of signal to noise ratio (S/N) • Special codes embedded in the message. Processing of the received message together with these codes usually results in error detection. • Once detected, error control strategy required. Either ignore the bad information or retransmit the message. • As transmission distance increases, signal strength attenuates (reduces). S/N diminishes. To preserve sufficient S/N at the receiver, repeater amplifiers or signal detectors, modulators, and transimitters sometimes become necessary at certain geographical locations in the channel.

Table 2-8 Key Features of Error Control

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Table 2-8 Key Features of Error Control

Data Transmission and Link Control

Modes

The direction of flow over the channel or transmission mode can take the following forms:

- Simplex
- Half duplex or
- Full duplex

Table 2-9 provides mode definitions and characteristics.

Traffic control systems can use any of the three modes; however, key links need half or full duplex to permit status checks and error handling.

Mode	Data Dlow Detection	Characteristics	Comments
SIMPLEX	Data flow in one direction only	Does not provide verification that data were received and acted upon Does not provide answer-back, status reporting, or validity checking	Commercial radio and television are examples Traffic control systems which provide no return informatin to a master controller or traffic operations center use this mode
HALF DUPLEX (HDX)	then Data flow in either direction, but only in one directin at a time	Require modem at each end of the line Require control capability to assure proper operation Uses latency time or turnaround time	In a copper wire transmission medium HDX requires two wires but may be used with four wires (four wires provide improved interference characteristics)
FULL DUPLEX (FDX)	Data flow possible in both directins at the same time.	Acts like two simplex channels in opposite directions Permits independent, two-way simultaneous communication May raise cost of channel Reduces the one-way capacity if frequency multiplexing is used on a single channel	In a copper wire transmission system, some FDX modems require 4 wires while others require only two wires. In the latter case the modem divides the channel into two subchannels to achieve simultaneous bidirectional service

Table 2-9 Transmission Model Characteristics

Techniques

Data transmission can be *parallel* or *serial*. Parallel transmission carries different signal elements over different channels; however, cost usually limits usage in traffic control systems, except over short, direct-wire links. Serial transmission uses a single channel and shares its capacity, via time-division multiplexing, among different field locations. A receiver and transmitter operating with serial coordinate via a process termed *synchronization*.

Two serial transmission techniques, *synchronous* and *asynchronous*, commonly find use in traffic control systems.

In synchronous transmission, modems at each end of the transmission medium provide time references locked together by synchronizing signals at the start of transmission. The information bits are sent in a continuous, uniformly spaced stream. Synchronization signals are also sent between blocks of transmitted data. This approach proves very efficient and commonly finds use in non-traffic control applications for transmitting large blocks of data at high data rates.

Traffic control systems more commonly use asynchronous transmission, particularly in the communication link between the traffic controller and the traffic operations center or field master. In asynchronous transmission no particular time relationship exists among the characters. Stop and start bits at the beginning of each character control transmission. Since it contains these additional bits per character, the data information rate is lower than for synchronous transmission.

Link Control

Modems (Modulator/Demodulator) require a series of control signals. These signals assume that both the transmitting and receiving modems are in condition to perform their respective functions. Key control signals are:

- Request to send (RTS) is a signal from the computer indicating it wants to send data.
- Carrier detect (CD or CXR) or received line signal detector indicates to the sender that the receiving modem has received the transmitting modem's carrier.
- Clear to send (CTS) is the signal to send to the transmitting computer that both modems are ready to perform their functions and that transmission may begin.

In half duplex communication the transmission path reverses at periodic intervals. The time to allow the modems to perform this function is *turnaround time*. Allowance for turnaround time may, in some cases, be programmed into the modem and in other cases controlled by software in the control center and field processors.

Historical Perspective

The trends in communications for freeway management systems and traffic signal systems are presented in Tables 2-10 and 2-11, respectively.

In the last 30 years, traffic systems have undergone evolution in the types of communications systems and techniques used. Due to dramatic changes in technology, communications leasing costs and functional requirements, certain techniques have become obsolete, while other methods, previously virtually unknown, have become increasingly attractive. Tables 2-10 and 2-11 trace this evolution and describe typical features prevalent during the decades.

DATE	MEDIUM	MULTIPLEX	EXAMPLE
Late 1960's - 1970's	Leased Telephone Lines	FDM	Chicago Expressway (Later some twisted wire pair used)
Early 1970's	Ownned Twisted Wire Pair	FDM	New Jersey Turnpike (planning replacement at current operation)
Early 1970's	Owned Twisted Wire Pair	FDM	Hampton Roads Tunnel - Viriginia
Early 1980's	Coaxial Cable	FDM/TDM FDM/TDM (date) FDM (video)	INFORM- Long Island SCANDI Detroit
Late 1980's	Fiber Optics (Copprt for data distribution network)	TDM (date)	Ontario Highway 401
Late 1980's	Area Radio Network	TDM	Ice warning system in New Mexico
Early 1990's	Cellular Radio	TDM	Temporary, changeable message sign in construction areas

Table 2-10 Historical Trends in Communications for Freeway Management Systems

DATE	Type od Requirements	Typical Field Equipment and Communications Capabilities
Late 1960's to Early 1970's	System Detectors: Inbound information variable (presence) sampled by central computer at 30 times per second Signal Control: Two outbound control signals, one inbound state signal, all provided by central computer at 1 or 2 times per second	Controllers: Electromachanical or simple electronic with no ancillary data storage capability Timing changed through intervals or phase command Communications: Moslty FDM [one channel per single signal or two related signals] with no data storage capability
Middle 1970's to Early 1980's	System Detectors: 4-8 bits for each, sampled at 1or 2 times per second Signal Control: Two outbound control signals, one inbound state signal for each major phase, status signals (e.g conflict monitor, outbound special function signals (Control signals may require 8 - 16 bits one time or two times per second)	Controllers: Electronmachanical, NEMA, timing through interval or phase command Communications: Mostly fixed byte polled TDM. Short term storage capability in field communication unit. Proprietary communications protocols and interfaces
Middle 1980's to Present	System Detectors: Considerable preprocessing in field (Transmission may vary from one time per second to one time per minute) Signal Control: Timing plans downloaded and implemented by field controller. (Typical communication intervals one minute. Data message may have many bits.	Controller: Type 170/179 NEMA controllers using proprietary protocols and interfaces. Communications: Mostly fixed have polled or variable byte polled TDM. Considerable storage and processing in communication unit or controller serving as communication unit.

Table 2-11 Communication Requirements Trends

Endnotes

1 (Popup)
K1 = 1.79 db/mi (22 gauge cable at 1000 Hz)
K2 = 0.65 db/mi (typical single mode fiber at 1300 nanometers (nm))
Note 1 D in miles / f in megahertz
Note 2 Signal controlled to specified limits by local exchange carrier

CHAPTER 3 - FIELD EQUIPMENT INTERFACES

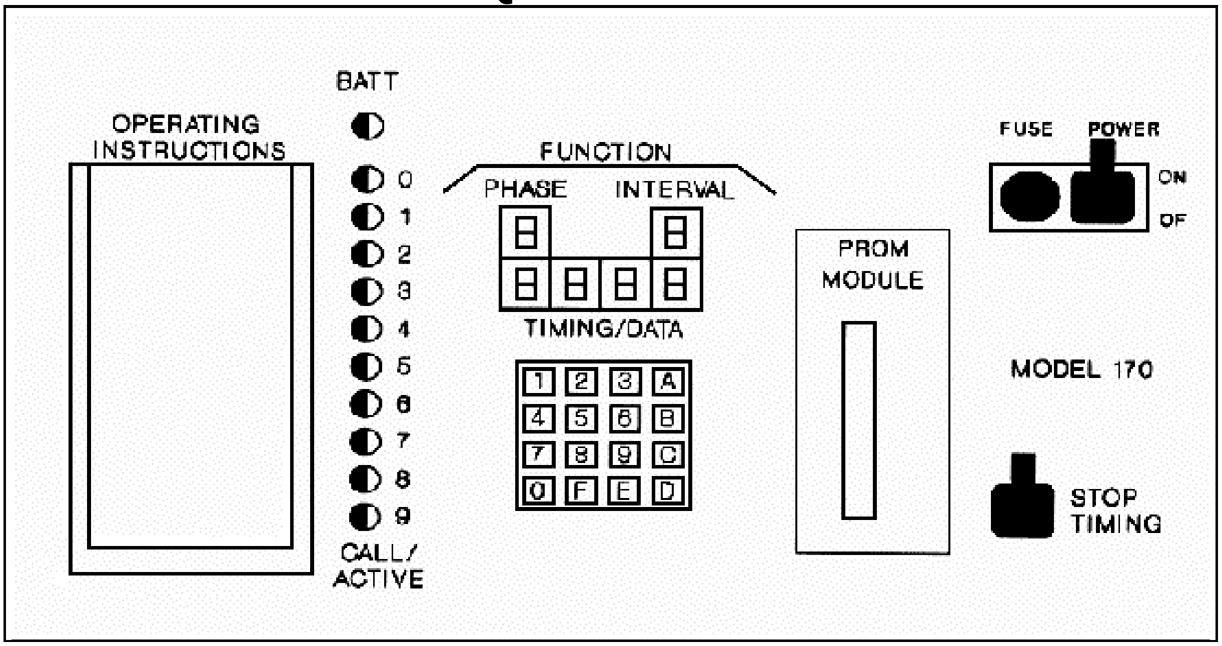

Figure 3-1 Type 170 Controller

Introduction

Via the communication medium, the traffic control center transmits to and receives information from:

- Local traffic controllers in the field
- Master controllers in the field which in turn communicate with the local traffic controllers

The communications system must interface with all types of local controllers present in the system including:

- Electromechanical
- Pretimed and actuated electronic
- NEMA TS1 and TS2
- Type 170/179
- Advanced Traffic Controllers

Need

To design a compatible communications system, the transportation professional must understand the following major system elements and their ability to function together:

- Traffic operations center and field master controller
- Communications medium
- Local controllers
- Changeable Message Signs (CMS)
- Highway Advisory Radio (HAR)
- Detection Devices

The transportation professional must also understand all the local controller types and their interaction with the various communications media available for selection.

Purpose

This chapter describes the physical control interfaces provided by traffic controllers and other field equipment and discusses the ways in which communication equipment electronically interfaces with these devices. The chapter also explores the relationship of the transmission medium and channel bandwidth with:

- Communication protocols and interfaces
- The type of local controller
- The type of field master, and
- Other field equipment.

Organization

Table 3-1 summarizes this chapter and its organization based on local controller type.

Electromechanical Controllers

A traffic signal system coordinates electromechanical controllers by selecting a timing dial to establish cycle length. The timing dials for each controller in a section must be synchronized to a common time reference. Manufacturers supply coordinating equipment to accomplish this synchronization and dial selection function via high voltage (115 V) interconnect cable.

In the early 1970's, computer systems began to interface with these controllers. One method of control provided "interval advance" pulses directly to the controller camshaft motor. In some cases, these pulses were provided directly through the cable and amplified by relays to obtain sufficient power to drive the motor. In other cases, frequency division multiplex (FDM) communication reduced communication cable requirements. The field equipment required to actuate the camshaft motor consisted of simple relay logic, and the design of this equipment was essentially independent of the controller manufacturer. The approach proved compatible with both owned telephone type twisted wire pair (TWP) cable and leased telephone lines.

Table 3-2 summarizes the influence of this and other controller types when used with twisted wire pair communications. The remaining sections of this chapter contain discussions of the other controller types shown in the table. (Controller types are listed in the approximate chronological sequence of their development.)

Electronic and NEMA TS1 Controllers

Electronic controllers were initially introduced for actuated controller applications. These controllers featured phase oriented control (rather than the interval control scheme used for electromechanical controllers). Manufacturers developed a standard (NEMA TS1) to which the functions of actuated controllers conform. (During this period pretimed controllers also used solid state technology.)

Characteristics of NEMA TS1 controllers relevant to communications include:

- NEMA TS1 controllers have no serial ports and no interconnect standards.

- Traffic equipment manufacturers provide field coordinating units or telemetry modules to adapt their own controllers to receive:
  - timing reference signals and
  - timing plan selection signals

which are provided by a master controller in the field and transmitted to the intersection.

Section Title	Purpose	Topics
Electromechanical Contollers	Influence of electromechanics controllers on communications	Interval control Use of FDM Coordinating equipment Non-proprietary protocols
Electronic and NEMA TS1 Controllers	Influence of electronic and solid state controllers on communications	Phase oriented control Field coordinating units Telemetry modules Remote Communications Unit (RCU) Proprietary protocols
NEMA TS2 Controllers	Influence of NEMA TS2 communications	Upgrade of TS1 Interconnect modem
Advanced Traffic Controllers (ATC)	Influence at ATC on communications	OAC Advanced Transportation Controllers
Changeable Message Signs (CMS)	Influence of changeable message signs on communications	Matrix based signs Message based signs
Detection of Devices	Influence of detection devices (sensors) on communications	Conventional traffic detectors Special purpose detectors New Technology detectors including video processing detectors
Highway Advisory Radio (HAR)	Influence of HAR on communications	Voice transmission Control signals

Table 3-1 Organization of Chapter 3

Corridor Type	Controller Standard or Industry Practice	Generaic Computer Traffic Control Systems	Traffic Equipment Manufacturer Supplied System
Electromechanical	Dial and camshaft controller functionally and electrically similar	Use of voice or telegraph lines lines with or without multiplex Simple non-proprietary protocols	Coordinating units use proprietary schemes
Electronic Pretimed and Older Electronic Actuated	No standards provided	System interfaces often possible using discrete control signals for each function	Proprietary interconnect schemes provide timing reference, control plan selection, and detector data return to master return to master.
NEMA TS1	Standard specified functions and equipment interfaces No communication or coordination standards provided. Standards provided. Standard for actuated controllers only.	Provision by manufacturers of communication equipment using discrete outputs Can coordinate NEMA, often other solid state and electro-mechanical controllers Mostly use TDMFSK on voice grade lines	Coordination through controller manufacturer's equipment and protocols. These systems evolved to current generation of closed loop systems
NEMA TS2	Future equipment standards are to include pretimes controllers and serial port access.	Similar to NEMA TS1	Modem for TWP or Telco lines included: Proprietary communication software to be provided b manufacturer
Type 170/179 Family	Equipment standards for standard serial ports and modern protocol. No communication software stand-ard provided	Communication software specified and provided by users, consultants, and system suppliers.	Closed loop systems using public domain and proppprietary protocols with standards modems

Table 3-2 Relationship of Protocols and Interfaces to Controller Types for Twisted Wire Pair

- Each manufacturer uses its own set of communication protocols.
- The coordinating unit provides access to the external interconnect (multipair cable or a serial port).
- The coordinating unit accesses the controller either through the backplane (physical interface between coordinating unit and controller microprocessor) or by discrete signals to the terminals of the controller connector (Figures 3-2a and 3-2b).
- For controllers designed to the TS1 standard, the use of a controller with a different manufacturer's master controller may prove possible.

Remote Communications Unit

The manufacturer normally programs NEMA controllers. Therefore, the designer or contractor has no control over the controller software, including communication protocols. Thus, for systems of the Urban Traffic Control System (UTCS) type (see Chapter 4, page 4-2), which do not use the controller manufacturer's master, a remote communications unit (RCU) marries the NEMA controller to the system. As shown in Figure 3-2a, the designer implements this interface by discrete signals between the RCU and the controller. The RCU is usually a semi-customized unit whose data protocol with the control center results from system requirements and communication control functions. Chapter 4 describes typical examples of these protocols.

NEMA TS2 Controllers

In 1992, industry adopted the NEMA TS2 specification. TS2 provides additional functional capability over the TS1 specification in a number of areas, by including pretimed controllers, for example. The TS2 Type 2 controller is intended to provide downward compatibility with TS1. From a communications viewpoint the NEMA TS2 standard provides for a 1200 bps modem (on Port 3) for interconnect purposes. This modem can accommodate communication with the manufacturer's field masters without need for additional modules (See Figure 3-2c). Interface with other than the manufacturer's field master is possible with the TS2 controller and is performed in the same way as with TS1 (see Figure 3-2a).

Type 170/179 Controllers

The California and New York Departments of Transportation initially introduced the type 170 traffic controller.(10) Since then, New York State DOT has introduced the Model 179 Controller and other jurisdictions have specified a number of upgrades.(41)
Characteristics of the Type 170/179 controllers relevant to communications include:

- The controller specification relates to equipment only; no software is specified.
- A number of manufacturers supply the equipment.
- The specifications provide for serial port communication service (up to 19.2 Kbps using the Model 414 Program Module) and an optional 1200 bits/second modem (Model 400) is available.
- A number of interface alternatives are available, some of which provide for more ports and higher data rates (Figure 3-3 shows two interface alternatives). No RCU of the type needed for NEMA controller interfaces is required for type 170 controllers.
- Since no software is specified, users must make their own software arrangements.
- A number of software packages have been developed for various signal control and freeway surveillance purposes.

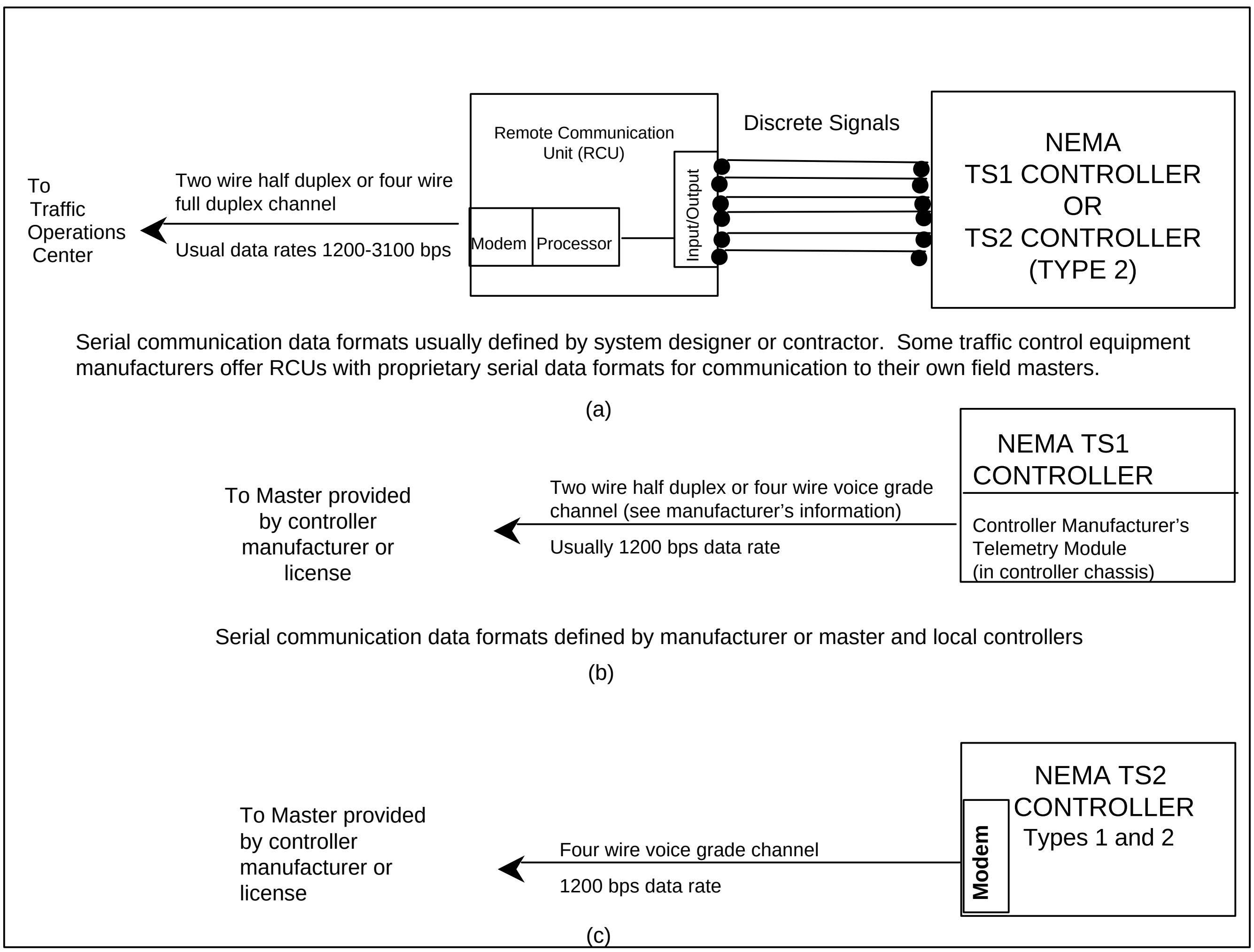

Figure 3-2 Communication Interface Alternative for NEMA Controllers

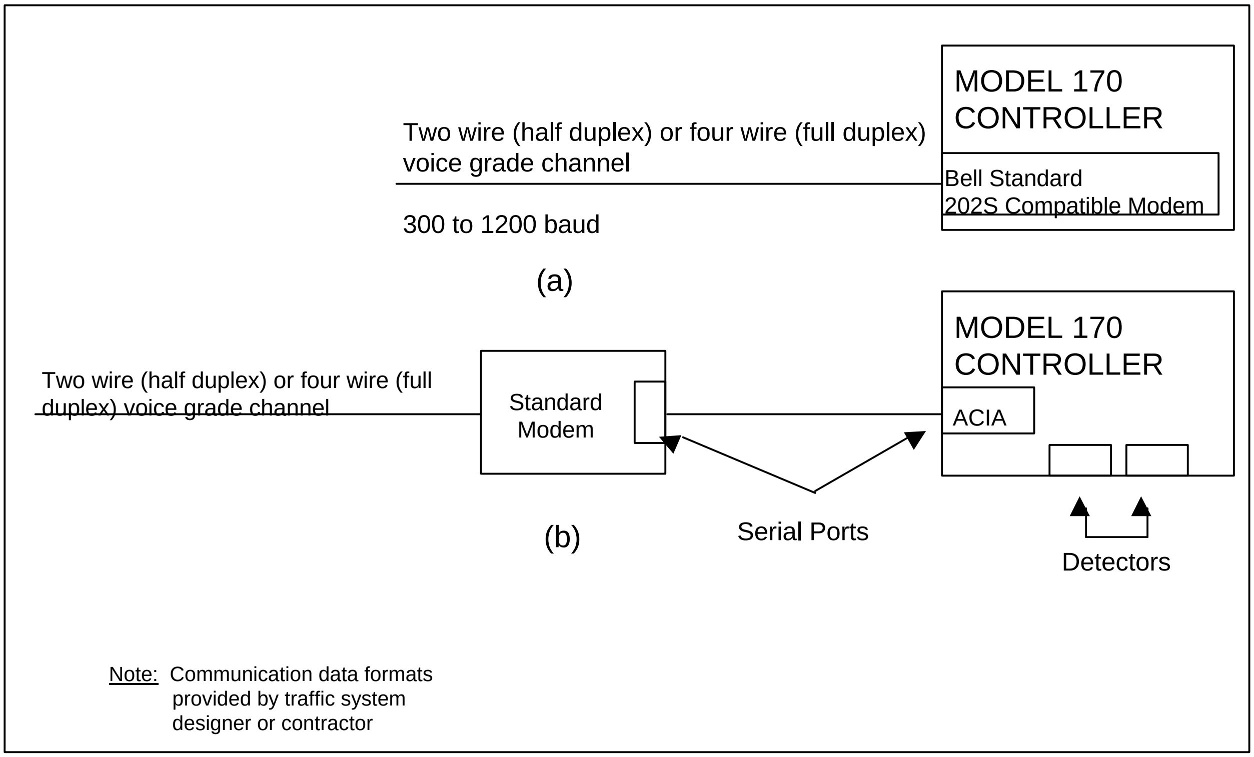

Figure 3-3 Communications Interface Alternatives for Model 170 Controller

The separation of the software from the equipment enables the user agency to develop or commission development of communication protocols which remain under its control so as to maintain compatibility with subsequent equipment purchases from multiple vendors. The user may also:

- Choose to purchase existing software packages,
- Use public domain software, or
- Purchase an entire Type 170 based closed loop system from a traffic manufacturer or system supplier.

Because Type 170 software is specified and controlled by the user, the controller may be used for functions far different from intersection traffic signal control. It has, for example, seen extensive use by:

- Various states for freeway surveillance and control,
- The Virginia Department of Transportation on I-664 for tunnel traffic control,
- The Colorado Department of Transportation in a similar application for the Hanging Lake Tunnel on I-70 (7), and
- Various states for control of freeway sprinklers.

Advanced Traffic Controllers

IVHS activity has generated interest in developing an advanced traffic controller with the ability to support a multitude of technologies. Two such efforts are currently underway. One represents a private sector effort, the Open Architecture Controller (OAC). (8) The California Department of Transportation (CALTRANS), in conjunction with the Federal Highway Administration, sponsors the other effort, the Advanced Transportation Control Computer (ATC)

(69).

Both controllers support the Motorola 68000 series of microprocessor units, capable of 16 MHz or greater CPU clock timing and 8 M bytes or more of memory. The OAC supports the Type 170 processor as well. The extra processing speed and memory addressing allow the use of a standard, real-time, multi-tasking operating system and software development based on higher level programming languages such as "C". The standard VME bus backplane allows virtually unlimited expansion with a large industrial product base of standard functional plug-in boards.

To date, communications interfaces to the two controllers have been to the RS-232-C standard (see Chapter 9). The CALTRANS ATC includes two such ports. However, the VME backplane offers a virtually unlimited choice of communications interfaces. By expanding into the VME backplane with plug-in boards, the ATC and OAC can be programmed to support such communications interfaces and protocols as RS-232-C, RS-422 and SONET described in Chapter 9.

Plug-in boards also support interfaces and protocols not described in this handbook which primarily transfer large data files among computers.

Changeable Message Signs (CMS)

While traffic control systems have used a number of CMS technologies in the past, the most popular current types include:

- Matrix based signs
  - Fiber Optic (FO)
  - Light Emitting Diode (LED)
  - Flip Disk
  - Flip Disk/FO
  - Flip Disk/LED
- Message Based Signs
  - Rotating Drum
  - Blankout

The matrix based CMS typically contains a microprocessor based field controller containing at least one serial data port. The traffic operations center computer transmits, usually through proprietary protocols, alphanumeric messages for display or codes to select stored messages. The traffic operations center usually transmits data over 1200 BPS or 2400 BPS half duplex channels. The controller may contain a built-in modem to receive data at these rates over two wire leased or private lines. Modems may accept rates up to 9600 BPS from other communication technologies such as fiber optics.

A 1200 BPS channel can accommodate six to eight CMS field controllers using a polled data format in conjunction with time division multiplexing.

Since some types of message based signs usually have a limited number of message selections, codes and discrete messages lines can control messages in the field. Two lines may select up to four messages. A remote communication unit (RCU) or discrete outputs on the Type 170 controller may provide the information for these message selections along with other traffic control functions.

Detection Devices

Most detection devices (sensors), including conventional traffic detectors such as inductive loop detectors and magnetometers, output presence data as a discrete signal whose duration represents vehicle presence over the detector.

Special purpose detectors such as overheight vehicle detectors and environmental sensors such as ice detectors provide a discrete signal output.

Certain unconventional vehicle detectors such as video image processing detectors (VIPS) have the capability of providing data at several locations within the camera's field of view. VIPS also can preprocess detector data and provide several output variables. Communications with these devices usually takes place through serial ports.

Highway Advisory Radio (HAR)

HAR requires two information types:

- Voice transmission to the field transmitter, and
- Control signals to the transmitter and roadway sign flasher indicating availability of an important message.

A voice channel usually carries the voice message. Another voice grade channel may carry the control signals using modems and serial interfaces or alternatively the data transmission protocols of RCUs or Type 170 controllers may include the control signals.

CHAPTER 4 - COMMUNICATIONS REQUIREMENTS

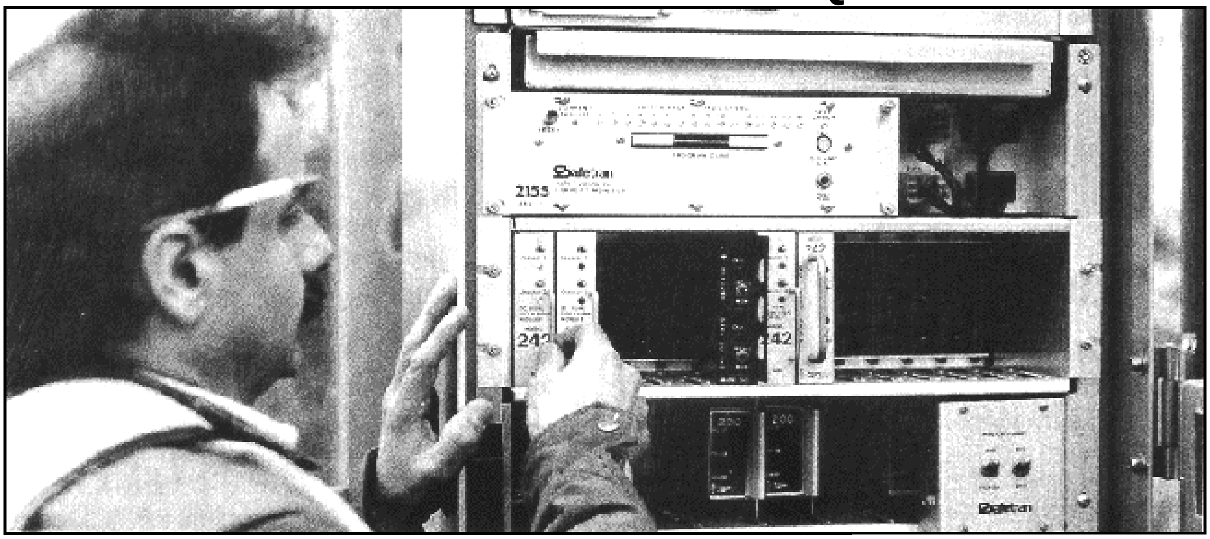

Figure 4-1 Advanced Traffic Management System Field Cabinet

Introduction

A traffic control system must communicate all real-time commands necessary to execute functions and transmit information between the field controller and field master or traffic operations center. This information includes: signal states, controller modes, equipment status, and detector data. In addition, the system may communicate certain data base parameters to the field (*download*) or from the field to the control center (*upload*). Depending on the system design, it can either directly command signal timing or select, via real-time command, a plan stored in the field controller's data base.

The requirements for communication of TV signals differ significantly from data communication requirements. Systems with TV require greater bandwidths, and if transmitted digitally, higher signal rates.

This chapter describes data and TV communications system requirements while Chapter 5 will describe alternative communication system architectures and relate them to system requirements.

Need

Field units and system architectures have become increasingly based on the improved capability for storing and processing data in the field. Currently, most systems use either short-term communication repetition intervals (0.5 to 2 seconds) or long-term intervals (10 seconds to one minute). Subsequent sections of this chapter provide examples of protocols based on each type of interval. The transportation professional must understand the relationships among system architectures, communication intervals and field storage capability and how these impact communications requirements.

A number of owned and leased alternatives exist for CCTV signal transmission. The transportation professional must understand these techniques as well as TV transmission alternatives such as:

- Full motion analog video
- Freeze frame/slow scan
- Coded TV (Codec)

Purpose

This chapter identifies communications requirements for the major classes of system architecture. It also presents the requirements for transmitting full motion analog video, freeze frame/slow scan video and coded TV.

Organization

Chapter sections as summarized in Table 4-1 correspond to requirements for the major architecture classifications and television types.

Requirements for Data Communication

Short Polling Cycles and Limited Field Storage Capability

Many currently operational systems use polling cycles in the range of 0.5 to 2 seconds. In these systems either the field communication unit or controller requires a modest level of data processing capability.

The communication system and data coding for the Boston, MA traffic control system (BTCS) (9) exemplifies the efficiency of this approach. As a typical UTCS system, BTCS controls both pretimed and actuated controllers. Figure 4-2 shows a general block diagram of the communications related portions of the system. Major features include:

- Each data stream and modem channel in the central communications unit (CCU) can service up to eight (8) signalized intersections.
- Each remote field communication unit (RCU) contains a separate address and responds only to the message associated with that address and intended for that site.
- After receiving a message, the RCU provides signals to the field devices, such as the controller, and transmits data on the state of its attached devices to the CCU.
- One or more bits in a fixed position in the serial message format represents each input from and output to a field device.
- At the appropriate instant, a signal changes the controller state to the next phase or timing interval.

Figures 4-3 and 4-4 show the data format structure for the command signals from the CCU in the BTCS traffic operations center to the intersection RCU and the reply signals from the RCU to the CCU (9). Tables 4-2 and 4-3 define the symbols used. In this system, the RCU can:

- Accommodate pretimed, NEMA TS1 and NEMA TS2 controllers
- Activate many of the functions of NEMA controllers, as well as special functions
- Report many controller states and local detector actuations

Each byte contains eight (8) bits of information as well as a start bit and two stop bits (not shown). The system uses the last byte of both the outgoing and incoming messages for error control purposes.

As shown in Figure 4-2, a portion of the RCU converts these message bits to discrete output signals or reads discrete input signals from field devices. The data format accommodates the maximum number of inputs possibly present at each field location. All field locations use this fixed structure regardless of the number of field devices actually present; thus, some communication capacity remains unused. Traffic signal and freeway surveillance systems have used this format extensively.

	Section Title	Purpose	Topics
DATA COMMUNICATION	Short Polling Cycles and Limited Field Storage Capability	Communications Requirements for this System Architecture	0.5 -to-2 second polling cycles Modest level of field data processing Data format structure - Control center CCU to intersection RCU - Reply signals from RCU to CCU - Reduction of communication burden - Accumulation of data - Transmission of data Development of communication requirements spread sheet
	Long Polling Cycles and Robust Field Stoarage Capability	Communications Requirements for this System Architecture	Ten-second to 1-minute polling cycles Polling techniques - Advantages and disadvantages of longer polling periods - Extensive field data processing - Larger field data base Contention techniques - Simultaneous access to communications channel
	Trunking and Distribution Systems	Communications Requirements for Larger Systems	Data rates Drops Backbone Hub or node
	Communication Overhead Burdens	Flow Control and Error Control	Overhead analysis
TV TRANSMISSION	Full Motion Analog Video Transmission	Transmission Requirements	Use of NTSC cameras Video resolution Update of frames Baseband video signal Control signal
	Freeze Frame/Slow Scan Video Transmission	Transmission Requirements	Resolution and gray or color level Tranmission time Transmit and receive units
	Coded TV Transmission	Transmission Requirements	Video compression techniques and standards Interframe coding Intraframe coding Coder-decodes (codecs) Video quality Interoperability standard (p x 64) Coded TV quality Cost

Table 4-1 Organization of Chapter 4

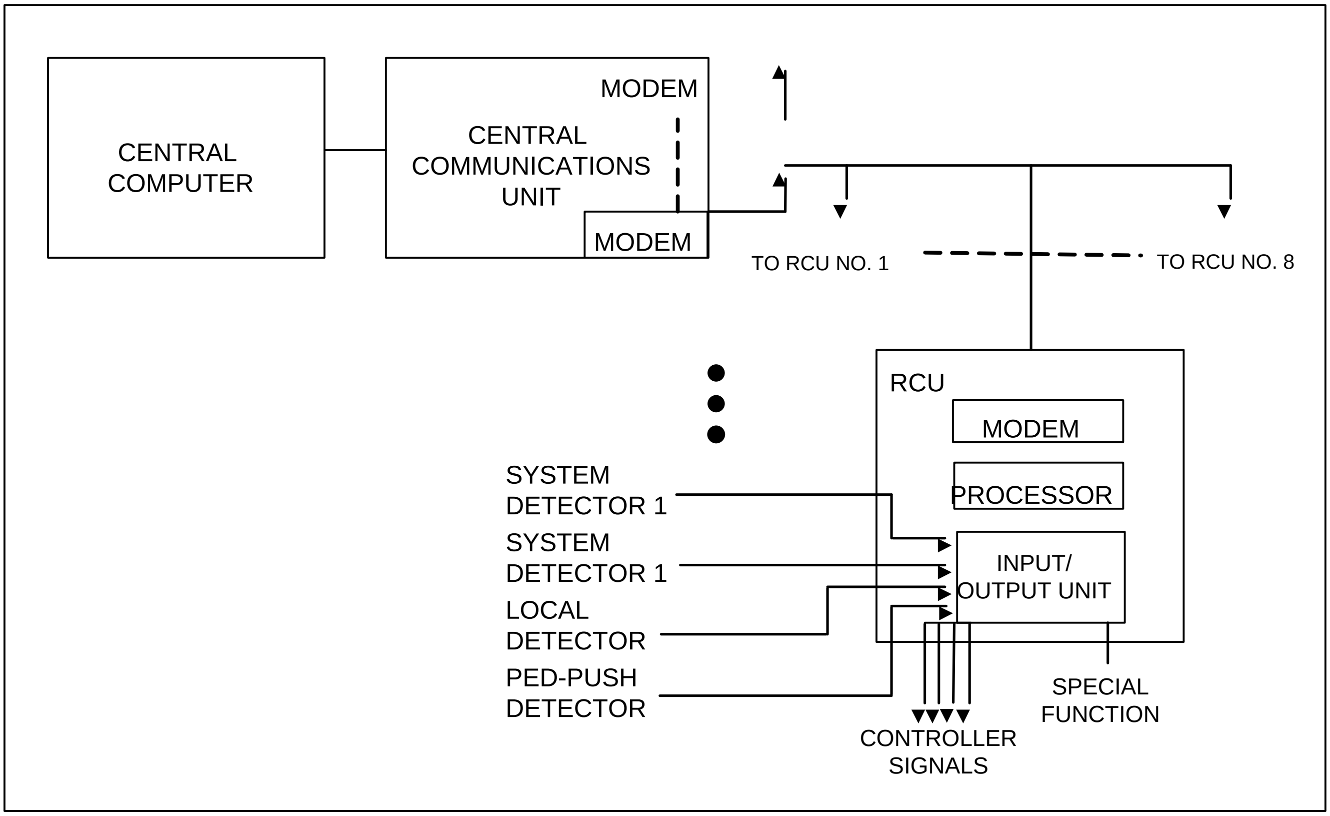

Figure 4-2 Communication Plan for Boston Traffic Control System

Byte 1	FO1	HOLD	DIAL REL	HOL	0	ADDR3	ADDR2	ADDR1
Byte 2	SP1	SF3	SF2	SF1	CALL ALL	PED CALL	FLASH	FO2
Byte 3	SP7	SP6	SP5	SP4	SP3	SP2	CALL FREE	PHASE OMIT
Byte 4	CK8	CK7	CK6	CK5	CK4	CK3	CK2	CK1

Figure 4-3 Data Format Structures, CCU to RCU Comment Clock, Boston Traffic Control System *Note (1)*

FO		Force off signal for ring
HOLD		Keep in coordinated phase
DIAL REL		Dial Release
HOLD		Keep controller on line (under computer control)
ADDR		Three address bits to identify controller on this line
SP		Spares
SF		Special Function
CALL ALL		Calls to all phases
PED CALL		Pedestrian recall function on selected phases
FLASH		Place controller in flash
CALL FREE		Disable the backup coordination signal (revert to local control)
PHASE OMIT		Omits selected phases
CK		Checksum bit for error control

Table 4-2 Traffic Operations Center to Intersection Commands

	7	6	5	4	3	2	1	0
Byte 1	G1	G2	G3	G4	G5	G6	G7	G8
Byte 2	SP2	SP1	CONT REP	PE	SYS FSH	FSH	CONF MON	DOOR
Byte 3	C1	C2	C3	C4	C5	C6	C7	C8
Byte 4	D1	D2	D3	D4	D5	D6	D7	D8
Byte 5	P1	P2	P3	P4	P5	P6	P7	P8
Byte 6	O1	V1	O2	V2	O3	V3	O4	V4
Byte 7	O5	V5	O6	V6	O7	V7	O8	V8
Byte 8	CK1	CK2	CK3	CK4	CK5	CK6	CK7	CK8

Figure 4-4 Data Format Structure, RCU to CCU Repsonse Block, Boston Traffic Control Systems

G		Phase green signal
SP		Spare
CON REP		Controller repair (puts controller on line form field location
PE		Preempt
SYS FSH		Transfer to flash at proper point in cycle
FSH		Transfer to flash
CONF MON		Conflict monitor active
DOOR		Cabinet door open
C		Checkbit - call on phase
DOOR		Local vehicle detector actuation
P		Pedestrian destector actuation
O		Vehicle detector occupancy overflow bit
V		Vehicle detector state change
CK		Checksum bit for error control

Table 4-3 Field to Traffic Operations Center Data Transfer

This same polling technique can interface with the Type 170 family programmable microprocessor controllers. The 170 family includes: (10)

· Specification of equipment commonly used in connection with controllers:
- conflict monitors
- switch packs
- flashers
- loop detectors
- magnetic detectors
- isolators

· Provisions to house this equipment and connect it to the control unit.

· The ability to accept discrete inputs from and provide discrete outputs to other devices (e.g., blankout and speed limit signs, overheight vehicle detectors). Together with user furnished software to control these devices, the 170 controller provides logical and physical interface functions in place of the RCU shown in Figure 4-2.
Transmission of detector occupancy and double detector (speed trap) data for freeway systems proves the highest single communication load for systems of this type. For example, if the local processor interrogates a detector every 1/60 second, and if the central computer polls the local processor once each second, the system must transmit six (6) bits each second to the control center since 6 bits can represent up to 64 samples of vehicle presence or absence information. If each controller services a number of detectors and/or speed traps, the communications

burden becomes considerable.

Figure 4-5 shows a technique commonly used to reduce this burden. As shown, occupancy data accumulates in a counter and is transmitted to the control center in larger quanta represented by the overflow bit. Speed trap data transmission sometimes uses a similar technique. The data transmitted to the control center ultimately averages to the same value as the input to the counter. However, in a particular time interval, errors can accrue and adversely affect control center data processing functions.

Table 4-4 summarizes the equations and relationships for estimating functional communication requirements for traffic signal systems with the general communication architecture described in this section. The communications system designer must then convert these functional requirements into physical requirements. Obtain the physical requirements by adding the following to the functional requirements:

- data transmission and link control requirements (see Data Transmission and Link Control, page 2-23)
- error detection and control requirements (see Error Detection and Control, page 2-20)
- capability for requirements growth during or subsequent to system design and implementation.

Communication Overhead Burdens, page 4-17, further discusses data transmission and error detection requirements.

To assist the evaluation of alternative communications channel capacities and technologies during preliminary design, see the spread sheet in Appendix B. Typical requirements for a traffic signal system communications system of the type shown in Figures 4-2 through 4-4 with a once per second polling interval form the basis of this spread sheet. The designer enters certain functional traffic system requirements, along with several assumed parameters, characteristics of the communication channel and technology. For these functions the spread sheet provides default communications requirements which the user may alter. This spread sheet provides a preliminary evaluation of the feasibility of the assumed communication characteristics. Computer disks for the spread sheets can be obtained from:

McTrans Center, University of Florida 512 Weil Hall, Gainesville, FL 32611-2083

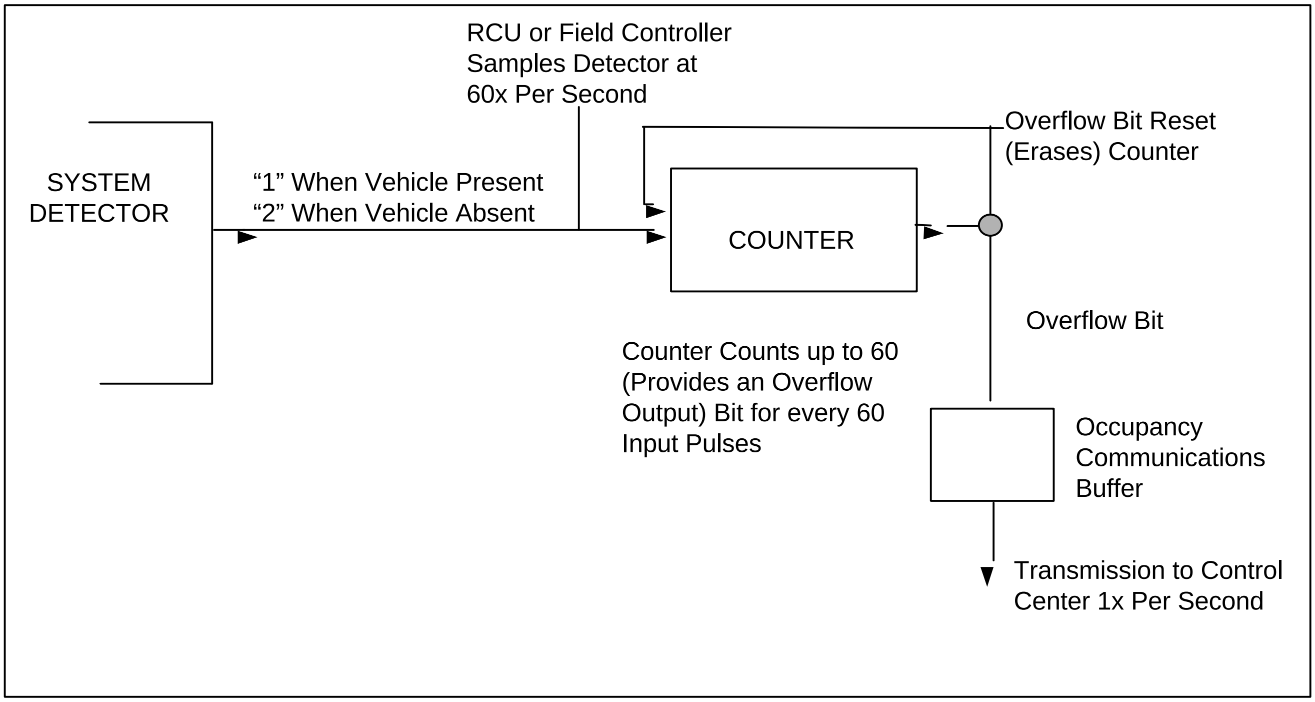

Figure 4-5 Use of Overflow Bit to Reduce Communication Requirements

Symbol	Definition
C	Maximum number of controllers on channel.
D	Maximum number of system detectors per controller.
F	Number of discrete controller functions to be provided
L	Maximum number of local detector inputs to controller to be reported.
P	Maximum number of push button inputs to controller to be reported.
TI	Total inbound bytes per controller.
TL	Total functional bytes per controller per poll.
TO	Total outbound bytes per controller.
Integer	Integer operator (obtain the interger portion of the function within parenthesis).

Function	Bytes Per Controller per Poll
1. Outbound message	Integer (1.44 in C + 0.99)/8
a. Controller address	
b. Number of discrete controller functions to be provided (F)	Integer (1.444 In F + 0.99)/8
TOTAL OUTBOUND	TO = Integer (a + b + 0.99)
2. Inbound message	
a. System detector occupancy	
1) Full accuracy data report	
a) Occupancy	0.75 D
b) Count, end of vehicle indication, and chatter	0.375 D
2) Overflow technique (Figure 4-5)	
a) Occupancy	0.125 D
b) Count, enc of vehicle indication,	0.375
and chatter	0.125 L
b. Local Detector Call	0.125 P
c. Push Button Call	T = Integer (a.1 or a.2 + b + c)/8 + 0.99)
TOTAL INBOUND	TL = TI + TO
3. Total functional data load per controller per poll	

Table 4-4 Functional Data Requirements for Traffic Signal Systems with Short Polling Times and Limited Field Storage Capability

Long Polling Times and Robust Field Storage Capability

Communications systems with long polling times and robust field storage capability use polling and contention techniques to reduce the requirements and burdens on the communication medium. The two following sections discuss these approaches.

Polling Techniques

With the advent of greater capability to process and store information in the field, current designs often feature longer polling periods. Periods of ten (10) seconds to one minute, or one traffic signal cycle, appear common. Table 4-5 indicates the advantages and disadvantages of longer polling periods.

Since these systems feature more extensive data processing in the field, the field data base becomes larger. To facilitate the physical installation and maintenance of this data base, modern design practice generally provides for the ability to change the data base through the communication system. This downloading process, and the corresponding uploading process (inspection and verification of the data base at the control center) becomes an additional communication requirement for systems of this type.

Advantages

·Usually result in a lower data rate requirement for each field unit to perform the same functions.
·Enable more field units to be serviced by a communication channel of given bandwidth or data rate.
·Provide a signal to select the appropriate timing plan from the field controller's memory rather than providing interval or phase control signals.*
·Enable higher resolution surveillance data to be communicated.
·Avoid use of data overflow schemes of the type shown in Figure 4-5.

Disadvantages

·Require more extensive processing of data for the field devices.
·Require larger field data base.
·Require capability to store a greater number of timing plans.

Table 4-5 Advantages and Disadvantages of Longer Polling Periods *Note*

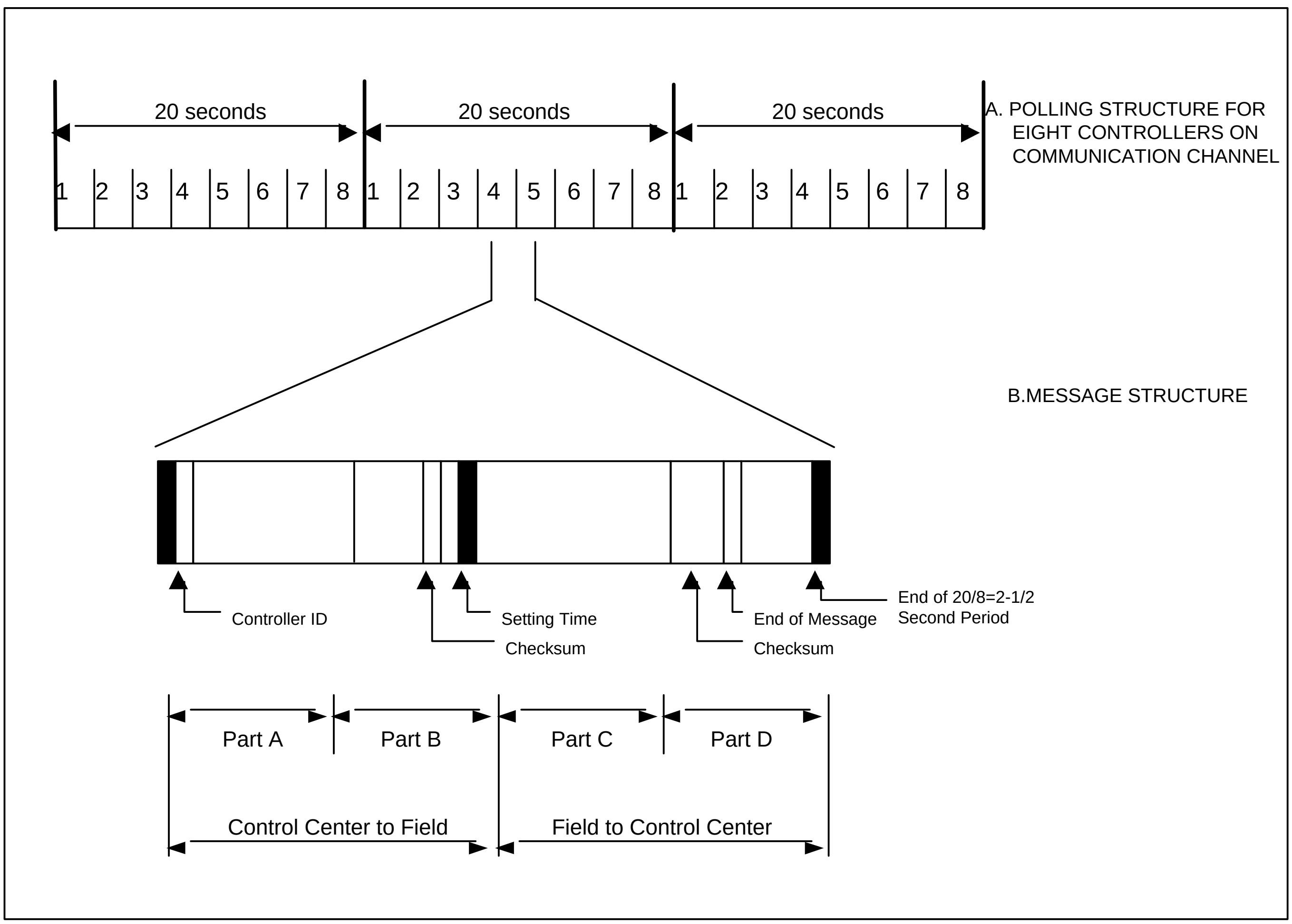

Figure 4-6 Example of Protocol Structure for Systems with Long Polling Intervals

This type of system does not use conventional polling message structures for data base changes (see Chapter 5) due to:

- the extensive field data base
- relatively infrequent data base changes
- need for changes in only a few variables

Instead, an identification code precedes the information to be downloaded.

Example

Figure 4-6 shows one method for implementing download/upload features.

The example in Figure 4-6A shows up to eight controllers serviced on a communication channel. This system polls each controller every twenty seconds.

Figure 4-6B shows the message structure. Parts A and B contain messages from the control center to the field. Part A contains the same variables during each polling cycle with the first portion consisting of a controller identification code. When this code matches the code contained in a particular field controller, it operates on the remainder of the message, while the remaining controllers on the channel ignore the message.

Part B of the message carries downloaded information or requests information for uploading. A code identifying the particular variable precedes the variable value. An additional bit identifies whether the value is to be uploaded or modified by the field controller. Because capability for only six downloaded variables is provided in this example, download of the entire data base may require several minutes. Part B also contains a checksum, used for communication error detection. In addition, Part B contains a period during which no information is transmitted, which serves as a "turnaround time" to allow the modems to reverse the transmission direction.

Parts C and D transmit information from the field controller to the central computer. Part C communicates the same variables during each polling cycle and Part D contains the capability to transmit up to six uploaded data base parameters per cycle. Part D also contains a checksum. The interval between the end of Part D and the start of the message for the next controller serves as the turnaround time.

Because systems with long polling cycles generally have a greater capability for autonomous operation, they usually require provision for time referencing the controller to an absolute time reference or to the central computer's time reference. One technique uses a periodic time reference message "broadcast" to all controllers on the channel. This reference may be embedded into the standard polling cycle.

Table 4-6 shows the equations and techniques for estimating the functional communication requirements for this type of surveillance and ramp metering system using a Type 170 controller (or one with similar capability) for field detector processing and ramp meter control. As for the signal control system, add the requirements for data transmission and link control (see Data Transmission and Link Control, page 2-23), error detection and control (see Error Detection and Control, page 2-20) and capability for requirements growth.

Appendix B provides spread sheets for assessing the preliminary communications design of freeway systems of this type with long polling cycles.

Contention Techniques

Previously described systems with short polling times and limited field storage capability require relatively rapid transfers of all communicated information, and this make efficient use of polling techniques. However, systems with a strong capability for information storage and processing requires less frequent information transfers. Furthermore, for most purposes, a more random relationship among the communication timing sequences to the different controllers in usually acceptable.

Under these conditions, conventional polling techniques result in a larger proportion of the messages carrying old, unnecessary information (i.e., no state change or new event has occurred since the last poll). An alternative approach, one in which a station on a channel communicates when it has a need, may provide more efficient use of channel capacity. Since termed “contention” techniques. Table 4-7 provides a comparison of several contention techniques.

With contention techniques, as the total demand begins to approach the channel capacity, delays to access the network increase greatly. In addition, depending on the technique used, the channel throughput may decrease with increasing demand. To assure acceptable communications service for traffic systems, the total demand should be held well below the system’s maximum throughput capability. Restriction of demand to no more than 50% of throughput capacity usually assures acceptable service.

Symbol	Definition
C	Maximum number of controllers on channel.
D	Maximum number of system detectors per controller.
F	Number of discrete controller functions to be provided
L	Maximum number of local detector inputs to controller to be reported.
P	Maximum number of push button inputs to controller to be reported.
TI	Total inbound bytes per controller.
TL	Total functional bytes per controller per poll.
TO	Total outbound bytes per controller.
Integer	Integer operator (obtain the interger portion of the function within parenthesis).

Function	Bytes per Controller per Poll	Typical Requirement
1. Outbound message		
a. Controller address	Integer (1.444 InC + 0.99)/8	0.5
b. Time or synchronization	Varies with design	3.0
c. Mode and metering plan selection	Varies with design	0.75
d. Reset detectors	0.125	0.125
e. Special functions and spares	Varies with design	2.0
f. Download	Typical: 6 Info bits + 6 ID bits/poll	12.0
TOTAL outbound bytes per poll per Controller	TO = Integer (a+b+c+d+e+f+0.99)	

Table 4-6 (Part 1 of 2) Functional Data Requirements for Freeway Surveillance Systems with Long Polling Times and Type 170 Controllers

Function	Bytes per Controller per Poll	Typical Requirement
2. Inbound message		
a. Metering mode identification	Varies with design	0.25
b. Processor failure/bulb failure	Varies with design	0.25
c. Metering rate implemented by controller	0.375 to 1.0	0.50
d. Outbound communication error	Varies with design	0.125
e. Spares	Varies with design	2.0
f. Upload	Varies with design Typical: 6 info bits	6.0
g. Requirements per detector and trap		
1) Occupancy and detector failure status		0.875
2) Maximum count/poll	Integer (1.443 In(0.8T) + 0.99)/8	0.50
3) Speed trap and failure status		0.875
4) Total detector bytes per controller	D (g1 + g2 + g3)	N/A
TOTAL inbound bytes per poll per controll	TI = Integer (a+b+c+d+e+f+g+0.99)	
3. TOTAL function data load per controller per poll	TL = TI + TO	

Table 4-6 (Part 2 of 2) Functional Data Requirements for Freeway Surveillance Systems with Long Polling Times and Type 170 Controllers

Technique	Characteristics	Throughput (Ref. 20)
1. Aloha	Station transmit data when it desires (no restrictions on initiation of transmission) Results in a large number of message collisions.	Approximately 14% of channel capacity
2. Slotted Aloha	Transmission occurs on demand but only at specified time boundaries	Approximately 37% of channel capacity.
3. Carrier Sense Multiple Access (CSMA)	Station must wait for clear channel before transmitting. If two stations transmit nearly simultaneously, both detect collisions. Transmission terminates and a retrans-mission attempted after a random delay. If repeated collisions occur, transmission delay increases.	Approximately 50% to 90% of channel capacity

Table 4-7 Contention Techniques and Characteristics

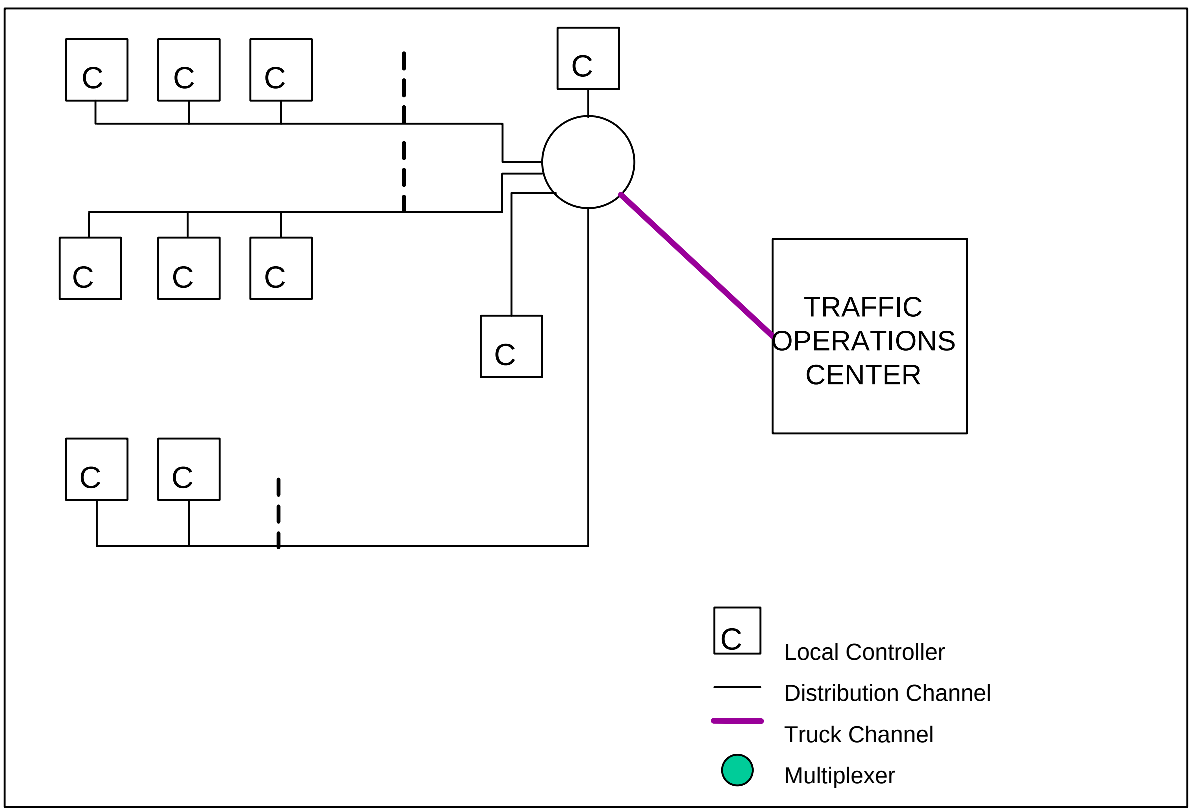

Figure 4-7 Trunking Configuration and Distribution Channel

Contention techniques have not generally been used to date for traffic control system communications based on owned land lines or leased telephone channels. Their use has been largely restricted to certain area radio network and spread spectrum radio systems (see Chapter 7) designed with multiple classes of applications in mind.

Trunking and Distribution System

Local controllers or RCUs for intersection and freeway systems typically use communication channel rates ranging from 1200 bits/sec to 9600 bits/sec.

In many cases, data from these channels must traverse a considerable distance. When this occurs, the designer can attain economies in the cost of both owned and leased communication systems when data from a number of local communication channels (termed "distribution" channels) is combined into a higher throughput channel or several such channels.

Trunking occurs when this combination takes place at a single point by means of a multiplexer. If the distribution channel uses multiplexing, the trunk multiplexing operates at a higher data rate. Figure 4-7 shows an example of this concept.

When high capacity channels have the capability to service a number of "drops" or distribution channels, the high capacity channel is usually termed a "backbone". Backbones may be configured in a number of topologies, as shown in Chapter 6.

The backbone usually carries field information directly to the control center. Connections between the distribution and backbone channels take place at a "hub" or "node". Equipment at these points converts the distribution channel signals to backbone signals. In cases where no right of way to the traffic operations center exists, leased channels can carry signals from field backbones to the TOC.

Because of its extensive capacity, the backbone system usually carries all of the communication requirements including data, voice, video and video controls. Figure 4-8 shows an example of the connection of field equipment to a hub. The channel bank and multiplexer adapts the different input signals to the backbone transmission requirements. Note that the figure shows the transmission of coded TV multiplexed to the same fiber as the other distribution channels.

Equipment at the traffic control center demultiplexes the signal into its appropriate components. If the total data channel rates exceed those which a computer serial port can handle, the channel bank provides the data on several serial ports. Alternatively, the data can interface to a computer bus using interface equipment provided by the computer manufacturer.

Chapter 6 describes fiber optic and T-system carrier technologies, among others, as providing capabilities higher than 1 Mbps. Trunking and backbone applications typically use these technologies.

Failures in trunking and backbone systems, unless redundant, may cause the simultaneous loss of communication with large numbers of controllers.

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	Information Bits	Communication Control Bits	Error Control Bits
1. CCU to RCU Message a. 3 message bytes b. Check sum byte	24	9 3	8
2. RCU to CCU Message a. 7 message bytes b. Check sum byte	56	21 3	8
TOTAL	80	36	16

Table 4-8 Overhead Analysis

$$\text{Overhead} = \frac{36 + 16}{80 + 36 + 16} = 39\%$$

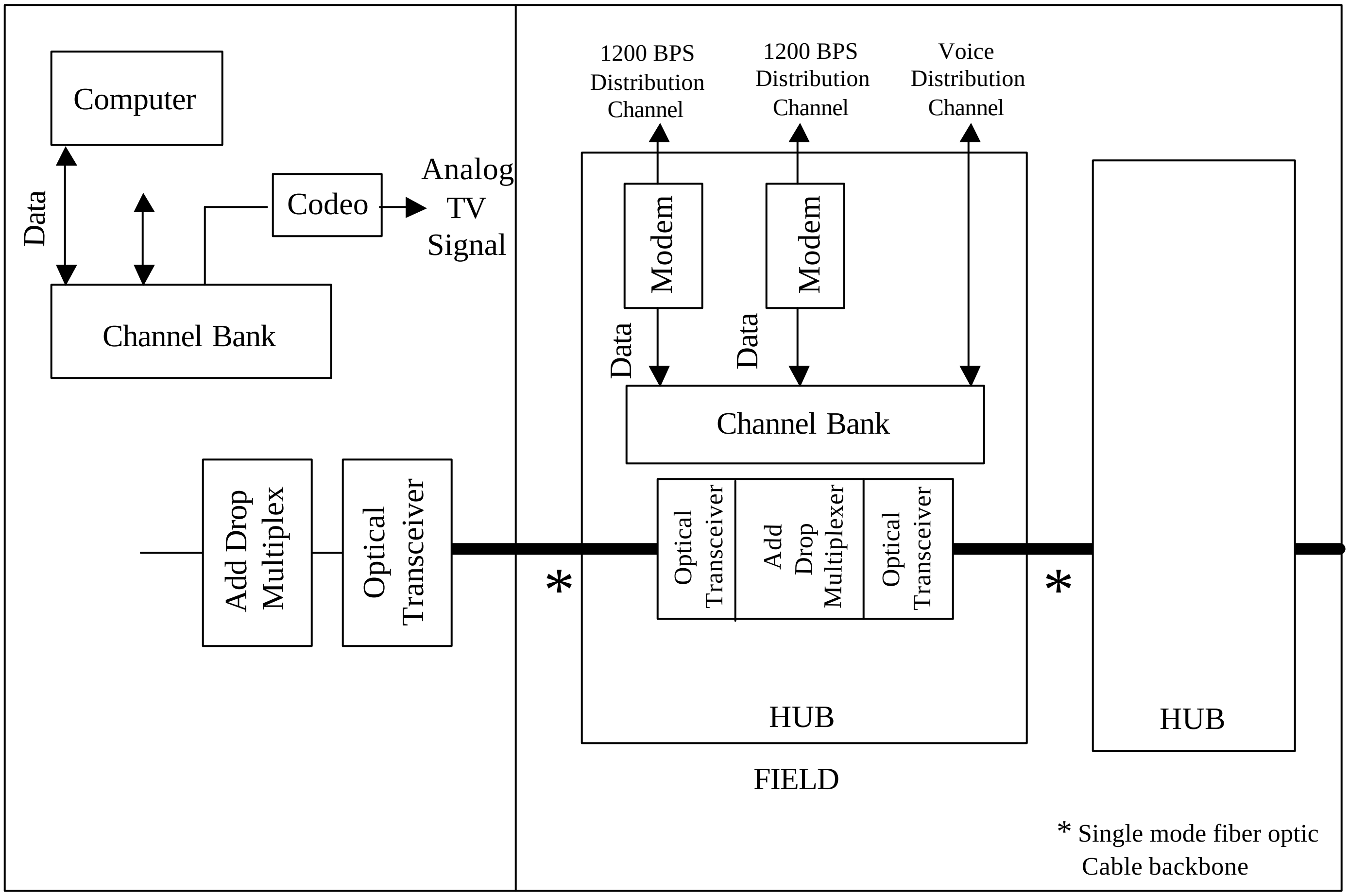


Figure 4-8 Device Connections to Bus Topology Fiber Optic Backbone

Communication Overhead Burdens

A data rate (e.g., 1200 bps) usually specifies the capacity of a communication channel. However, from the user's perspective, some value less than the data rate actually conveys traffic information. Some fraction of the data rate represents communication overhead required for flow and error detection purposes (see Error Detection and Control, page 2-20).

Overhead burdens of 40% or higher often typify the asynchronous transmission schemes used for traffic control. Table 4-8 provides an overhead analysis for the data formats in Figures 4-3 and 4-4.

Communications Requirements for CCTV

Background

Closed Circuit TV (CCTV) already forms an integral part of many traffic control applications, with roadway monitoring, incident verification, and security as common functions. The primary components of a closed circuit television system include:

- Cameras mounted on poles or existing structures (buildings, overpasses, etc.) at field locations.
- Camera accessories, including a pan (horizontal movement) and tilt (vertical movement) assembly.

- Monitors in the traffic operations center.
- Peripheral devices (video tape recorders).
- Communications (coaxial cable, fiber optics cable, or microwave transmission) to link field sites to the traffic operations center.

Since video requires much more bandwidth than the other voice and data functions typically provided by traffic control systems, CCTV frequently becomes the dominant factor in the communications network design.

In freeway traffic management systems, operators verify incidents increasingly via CCTV. Other recent trends show replacement of conventional vidicon tubes with solid state cameras to reduce maintenance needs and specification of compressed video techniques (CODEC) to reduce bandwidth requirements.

Full Motion Analog Video Transmission

Video cameras used for most traffic control applications conform to standards defined by the National Television Standards Committee (NTSC), which has defined the color television standard used in most of North America and Japan. NTSC video cameras generate an analog signal with the characteristics shown in Table 4-9.

Characteristic	Value
Bandwidth	4.2 MHz
Transmission Channel	6.0 MHz
Video Resolution	700 pixels (picture elements) x 525 lines
Aspect Ratio	4 : 3
Frame Update	30/second

Table 4-9 NTSC Standards

A variety of privately owned media (e.g., coaxial cable, fiber, microwave radio) or leased facilities can transmit full-bandwidth analog video and control (i.e., pan, tilt, zoom) signals (see Chapters 6 and 7 for further discussion). Often, a dedicated coaxial cable or fiber between the camera and the nearest communications hub transmits one baseband video signal. The same video channel or a separate communications channel may transmit control signals. Once a communications hub concentrates multiple analog video signals, a technique such as frequency division multiplexing can transmit them on a backbone to the traffic operations center. The coded TV options described below may prove more appropriate for a given traffic control application for a variety of reasons. For example, with leased communications facilities it may prove cost effective to code video to use less bandwidth. Similarly, applications which use a digital communications backbone for voice and data may benefit from using the same digital backbone for video rather than a separate analog video backbone. Finally, to provide a high quality video signal for some applications (e.g., video transmitted over a long distance) may require digital transmission since the latter regenerates signals to filter out noise rather than amplifying both the signal and noise as with analog transmission.

Freeze Frame Video Transmission

A wide variety of applications including traffic control have used freeze frame or slow scan video image transmission. In general, freeze frame techniques capture a black and white or color image and code it for transmission over standard voice grade telephone circuits or other narrowband communications media. After transmission, equipment reconverts the coded signal to a still image displayed on a television monitor.

Freeze frame transmission times range from a few seconds to several minutes depending on factors such as:

- the modem data rate,
- image resolution,
- black & white or color image, and
- shades of gray.

Table 4-10 presents scan times reported by one product vendor for color and black and white images when transmitted on a voice grade channel. For example, an NTSC monochrome image with a resolution of 512 x 480 and 64 gray scale levels (6 bit) would take 35 seconds to transmit (11). List price for the product described in Table 4-10 ranges upward from $5500 per unit depending on the options selected. Each video circuit requires two units (transmit and receive).

Monochrome	
Resolution and Gray Level	Transmission Time 525 Line
256 X 240X 6	35 Seconds
256 X 480 X 6 cr 8	76 Seconds
512 X 480 X 6 cr 8	152 Seconds
Color	
Resolution and Color Level	Transmission Time
512 X 240 X 6	72 Seconds
512 X 480 X 8	152 Seconds

Table 4-10 Representative Freeze Frame Scan Times (on voice grade channel)

Coded TV Transmission

<u>Video Compression Techniques and Standards</u>

Video compression techniques take advantage of data redundancy and human visual limitations to reduce the transmission bandwidth required to transport video signals. *Interframe coding* techniques eliminate redundancy between successive frames by transmitting only the differences between frames, while *intraframe coding* eliminates redundancy within a video field (12). For example, video compression may result in transmission of 12 frames per second rather than the 30 frames per second specified by the NTSC.

Today, video compression finds use most widely with videoconferencing systems, which package the algorithms as part of video coder-decoders (codecs) that convert analog video into a digital signal. A full-bandwidth analog video signal requires approximately 4.2 MHz of bandwidth, and nearly a 45 Mbps channel when digitized (13, 14). Compression allows transmission of a full motion digitized video signal at rates as low as 56 kbps, although extremely low rates may result in noticeable video quality degradation (12, 15).

Until recently, codec vendors had only implemented proprietary video compression algorithms, meaning codecs from different vendors could not be used together. However, the Consultative Committee for International Telegraph and Telephone (CCITT) H.261 recommendation defines a videotelephony standard which codec vendors currently implement, thereby providing interoperability. The standard, sometimes called Px64 ("P by 64"), supports data rates in multiples of 64 kbps, ranging from 64 kbps to 2 Mbps (16).

Coded TV Quality

Currently, no standard metric exists to judge the quality of coded video output. Two factors which influence a viewer's perception of video quality are *resolution* and *frame rate.* Many codecs which transmit video at rates of 384 Kbits per second or below provide a video resolution of 256 pixels by 240 lines, in comparison to the 700 by 525 NTSC resolution. The H.261 standard specifies a resolution of 352 pixels by 288 lines (15).

Frame rate refers to the number of times a display updates each second, with extremely low frame rates producing "jerky" motion sequences. While codec manufacturers include maximum frame rates as part of equipment specifications, the frame rate actually used for a particular video sequence changes adaptively based on the amount of bandwidth available and the amount of video processing performed by the video coding algorithms. For example, in a video sequence with much motion the codec might transmit fewer frames each second to compensate for the additional video processing required.

As part of a study performed for the Connecticut Department of Transportation, the quality of coded traffic surveillance video was evaluated for codec equipment from three manufacturers. Table 4-11 derives from the 1990 report and provides a summary of the codec equipment specifications and quality ratings (13). For the two codecs operating at 384 Kbits per second, the video quality for freeway surveillance and camera movement operations rated as either "good" or "excellent".

Codec can transmit video at even lower data rates, i.e., 64 and 128 Kbits per second. The picture quality at a given transmission rate varies with the manufacturer. Prior to preparing a specification, the user should attend demonstrations provided by the manufacturers to identify an acceptable transmission rate.

Much codec equipment designed for teleconferencing needs does not satisfy NEMA environmental requirements for traffic equipment. The designer must specify appropriate environmental enclosures to use this equipment in the field.

Cost

Table 4-11 provides representative costs for the year 1990. The cost of video codec equipment continues to decrease and the demand for consumer products which use video codec technology will likely increase rapidly. One microelectronics vendor has already announced an H.261 compatible video codec chip set expected to substantially reduce the above costs by 1993.

Traffic Control System Applications

Codec provides video quality sufficiently high for traffic monitoring applications without the need for owned land lines. Where only critical locations require TV surveillance, codec becomes an attractive alternative. For example, where a freeway surveillance system uses spread spectrum radio or leased lines for data applications, the communications network could transmit codec information from several cameras to the control center. The capitalized cost of such a system may prove lower, in many cases, than for a communication system based on owned land lines.

Name	Rembrandt 11/06	Teletraveler	C300
Manufacturer	Compression Labs	Concept Communications	Picture Tel
Video Resolution (pizels)	256H x 240V	256H x 200V	256H x 240V
Color	Yes	Yes	Yes
Data Rate	56-384 Kbps	56-768 Kbps	56-384 Kbps
Maximum frame Rate	15 fps	3 fps	10 fps
Compatible with Proposed CCITT Standard	Yes	Yes	Yes
Power Consumption	400 watts	80 watts	400 watts
Operating Environment	32-115°F 15-85% Humidity	32-160°F 20-80% Humidity	50-104°F 15-80% Humidity
Video Quality * (freeway surveillance)	Good	Fair	Excellent
Video Quality * (camera movement)	Good	Poor	Excellent
Unit Cost	$31,500	$6,000	$19,500

Table 4-11. Connecticut Department of Transportation Codec Evaluation (Table Reproduced from (Ref.13))

** At highest possible data rate.*

Endnotes

1 (Popup)
Start bit and 2 stop bits will be added to each byte by CCU.

2 (Popup)
This timing plan select approach has also been used for short-term field storage systems.

CHAPTER 5 - COMMUNICATION ARCHITECTURES

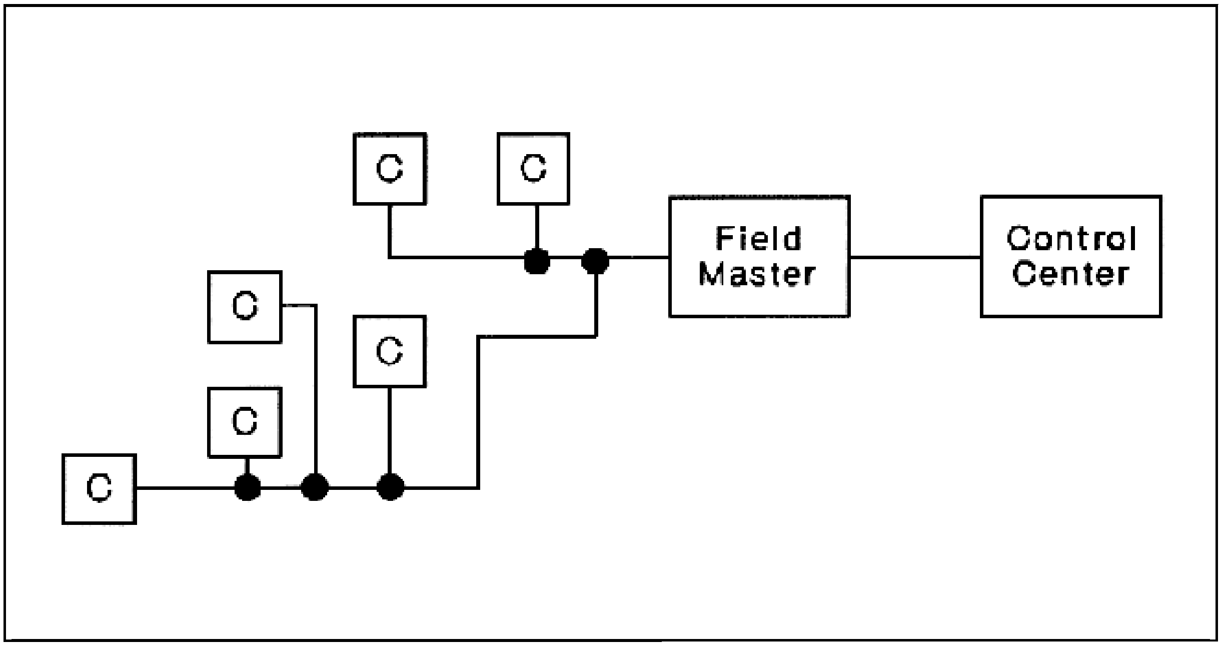


Figure 5-1 Communications System Architecture

Introduction

The communications system generally proves the most critical and expensive component of a traffic control system. To implement a successful communications system, the designer must select an efficient and cost effective communications architecture.

Need

The transportation professional must understand the various communications architecture alternatives and how they fulfill traffic control functional objectives and system requirements.

Purpose

This chapter presents technology and architecture alternatives for traffic control systems. It allows the transportation professional to relate traffic system requirements to communication architectures.

Organization

The chapter first classifies system architectures and then presents examples of each. Table 5-1 summarizes the chapter organization.

Select Title	Purpose	Topics
Classification of Communication Architecture	Defines and describes major communication architecture types	Central Distributed - Trunked/Backbone Hybrid
Examples	Shows relationship of representative traffic architectures to communication architecture	Central architecture and short polling cycle - Signal system - Freeway management system Central architecture and long polling cycle - Freeway management system (ramp metring) Distributed architecture - Closed loop signal system Traffic control processing functions
Summary of Common Applications of Communications Architecture	Correlated system requirements and system architectures with communication architectures with	Comparison table

Table 5-1 Organization of Chapter 5

Classification of Communication Architectures

Communication architectures for traffic control systems fall into three major classifications:

- Central
- Distributed
- Hybrid

The following sections describe these architectures.

Central Architecture

A system possesses a *Central Communication Architecture* if:

- Only one level of computation occurs prior to the signals reaching the field controller.
- One communication protocol exists between the control center and field controller.
- One data rate exists between the control center and field controller.

Figure 5-2A illustrates a central architecture.

Distributed Architecture

A system features a *Distributed Communication Architecture* if:

- Multiple levels of computation exist in the field (see Figure 5-2B), or
- The data rate changes between the control center and field controller.

A communications system is *trunked,* a form of Distributed Architecture, (see Figure 5-2C) if:

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

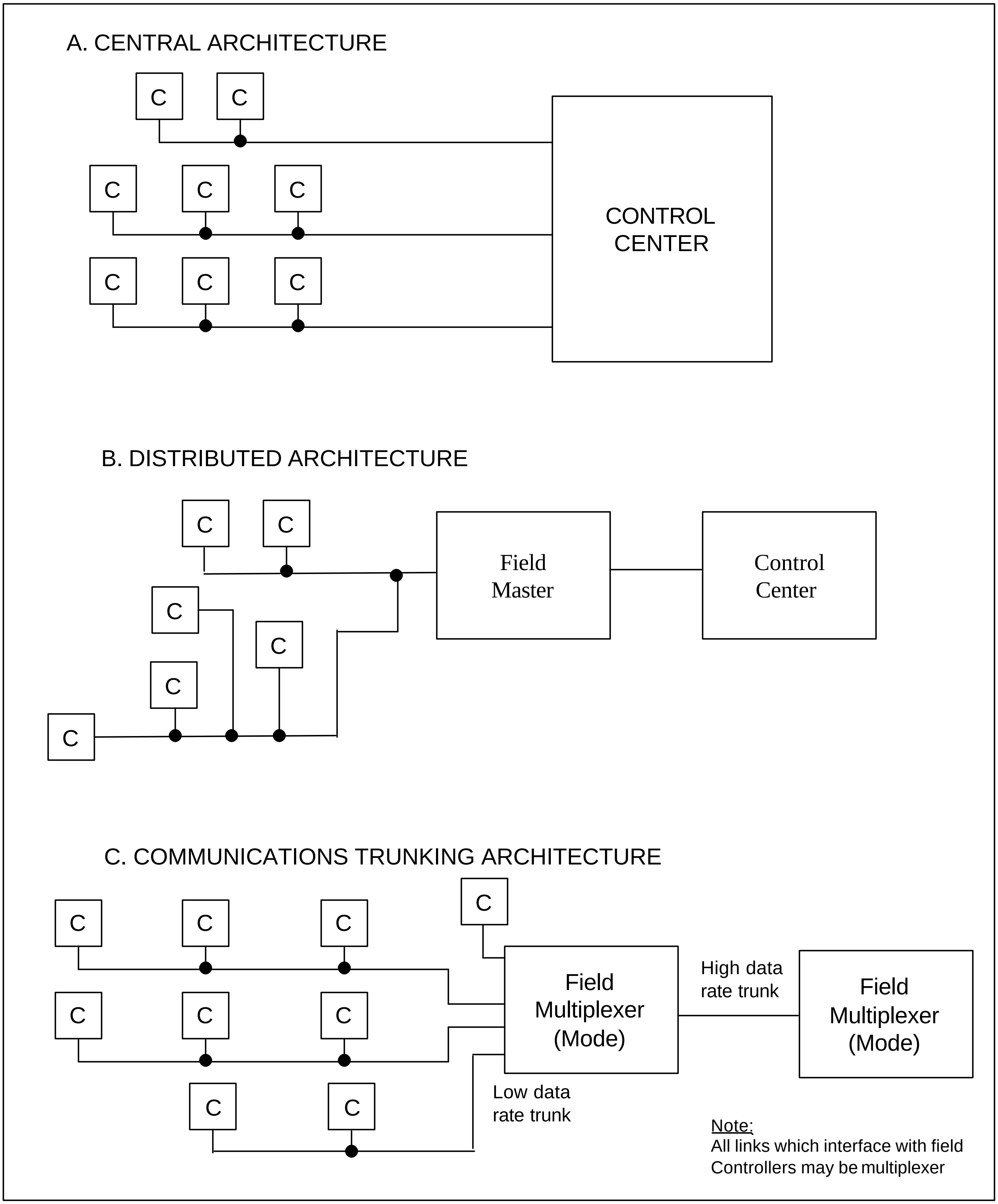


Figure 5-2 *(Sheet 1 of 2)* Architecture Classifications

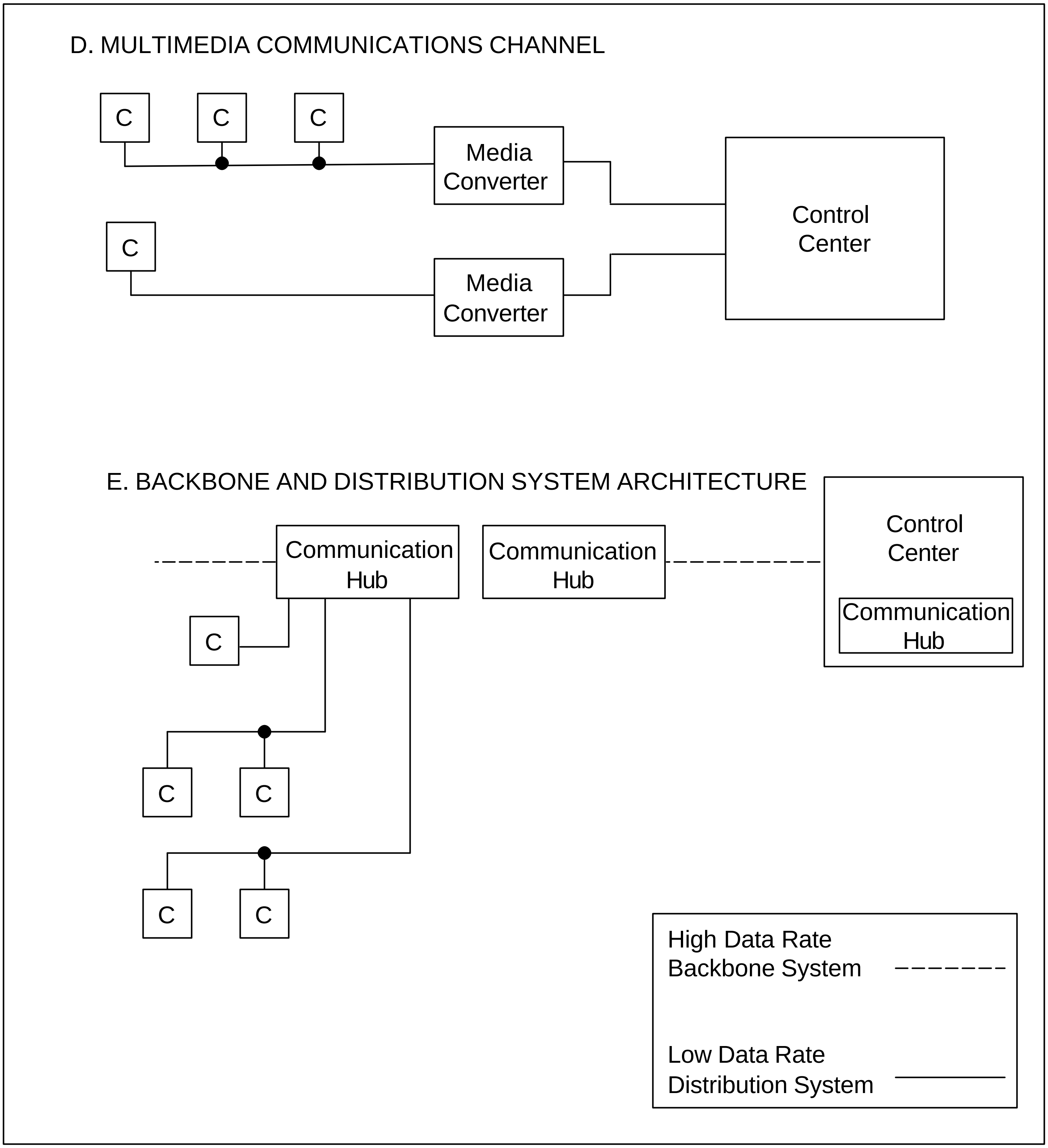


Figure 5-2 *(Sheet 2 of 2)* Architecture Classifications

Hybrid Architecture

If portions of the system feature both of the above characteristics, then it has a *Hybrid*

Architecture.

Backbone

Another form of distributed communications architecture using multiple data rates is *backbone* based, as shown in Figure 5-2E. The high data rate backbone connects a series of field communication hubs or nodes. Equipment at each hub transforms these high data rate channels into a greater number of low data rate *distribution* channels.

Multimedia

If more than one medium makes up the communications path between the control center and Field Controller without altering the data rate and transmission protocol, then the system features a *multimedia* communications channel (see Figure 5-2D). Channels of this type do not affect the architecture definition.

Examples

This section presents example communication system architectures in the context of their traffic control functions.

Chapter 4 describes traffic system requirements in terms of short term polling and longer term polling requirements. The field controller and other equipment as well as functional requirements dictate distinction.

Example 1

Figure 5-3 shows a typical example of a signal system with a central architecture and short polling cycle. Many current systems of the UTCS type with NEMA controllers use this architecture. Chapter 6 further describes system characteristics. This general architecture has also seen use with other media such as coaxial cable and fiber optics, but usually with higher data rates.

Example 2

Freeway surveillance and control systems have used similar control architectures as shown in Figure 5-4. The system shown uses a proprietary protocol with a non-standard data rate.

Example 3

Figure 5-5 shows a freeway surveillance and ramp meter control system using a central architecture with a longer polling cycle. The system includes:

- One communication channel via leased voice grade telephone lines. The lines are split at one Telco central office to run to Telco central offices 2 and 3 situated closer to the field equipment.
- Type 170 Controller and its peripherals that provide the modem, detectors and input-output circuitry to service the field equipment.
- Use of a leased T1 communication channel for the television camera(s) (see Chapter 6). This channel can carry digital information at a rate of 1.544 Mbps. A codec device (Chapter 4) codes the analog TV signal into digital pulses and decodes it in the control center.
- A communication service unit/data service unit (CSU/DSU) to interface with the leased

T1 lines.

- A 9.6K bps traffic control channel using leased service to a field site. The field site Transmits data by spread spectrum radio (Chapter 7) to controllers on the freeway.
- Occasional use of spread spectrum radio repeaters to overcome power level and line of sight limitations.

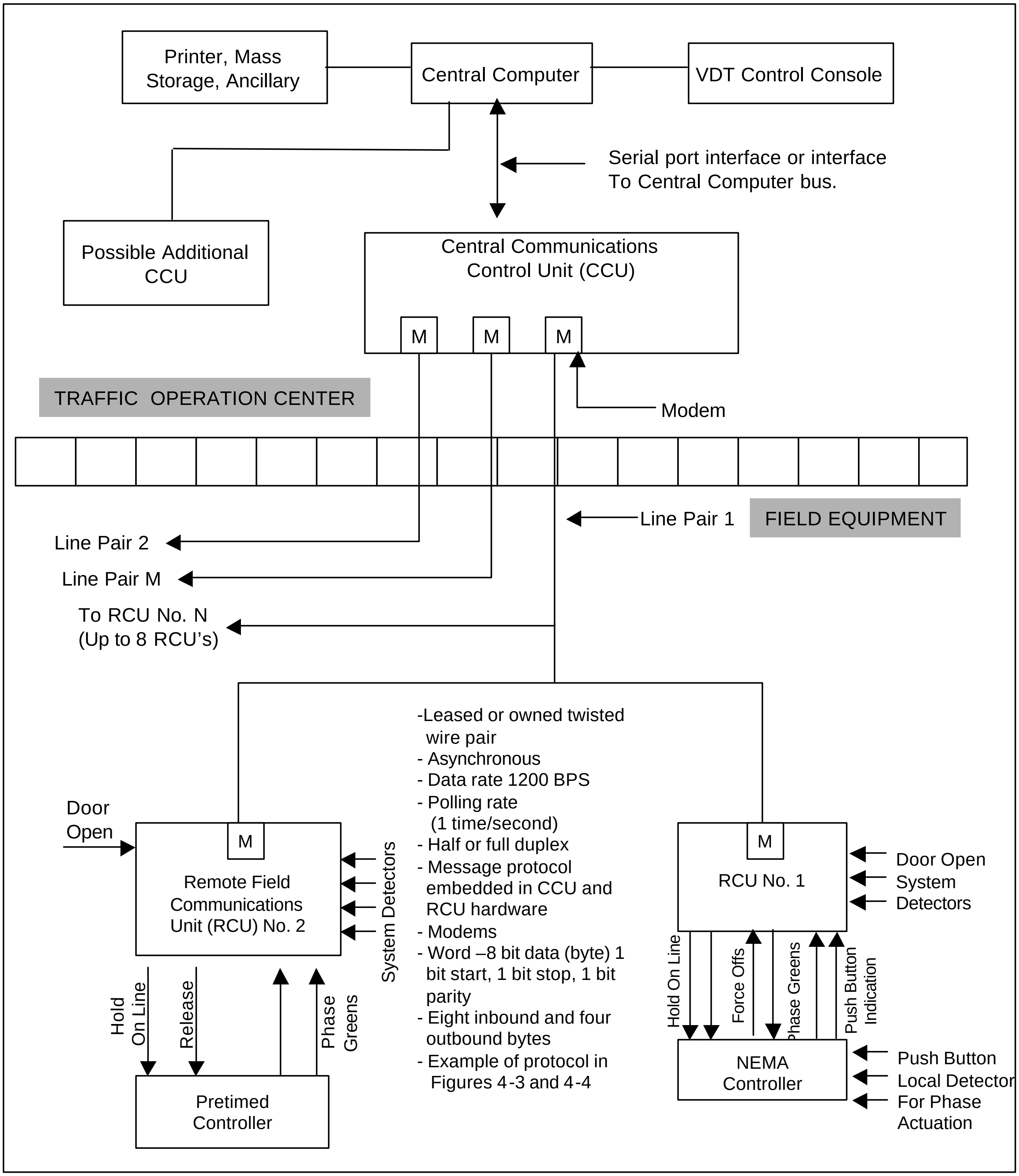


Figure 5-3 Example of Central Control Architecture for Signal Systems Short Term Field Storage

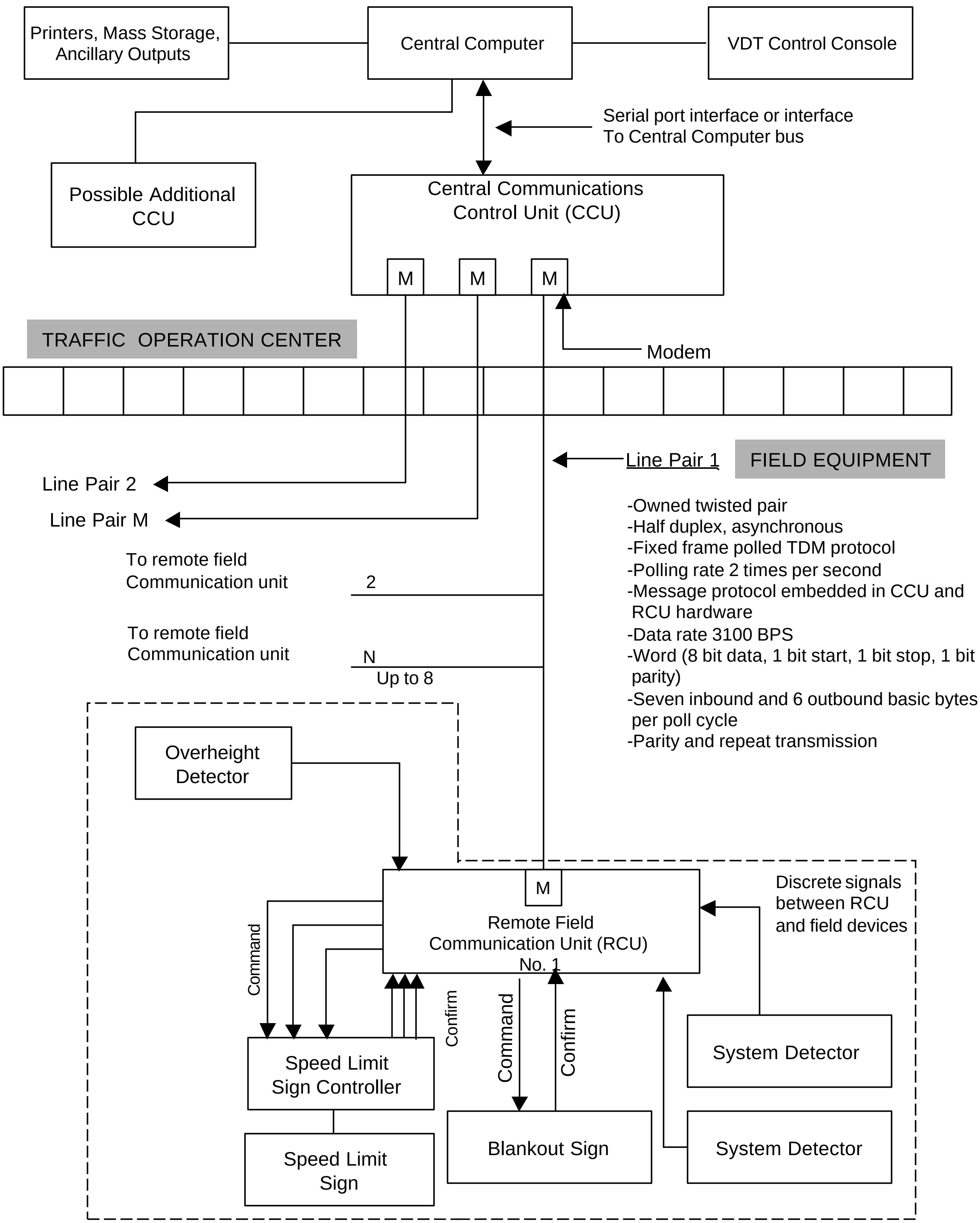


Figure 5-4 Example of Central Control Architecture for Freeway Systems with Short Term Field Storage

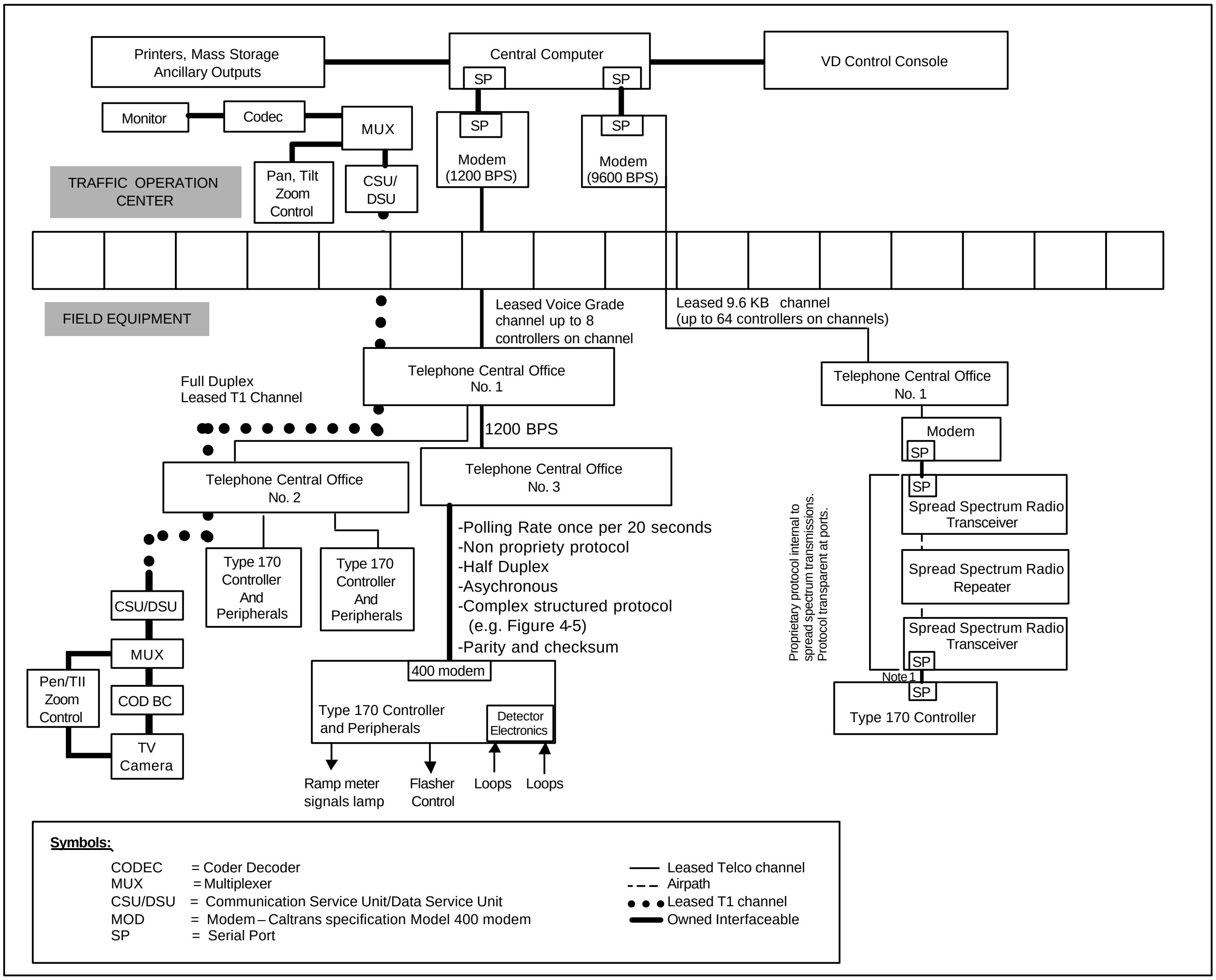


Figure 5-5 Example of Central Control Architecture for Freeway Systems with Long-Term Field Controller Storage

Example 4

Figure 5-6 depicts a closed loop system, an example of a distributed architecture for signal systems (Chapter 4). Traffic controller manufacturers commonly provide systems of this type. Table 5-2 (Ref. 17) compares location of functions in a closed loop system with a traffic operations center based central architecture system.

Summary of Common Applications of Communication Architectures

Table 5-3 summarizes common applications and examples of the communication architectures described in this chapter.

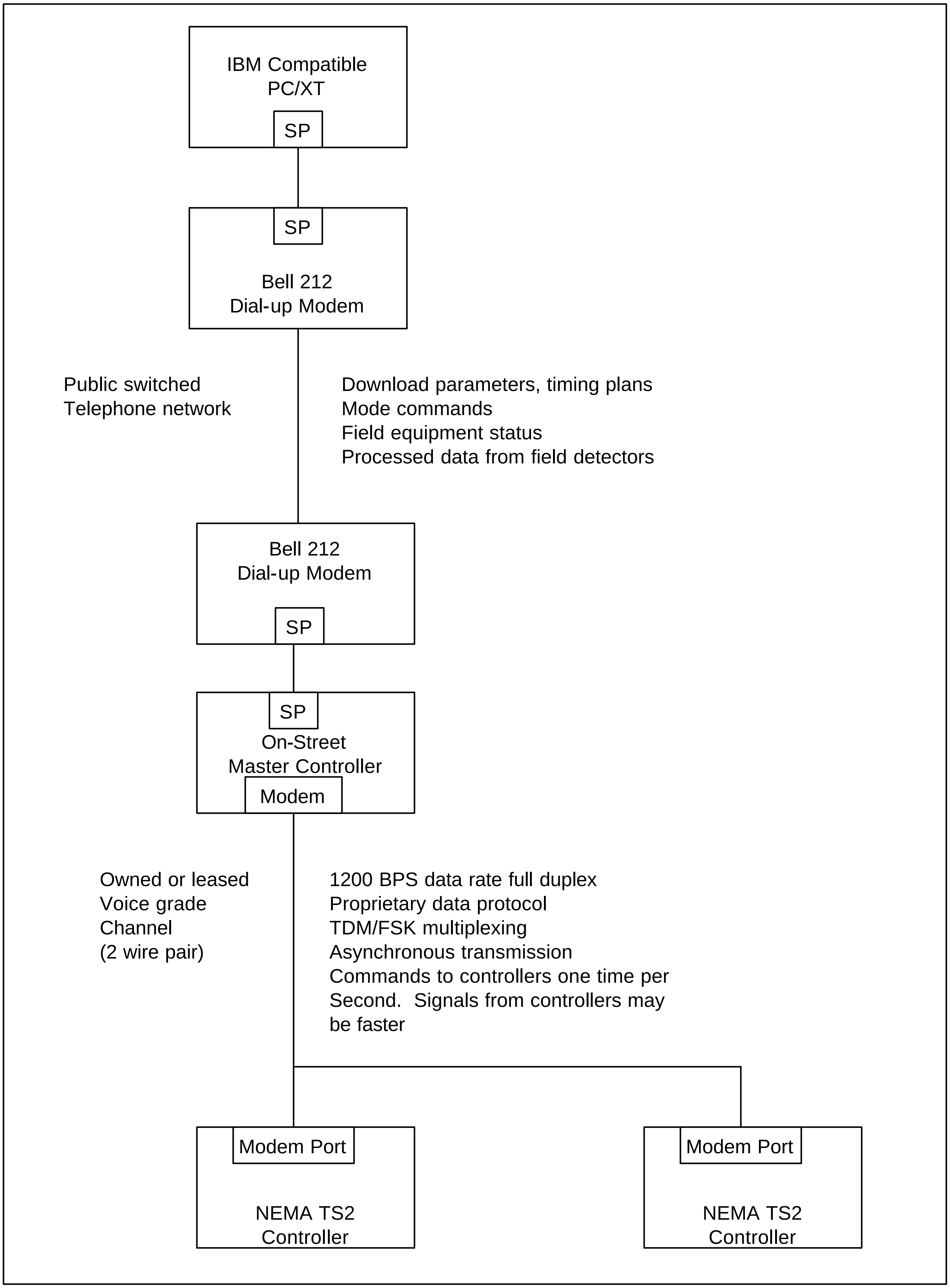


Figure 5-6 Distributed Communication Architecture

PROCESSING FUNCTION	CENTRAL COMPUTER BASED SYSTEM	CLOSED LOOP SYSTEM		
		CENTRAL	MASTER	LOCAL
CONTROL				
Manual selection of signal timing	✓	✓		
Using detector data to select signal timing	✓		✓	
Time-of-day selection of signal timing	✓		✓	
Control of timing for each signal phase	✓		✓	
Sequencing for vehicle and pedestrian movements	(Local)			✓
Signal preemption for emergency vehicles	(Local)			✓
Upload/download of data to masters and locals	✓	✓	✓	
Off-line generator of timing using optimization programs	✓	✓		
MEASUREMENT OF TRAFFIC FLOW				
Monitoring local intersection operation	✓		✓	
Processing detector data to derive traffic flows	✓		✓	
Monitoring local intersection operation	✓	✓		
SYSTEM MONITORING				
Monitoring local intersection operation	✓	✓		
Display of system status on mimic maps or computer Generated graphics	✓	✓		
Graphic displays of signal phases and detector data	✓	✓		
Equipment fault monitoring	✓		✓	

Table 5-2 Traffic Control Processing Functions

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

Table 5-3 Common Application of Communications Architecture

CHAPTER 6 - LAND LINE ALTERNATIVES

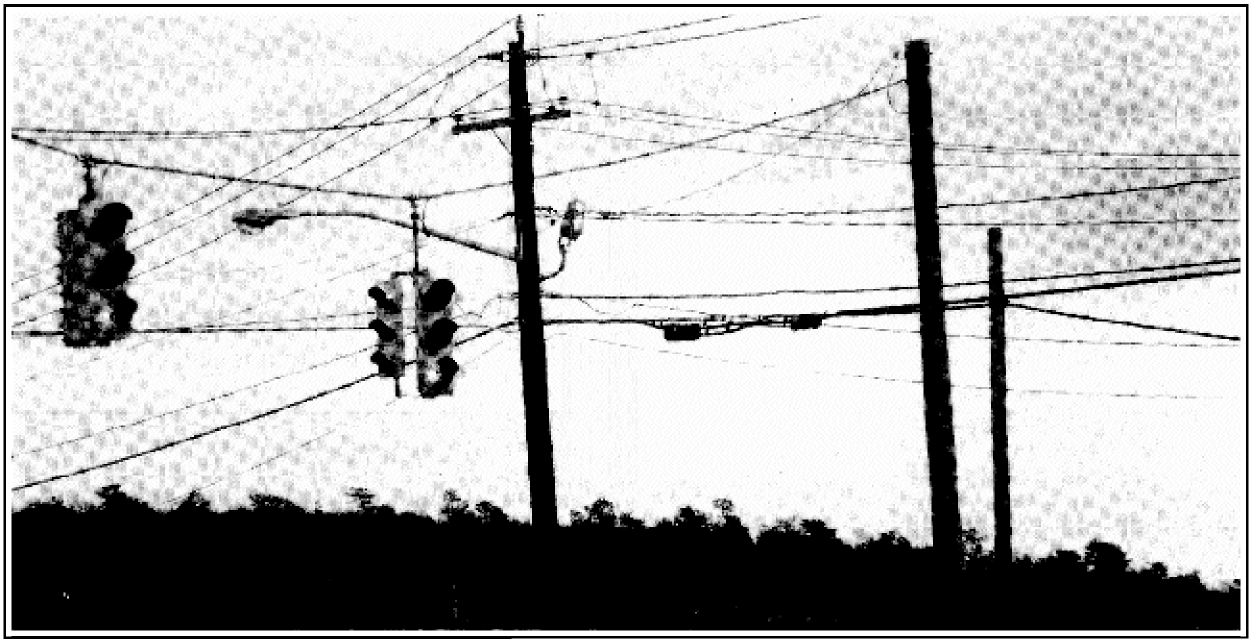


Figure 6-1 Telephone Company Lines

Introduction

Wire cable (land line), either leased or owned, represents by far the most prevalent form of traffic control systems communications medium. This chapter deals with land line communication techniques currently operational, being designed or considered for future use.

Need

Because land line alternatives predominate in traffic control systems, the transportation professional needs a thorough understanding of the associated technologies, characteristics, costs, options and design considerations.

Purpose

This chapter describes the relevance to traffic control systems of the following land line communication technologies:

- Voice grade analog channels
- Coaxial cable
- Fiber optics
- Leased lines

Organization

Table 6-1 summarizes the organization of this chapter.

Section Title	Purpose	Topics
Voice Grade Analog Channels	Describes the use of this medium in traffic control communications	Characteristics Twisted wire pairs Data communications equipment Noise and interference Design considerations Installation considerations Use of existing facilities
Coaxial Cable	Describes the use of this medium in traffic control communications	Characteristics Data communicatin equipment Design consideration
Fiber Optics	Describes the use of this medium in traffic control communications	Characteristics Cable options Data communicatins equipment - Transmissers and receivers - Modems and repeaters - Standards - Multiplexing Examples - Network-topology - Media - Transmission systems Conclusions
Leased Line Options	Describes the use of this medium I traffic control communications	Characteristics Local exchange carriers Cable TV providers Alternative metropolitan area network vendors
Future Directions	Describes trends in the communications marketplace	Fiber to the curb/home Competition in the loop

Table 6-1 Organization of Chapter 6

Voice Grade Analog Channels

Owned or leased voice grade channels have proven the most commonly used technology for traffic control system communications. Owned channels usually consist of twisted wire pair cable. The jurisdiction obtains leased voice grade channels, shown in Figure 2-14, from the local exchange carrier (LEC), i.e., the local telephone company.

Characteristics

Characteristics of voice communications include:

- two-way conversation,
- relatively low speeds, and
- wide dynamic range.

Echoes, phase changes and noise, unless extreme, do not disrupt voice communication. On the other hand, digital data is characterized by:

- high speeds,
- relatively narrow dynamic range, and
- a higher sensitivity to errors.

Depending on the modem type used to transform it to an acceptable analog form, digital data can exhibit strong sensitivity to short bursts of noise and phase changes.

Voice grade channels most commonly use serial data transmission employing time division multiplexing (TDM) with frequency shift keying (FSK) modulation. Data rates up to 3100 bps have been used with FSK for traffic control systems; however, rates of 1200 bps appear most common.

Twisted Wire Pairs

Twisting insulated copper conductors into pairs reduces electrical interference since the conductors produce fields that tend to "cancel out". A binder group consists of a number (i.e., 25) of color coded twisted pairs stranded together. The amount of twist applied to pairs within a binder group varies to reduce *crosstalk*, interference due to signal ingress in one communication channel caused by signal egress from an adjacent channel. Manufacturers twist multiple binder groups together around a common axis to increase the number of conductors in a cable.

Today, most outside plant copper cable conforms to either the Rural Electrification Administration (REA) or Bellcore electrical specifications. Table 6-2 summarizes some REA specifications with wire diameter described by American Wire Gauge (AWG) sizes. Most wire used for traffic system communications lies between 19 and 26 gauge (the larger the gauge, the smaller the diameter).

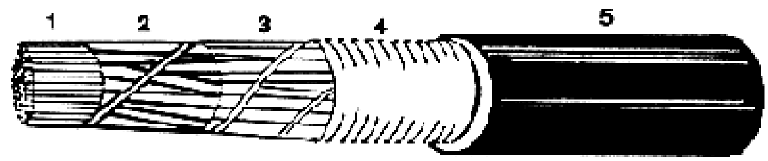
Table 6-3 provides representative data for multiconductor cable.

Number of Pairs	Cable Diameter (inches)	Cable Weight per Foot (lbs)	Year 1992 Unit Cost * (100 feet)
6	0.51	0.11	$ 32.39
25	0.78	0.28	$ 75.17
50	1.00	0.48	$ 129.33

Table 6-3 Copper Cable Dimension and Cost Data

* *Cost is for a 22 guage PE 39 cable with solid insulated conductors and a core that is filled with FLEXGEL filling compound for moisture protection.*

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.

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-inch 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 severe service areas. Cable includes a steel shield over the aluminum shield.

Table 6-2 Summary of REA Cable Specifications

Wire has resistance, and wire pairs have capacitance, both of which attenuate the signal. Attenuation depends on:

- Signal frequency,
- Conductor size,
- Cable length,
- Number of splices and connections

As the diameter decreases and operating frequency and cable length increase, attenuation in twisted pair cable increases. Attenuation results in loss in signal level between two points, which makes the signal more susceptible to other impairments, such as noise. The proximity of other wires, especially power cable often laid close to telephone lines, can introduce noise or interference.

The greater attenuation at the higher frequencies may result in a form of amplitude distortion. Attenuation distortion refers to amplitude distortion in standard voice grade channels.

Loading coils can reduce attenuation distortion by making attenuation more constant over a given frequency range. Figure 6-2 (21) shows attenuation characteristics as a function of gauge, frequency and loading. Where used, load coils are typically placed about every 6,000 feet.

<u>Example</u>

Figure 6-3 shows a system serving seven controllers on an owned twisted wire pair channel using time division multiplexing (TDM) with frequency shift keying (FSK) modulation.

The general characteristics of this design include:

- Use of TDM for multipoint addressing of controllers on the same channel.
- Use of AWG 22 twisted shielded wire pairs.
- Use of modems which conform to Bell 202 specifications. This provides FSK modulation and supports a half duplex two wire channel or a full duplex four wire channel. This design will use a two pair (four wire) channel.

Design parameters implied by these characteristics include: [1]

- Modem frequency of 1200 cps; space frequency of 2200 cps.
- Modem transmission levels settable at 0, -2, -4, -6 and -8 dBM.
- Receiver sensitivity range of 0 dBM to -40 dBM.
- Error rate less than 1 bit in 100,000 with a signal to noise ratio of 16 dB in the 300 - 3000 Hz range.
- Cable pair losses 1.8 dB/mile at 1200 Hz and 2.6 dB/mile at 2200 Hz (see Figure 6-2).
- Insertion loss at controller line drops typically measures 0.5 dB for this technology. Thus, the seven line drops represent 3.5 dB of loss.

The cable pair loss at 2200 Hz over the cable length equals:

2.6 dB x (distance to furthest drop in Figure 6-3) = 2.6 dB x (4 + 6 (1/3)) miles = 15.6 dB

Table 6-4 shows the power budget for this system.

Since the signals will be received in the range of 0 dBM to -19.1 dBM (which lies within the receiver's dynamic range), and the power margin remains sufficiently high to provide a suitable safety factor, this design appears acceptable.

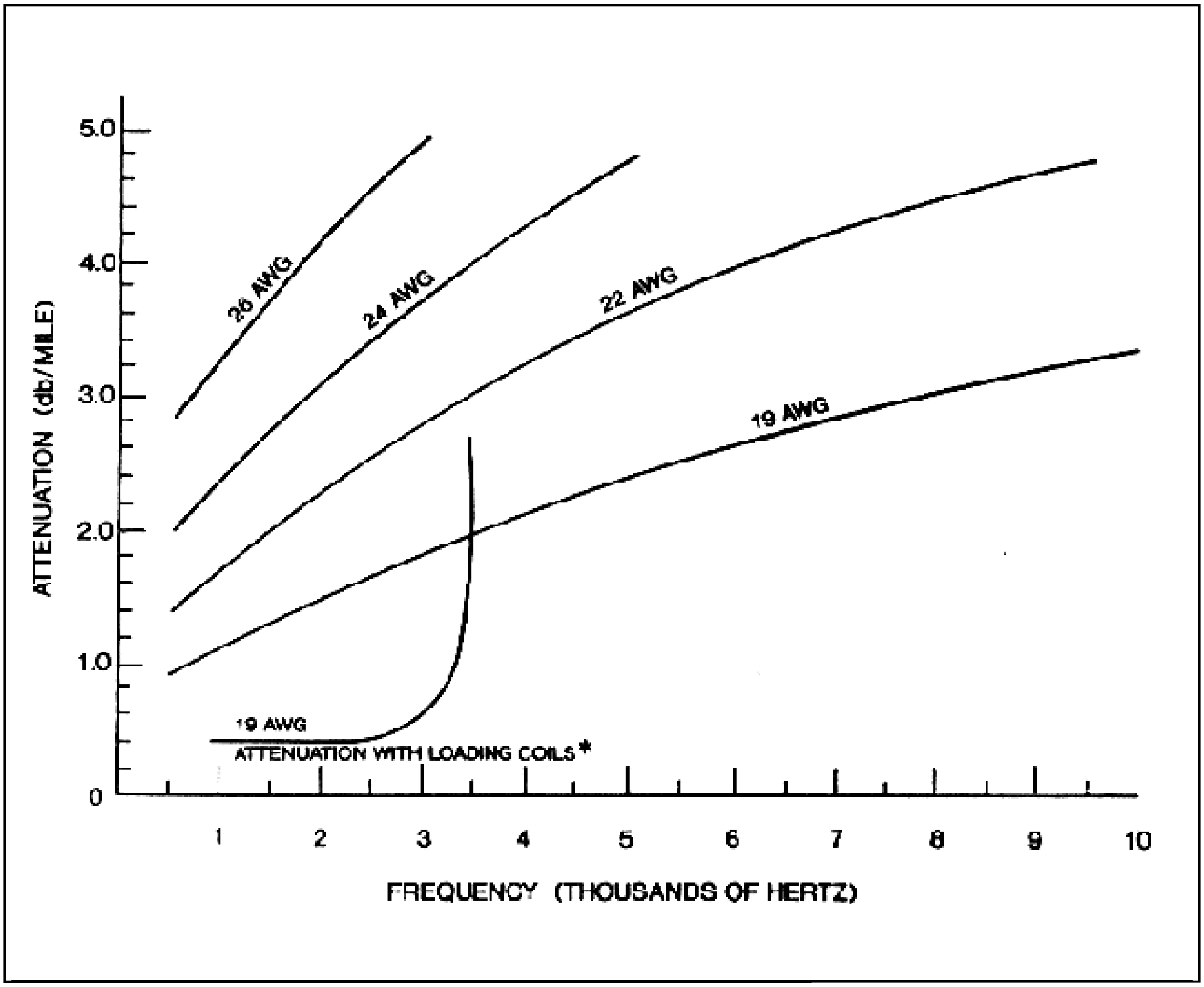


Figure 6-2 Attenuation Characteristics for Twisted Wire Pairs

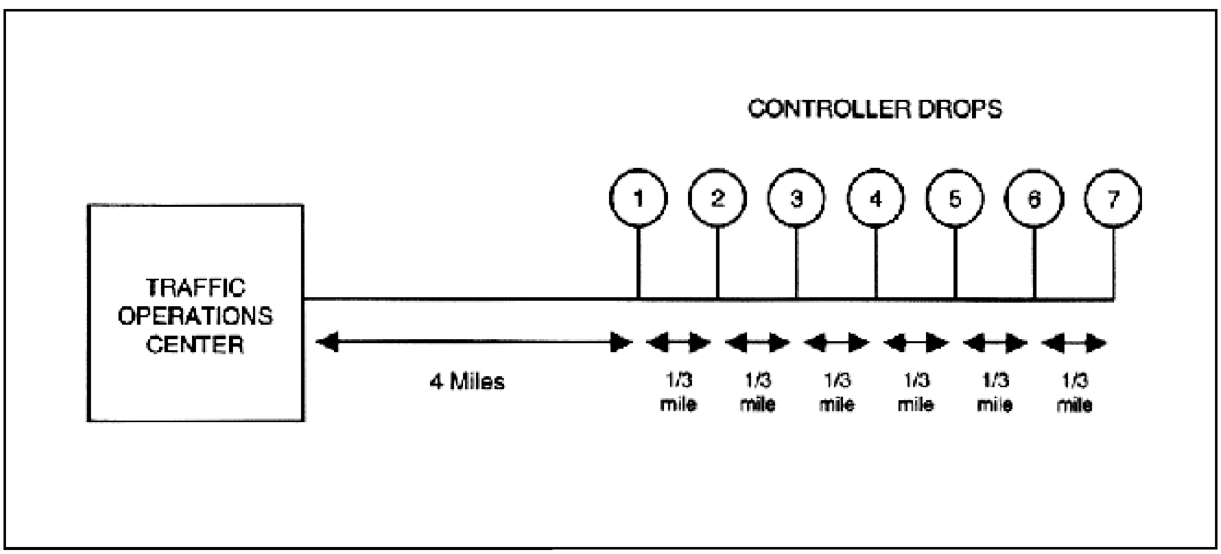


Figure 6-3 Geometric Layout for Example

Transmitter Power	0 dBM

Receiver Sensitivity	-40.0 dBM
Power Budget	40 dB
Cable Loss	-15.6 dB
Insertion Loss at Controllers	-3.5 dB
Power Margin	20.9 dB

Table 6-4 Power Budget for Illustrative Example

Longer cable lengths will, at some point, result in insufficient power margin and the design must include repeater amplifiers.

The more conservative approach for owned systems selects full duplex transmission using two wire pairs to avoid problems related to line reflections and turnaround time frequently encountered with single pair systems.

Data Communications Equipment

Standards

Chapter 3 describes the requirement to use specialized communication equipment such as RCUs in some designs, whereas other situations permit standard modems. Voice grade channels permit a number of available modem standards. A standard modem conforms in protocols, interfaces and signal transmission characteristics to those manufactured by Western Electric for the Bell System prior to its breakup or with the recommendations of the Consultative Committee for International Telephone and Telegraph (CCITT). Modems in this class typically were designed for leased or switched telephone lines but usually prove compatible with owned voice grade lines. A number of vendors can supply most standard modems. Table 6-5 (19) summarizes the characteristics of a number of popular standard modems; however, not all shown have found use for traffic system communications.

Equipment Alternatives

The following paragraphs describe twisted wire pair communication alternatives for NEMA and Model 170 controllers.

- NEMA Controllers

  Currently, manufacturer supplied closed loop systems based on NEMA controllers typically use two voice grade line pairs to communicate with up to 24 or more controllers and 24 or more system detectors. As shown in Figure 3-2, controllers built to the NEMA TS2 standard contain built in modems which communicate with a similar modem in the field master.

  A proprietary TDM/FSK multiplexing protocol with a 1200 BPS modem is common and the protocol and timing requirements usually differ among manufacturers. Thus, the user essentially remains tied to the initial supplier for future equipment support. Expansion of the system using controllers supplied by another manufacturer may or may not prove possible.

  When used in a closed loop system the NEMA controller processes system detector data and communicates the processed data to the field master along with controller status signals.

	Modem Type	Data Rate	Transmission Technique	Modulation Technique **	Transmission Mode * (Half or full duplex)
Bell System	103 A, E	300	asynchronous	FSK	Half, full
	103 F	300	asynchronous	FSK	Half, full
	201 B	2400	synchronous	PSK	Half, full
	201 C	2400	synchronous	PSK	Half, full
	202 C	1200	asynchronous	FSK	Half
	202 S	1200	asynchronous	FSK	Half
	202 D/R	1800	asynchronous	FSK	Half, full
	202 T	1800	asynchronous	FSK	Half, full
	208 A	4800	synchronous	PSK	Half, full
	208 B	4800	synchronous	PSK	Half
	209 A	9600	synchronous	QAM	Full
	212	0-300	asynchronous	FSK	Half, full
		1200	asynchronous/ synchronous	PSK	Half, full
CCITT	V.21	300	asynchronous	FSK	Half, full
	V.22	600	asynchronous	PSK	Half, full
		1200	asynchronous/ synchronous	PSK	Half, full
	V.22 bis	2400	asynchronous	QAM	Half, full
	V.23	600	asynchronous/ synchronous	FSK	Half, full
		1200	asynchronous/ synchronous	FSK	Half, full
	V.26	2400	synchronous	PSK	Half, full
		1200	synchronous	PSK	Half
	V.26 bis	2400	synchronous	PSK	Half
Bell System	V.26 ter	2400	synchronous	PSK	Half, full
	V.29	9600	synchronous	QAM	Half, full
	V.32	9600	synchronous	QAM	Half, full

Table 6-5 Standard Modem Characteristics

** In some cases, modem types indicated as half duplex will operate in full duplex mode in a 4 wire configuraton.*
*** FSK - Frequency shift keying*
PSK - Phase shift keying. Some PSK modems encode more than one data bit with each signal transmission.
QAM - Quadrature amplitude modulation (a combination of amplitude and phase modulation). QAM modems encode more than one bit with each signal transmission.

Central computer controlled traffic controll systems of the UTCS type (see Figure 5-3) multiplex (TDM/FSK) a group of controller data (typically up to 8) over one or two twisted wire pair. Characteristics of this arrangement inlcude:

- The field unit (RCU) provides discrete signals to the controller and accepts controller status signals and detector data.
- A central communications unit (CCU) is located at the traffic operations center.
- A polling cycle of typically 1 second.
- Detector data sampled between 15 and 120 times per second by the RCU.
- Occupancy (proportional to the number of "vehicle present" samples in a polling period) stored and returned as a digital number. In some cases a special form of coding reduces the number of occupancy bits returned (see Chapter 4).
- The return of the number of detector state changes to provide volume.
- Logic in the RCU to report detector chatter (sign of detector malfunctions).
- The return of other status signals such as pedestrian signals, cabinet door open warnings, etc.

A number of suppliers (who operate independently of the controller manufacturer) furnish communication equipment of this type, and one design usually can service all controllers in a system. The communications manufacturer typically codes the protocol software, often tailored to the particular system's special requirements and functions and documented in the equipment manual. In some cases the traffic operations center and field equipment contain a standard modem protocol (e.g., Bell 202S); others use non-standard modems. This field equipment may sometimes be acquired from other manufacturers, but often is no longer available for future buys if the original supplier has left the traffic control business.

NEMA TS1 does not specify a communication interface. However, most manufacturers of systems controlled by field masters provide a telemetry module (see Figure 3-2b) to implement communication with their master using a proprietary protocol.

With the adoption of NEMA TS2 in 1992, several manufacturers began to design controllers to this standard. The TS2 standard provides for a modem output leading to the configuration shown in Figure 3-2c. The manufacturer uses the modem for communication to a field master. This configuration (Figure 3-2a) still requires an RCU for control by a central computer with software not provided by the controller manufacturer.

- Model 170 Controllers

  A system communicates with Model 170 Controllers using the optional Model 400 modem shown in Figure 3-3a or through a serial interface port (Figure 3-3b), via an external modem. As shown in Figure 5-5, the controller preprocesses detector data and formats various discrete signals for communication in both directions.

  A number of communication equipment manufacturers provide equipment to replace the Model 400 modem with special purpose modules. These provide higher data rates, alternative modem standards, and in some cases compatibility with other media such as radio technologies and fiber optics.

Noise and Interference * **(1)**

A multipair cable can transmit several channels of information - one channel for every two pairs in a full-duplex network. Since the cable conveys more than one signal simultaneously, it can experience crosstalk which, as discussed in Chapter 2, results in the reception by one pair of portions of a signal from an adjacent pair. The twisting of pairs can minimize this inductive coupling of signals. As shown in Figure 6-4, the same current flows in each conductor, but in opposite directions. Thus, the current in each conductor produces a magnetic field also in the opposite direction. The two induced fields largely cancel each other, thereby minimizing the amount of energy transferred to adjacent pairs. The design should also keep all signal levels to a minimum.

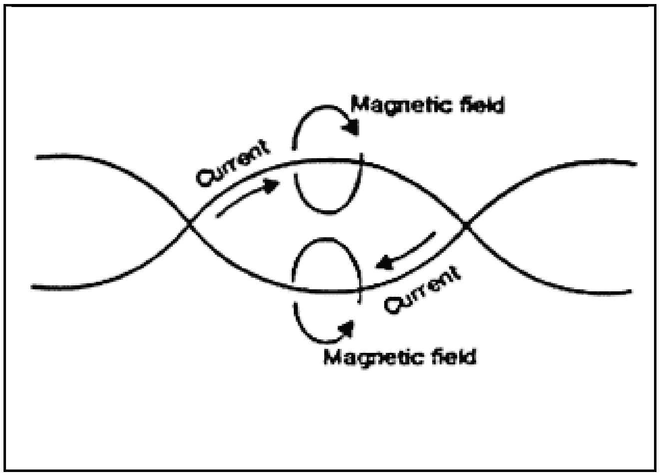


Figure 6-4 Crosstalk Reduction by a Twisted Wire Pair

Sixty (60) Hz power sources are typical noise sources in twisted-pair cable. Sixty (60) Hz noise does not significantly affect typical twisted-pair system modems (e.g., Bell 202 standard) as these filter out signals below 750 Hz. However, harmonics (multiples of the fundamental power line frequency) may cause interference.

Impulse noise also interferes significantly with communications and results from the following sources:

- Natural, such as lightning,
- Human-made, such as auto ignitions and electrical equipment.

Some noise may result from incomplete cancellation by the twisting or by coupling through the capacitance of the transformer at the input to the modem. Transformers with low coupling capacitance or a grounded shield between the primary and secondary transformer windings can reduce this noise.

Proper care taken in cable system design and construction can hold noise levels in twisted-pair cable to very low levels. The cable shield reduces the effect of induced signals and noise but to minimize the latter, the design should include the following precautions:

- Ideally, the shields of all 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, possibly disrupting system communication.
- When a large cable network has a single ground, the electrical potential on the shield can become quite large and constitute a hazard to anyone working in a field cabinet. In these circumstances good practice divides the cable network into "grounded sections". Each section has a single ground location and the cable shields within a section are continuous to ground; but the shields are not bonded between sections.
- In aerial installations, good practice also grounds the messenger cable.

Design Considerations

A twisted-pair communications network design must include a number of factors:

- Number of pairs required for initial system and subsequent expansion. This becomes a function of:
  - Total number of field drops,
  - Maximum number of drops allowed on each channel, and
  - Network configuration.
- Gauge of wire.
- Cable routing and installation techniques. This becomes a function of:
  - Field drop locations,
  - Existing communication facilities,
  - Cable termination requirements and,
  - Cost.
- Environmental effects, such as moisture entry, noise, and transients.
- Other considerations such as repeaters, special functions of the system, and testing.

These factors interrelate. For example, use of a smaller gauge (i.e., larger diameter) conductor offers lower attenuation thereby increasing repeater distances. But the overall diameter of the cable increases, problematical in an existing conduit network with limited space. Similarly, filled cable (PE-39) often prevents moisture migration problems, but its increased stiffness may make installation more difficult.

Installation Considerations

Twisted-pair cable can be installed by one or a combination of four method(s):

- Underground, in conduit,
- Underground, by direct burial,
- Aerial, utilizing existing/new utility poles,
- Support of cable or conduit by bridges, overpasses, and elevated highway and rail structures.

The method(s) selected will have a significant impact on both installation and maintenance cost (see Chapter 10). Aerial installations become subjected 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.

A twisted-pair cable network design must pay close attention to:

- cable sizes,
- minimum bending radii, and
- cable weight.

Cable diameter and stiffness will impact the design of a new conduit network, and 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 direction,
- the bend of the conduit as it enters a cabinet or junction box, and
- the weight of aerial cable.

Moisture in twisted-pair cable networks constitutes a major problem. It increases attenuation and leakage, and can also increase crosstalk and cable noise by introducing signal reflections. Cable splices prove the primary source of moisture entry. Thus, the design should specify splices:

- on telephone-type terminal blocks inside weatherproof cabinets or,
- in non-reenterable waterproof splice enclosures for aerial installations.
- *Imperfections* in the cable jacketing allow another source of moisture entry. Careful installation must:
- Assure that the cable does not drag on the pavement or rub against jagged conduit ends causing cuts or abrasions.
- Seal cable ends during pulling operations to prevent moisture entry.

Installation should not exceed the maximum pulling strength of the cable; otherwise, damage to the conductors, shield and/or jacket may result. Therefore, installation specifications should require either hand-pulling or tension monitoring using a strain gauge.

Electrical transients from natural phenomena such as lightning impact twisted-pair cable networks. The probability of a cable lightning strike depends on:

- storm frequency,
- terrain, and
- type of cable installation.

For example, aerial cable routed in open terrain becomes 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. Thus, good practice provides transient protection to prevent damage to sensitive electronic devices connected to the cable (see Appendix C).

The protective devices most commonly used provide two-stage protection. The primary stage consists of a three-element gas discharge tube, while secondary protection consists of solid-state voltage clamps. These 2-stage devices:

- provide a path to ground for current surges,
- respond within a few nanoseconds, and
- provide automatic recovery after the transients are removed.

Protective devices come in several mounting arrangements, including:

- circuit board connection,
- terminal block,
- plug-in, and
- stud fastening.

The design should include protective devices:

- on all cable pairs,
- at both ends of the cable circuit:
  - where it enters the central facility, and
  - where it enters each field cabinet.

The design should call for thorough *testing* after installing a twisted-pair cable network. 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.

Use of Existing Facilities * (2)

The use of existing cable and conduit can significantly reduce the cost of the communications network, thereby reducing the overall cost of the traffic control system. However, the designer must carefully examine existing cable to ascertain its adequacy for traffic data communications. The design or installation quality of the existing resources may prove unsuitable, or the facilities may have severely deteriorated since their installation.

The designer should assure sufficient testing of any existing cable plant considered for a traffic control system. The test should:

- send the appropriate signals through the various transmission links,
- return the signal from the opposite end of the link, and
- compare the returned signal with the transmitted signal to determine the suitability of the existing cable network for communications.
- Tests of existing conduit runs include:
- physical *rodding* to access collapsed or broken conduit. The designer can then decide whether to have the conduit repaired, or install a new conduit run,
- *tugging* on any existing cables at each junction box and termination point in lieu of rodding. If the existing cables move freely, then the conduit can likely be used. Stuck cables imply a construction or blockage, and the designer should specify a new conduit run.

The latter survey typically proves easier and less time consuming than rodding, but may result in more new conduit than actually required. (The conduit "blockages" may simply result from mud or silt, easily cleared by rodding).

The designer should also consider the existing conduit's size and layout. Important factors include:

- Sufficient conduit capacity for the new communications cable(s).
- The conduit network layout and its appropriateness for pulling and terminating the new communications cable(s):
  - spacing between pull boxes,
  - number of conduit bends between pull boxes,
  - radii and
  - degree of bends

- Possible code violations.

Often, the jurisdiction can:

- install communication cable in a utility company duct's spare conduit, or
- use space on joint-use utility poles.

The jurisdiction should reach a franchise agreement with the utility company for such arrangements. In the absence of a formal agreement, the jurisdiction should formalize this joint use by a letter of understanding prior to commitment of funds for the communications system installation.

The designer should field check with utility representatives, alternative cable routings that use existing joint-use pole lines to determine:

- the adequacy of the pole line and
- any required *utility adjustments*.

Utility adjustments can prove extremely costly, particularly on poles where perpendicular lines intersect, or on poles with primary or secondary transformers. Utility company representatives may suggest alternate cable routings that result in lower costs.

Utility companies usually have regulations governing the installation of cable in their ducts. Examples include:

- the required presence of a utility inspector when contractors work in their facility;
- limitations on the type of cable and transmissions permitted in their ducts; and,
- the requirement in some instances that utility company personnel install the cable.

The designer should also consider the delineation of responsibilities between the utility company and owner (e.g., who has the responsibility for clearing a blocked duct or repairing a collapsed duct). These utility requirements may impact the cost of a communications alternative and the designer should analyze them to the extent possible during the trade-off study).

When a communications alternative requires new poles and conduit, the designer should field check the proposed routing and layout to:

- determine any additional required right-of-way,
- identify any obstructions that may affect the routing, and
- provide an accurate estimate of quantities.

The designer should particularly identify the required quantity of new underground conduit installed in trench 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 prove time consuming and somewhat costly. It should, however, be accomplished either during the traffic engineering analysis or at the very beginning of system design. Only in this manner can the designer reliably estimate costs for the communications network alternatives. More often than not, the funds and time spent during this step of the communications trade-off analysis pay significant dividends. In numerous instances, existing communication facilities did not prove feasible, resulting in major unanticipated increases in construction costs, project delays, and contractor claims.

When using existing conduit for communications cable, contract documents should include pay items for cleaning existing conduit runs and conduit repair. 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?

Coaxial Cable

Coaxial cable provides the communications media for many traffic control applications, especially for those systems implemented prior to the late 1980's. Since that time, most traffic control systems using owned cable facilities and requiring a high capacity landline communication backbone have deployed fiber optic cable. This choice results from the higher communication reliability and lower maintenance and adjustment effort required. However, video surveillance applications still widely use coaxial cable, typically providing a dedicated transport between camera and backbone communications hub.

Coaxial cable technology using community antenna television (CATV) services remains a viable technology for backbone applications in some cases as discussed later in this chapter.

Characteristics * (3)

A coaxial cable (coax) consists of a center conductor within an outer cylindrical conductor, separated by a dielectric material (i.e., insulator). Figure 6-5 shows a schematic of coax cable construction, which typically has the following characteristics:

- the center conductor uses copper clad aluminum,
- the outer conductor (i.e., shield) uses aluminum as braided metal fabric, corrugated semi-rigid metal, or a rigid metal tube,
- the dielectric may consist of either a solid (e.g., foamed polyethylene) or a gas. (In the latter case, insulating spaces separate the center conductor from the outer conductor),
- the outer jacket consists of low density, high molecular weight polyethylene, the cable may also have armor (i.e., steel tape) for direct burial in gopher areas.
- Coaxial cable varies greatly in size and construction, from the flexible 1/4" diameter cable (RG-59) used in a CATV subscriber drop, to 8" diameter rigid coax used to carry television broadcast signals from the transmitter output to the antenna. Traffic control applications commonly use a 3/4" semi-rigid coax for trunk lines, with smaller diameters used for connections between the trunk and field drops. Table 6-6 summarizes the characteristics of a 3/4" coax cable.

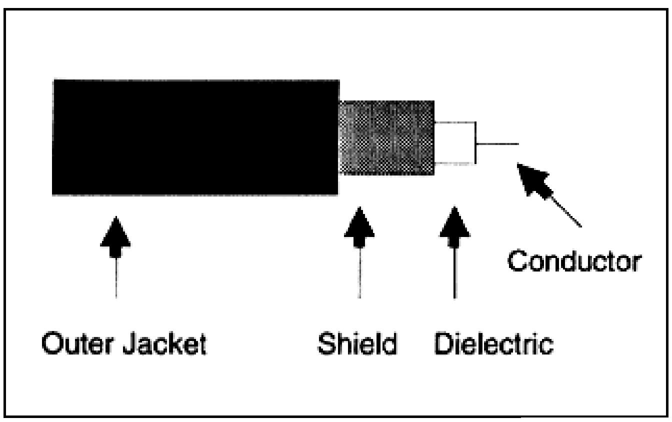


Figure 6-5 Coaxial Cable Construction

The construction of coaxial cable results in some attractive electrical characteristics. The cable itself proves extremely immune to noise and transients from external sources; however, connections become susceptible. The installer must splice carefully and the owner maintain these connections more frequently than for twisted wire pairs.

Coaxial cable has a wide bandwidth, on the order of 350 MHz. This provides sufficient bandwidth for video, data and voice services in most traffic control applications.

- Impedance - 75 ohms
- Cable Attenuation (at 68 degrees Fahrenheit)

5.2	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 degrees Fahrenheit
- Minimum Bending Radius - 9-11 inches depending on manufacturer

Table 6-6 Characteristics of 3/4-Inch Coaxial Cable

Data Communication Equipment * (4)

Coaxial cable networks for traffic control typically use frequency division multiplexing to subdivide the cable bandwidth into appropriate channels for data, video and voice transmission. On several of these channels, usually 50 KHz to 100 KHz wide, TDM techniques then communicate the data.

The frequency spectrum of most coaxial cable systems divides into two parts. *Upstream* channels use one range of frequencies, while the other frequency range comprises *downstream* channels. Upstream refers to the *head end* of the trunk, usually at the traffic operations center. Thus, the upstream direction runs from the field drops to the operations center, while downstream represents the direction from the operations center to field locations. The head end can be elsewhere in shared or leased facilities.

Most coaxial cable networks must branch out from the head end to serve multiple drops. Figure 6-6 (21) schematically represents a coaxial communications system for traffic control. *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 signal's direction. A *directional coupler* combines signals propagating in one direction on a cable onto another cable, while substantially isolating signals from the opposite direction. Field drops use *taps* to divert the necessary signal to and from the trunk cable.

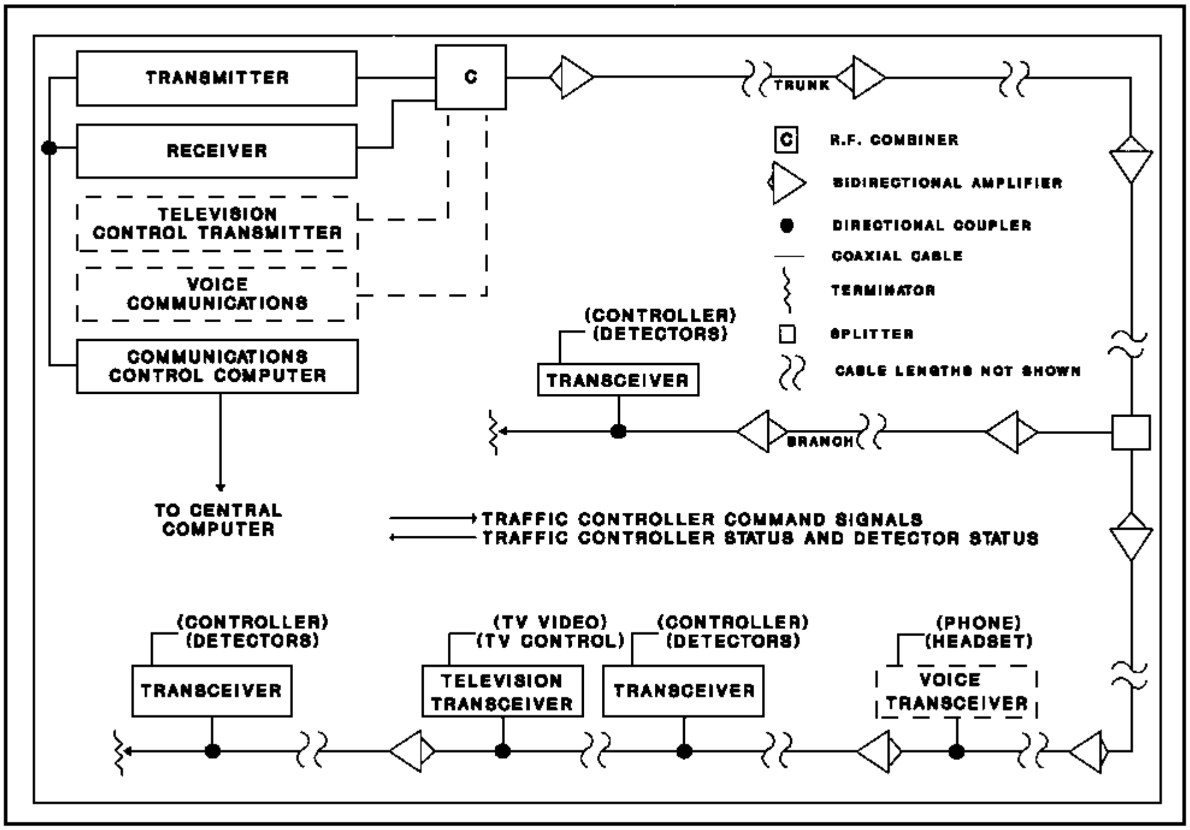


Figure 6-6 Coaxial Cable Communications

Repeater requirements in coaxial cable systems depend on:

- transmission frequencies,
- cable size,
- number of connectors,
- 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. Note that a coaxial system amplifies the signal rather than regenerating it at each repeater. This amplifies the incoming signal, along with any amplifier and external noise. So while the amplifier boosts signal level, it does not improve the signal to noise (S/N) ratio. These noise impacts accumulate in each cable section, thus limiting the number of cascaded repeaters. This limit of approximately sixty (60) repeaters has not impacted traffic control systems using this technology.

Coaxial systems use unidirectional broadband amplifiers. Thus, coaxial systems must incorporate low-pass or high-pass filters to amplify the appropriate portion of the spectrum in the appropriate direction. Manufacturers usually package as a single unit the filters and amplifiers for both directions.

Attenuation in coaxial cable varies as a function of temperature. Amplifiers can automatically compensate for these thermal variations using Automatic Gain Control (AGC) with pilot signal generators to provide reference signal levels. Nevertheless, technicians must sometimes manually retune amplifiers.

For data communications, multiple vendors supply off-the-shelf modems required by a coaxial cable system. Modems typically support data rates from 1200 bps to 10 Mbps with computer industry standard data interfaces such as RS-232 and RS-422. In the selection of a modem, a designer should pay particular attention to the operating temperature range. Many commercial grade modems have temperature ratings far below NEMA specifications for traffic control devices. Such modems may be sensitive and their output may drift outside of the allocated frequency interfering with adjacent channels and disrupting system communications, if ambient temperatures exceed maximum limits (or fall below minimal).

When system design requires an RCU, industrial support has proved less available than for standard modems which interface with serial controller ports. Although coaxial systems commonly used RCU's in the past, designers considering this configuration for new systems should carefully assess supplier availability.

Design Considerations

The design of a coax network may prove more complex than a twisted-pair network. The system may only require a single cable with taps to each field drop, but numerous other design issues surface. To resolve these, the design must:

- determine locations of amplifiers, couplers, splitters, and pilot generators;
- provide power for the amplifiers;
- compensate for temperature extremes and rate of change;
- minimize RFI/EMI; and
- allocate 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
- direct burial, or
- overhead on utility poles.
- The installer should assure the following:
- The conduit must not have any bends between pull boxes other than gentle curves leading to and from the pull boxes/cabinets. If pulled through a severe bend, the outer conductor may collapse and a permanent shift of the inner conductor from the center may also result.
- The installer should not exceed the maximum pulling tension specified by the manufacturer.
- The installer should place cable splices and connections only in weatherproof cabinets to minimize moisture entry and noise ingress.

Of importance also, the cable installation specifications and construction supervision must provide good quality control. Where regulations permit, the designer should include prequalification requirements (e.g., previous experience) in the contract documents for the contractor/subcontractor responsible for installing the coaxial cable network. Furthermore, the installer should thoroughly test the entire installed cable network 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 exceeds that of twisted-pair networks. This results from 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.

Fiber Optics

Starting with the 1980's, the telecommunications industry deployed fiber optic communications systems to provide high volume, cost effective trunks for voice and data. As the cost of deploying and maintaining fiber has decreased, fiber optic communications finds other applications, including:

- local and wide area networks,
- point-to-point data communications links,
- cable TV trunk and distribution networks.

In addition, fiber has become the communications media of choice for many traffic control system applications.

The following sections describe:

- general optical communications characteristics,
- cable options,
- interconnection and installation considerations,
- communications equipment.

Subsequent sections present case studies of systems which use fiber for traffic control applications.

Characteristics

The speed at which a ray of light travels through a transparent material depends on its properties. If a light ray obliquely impinges the boundary of two different materials, it will change its direction at the boundary. Figure 6-7a illustrates this phenomenon, called refraction. The index of refraction equals:

$$n = \frac{\text{speed of light in free space}}{\text{speed of light in material}}$$

As shown, when $n_1 >> n_2$ the refracted ray bends away from the normal according to Snell's Law,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

The critical angle of incidence θ_c occurs when $\theta_2 = 90^o$ and light does not enter the second material. Figure 6-7b shows this angle,

$$\theta_c = \sin^{-1}(n_2/n_1)$$

At angles greater than θ_c, the light ray reflects (Figure 6-7c) and the angle of incidence equals the angle of reflection.
Fiber optics communication uses these principles to transmit signals through a fiber (Figure 6-8) composed of:

- a core region,
- cladding, and
- coating.

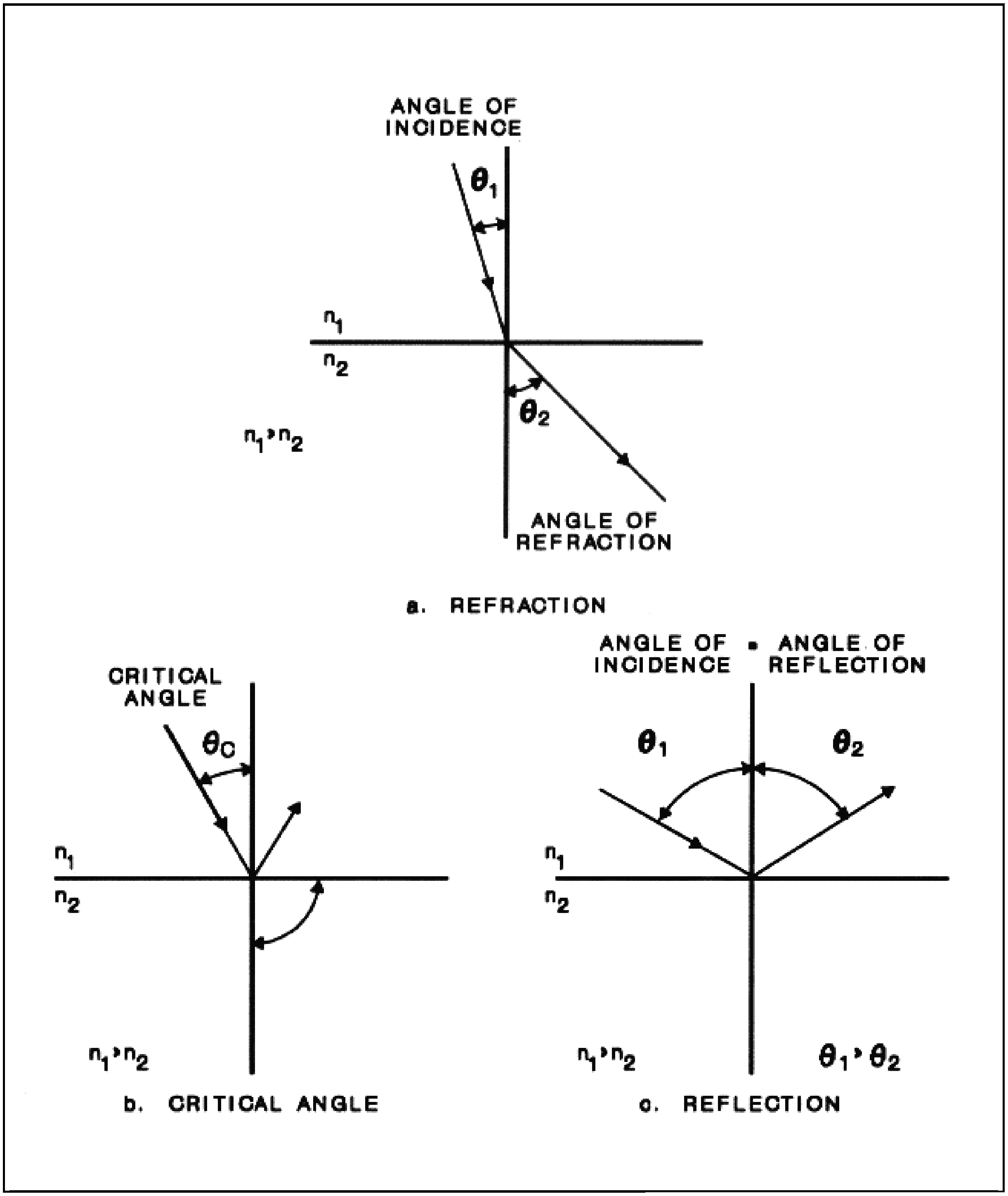


Figure 6-7 Angles of Incidence, Refraction, and Reflection

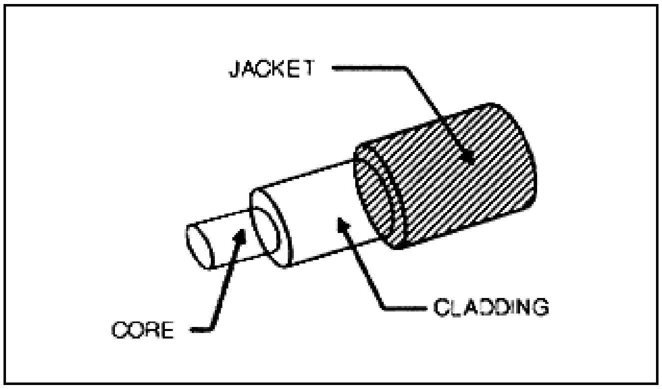


Figure 6-8 Fiber Optic Cable

Light propagates through the fiber core typically made of silica glass and possibly *dopants* that alter the optical properties. A *cladding* also composed of silica glass and dopants but having a slightly lower optical density (refractive index), surrounds the fiber core. This causes the reflection of a lightwave and continued propagation through the core. A protective jacket surrounds the cladding.

Figure 6-9 depicts light entering at the left and propagating through the fiber. Light rays entering the core at less than the critical angle refract into the not highly transparent cladding and attenuate. Light rays entering at greater than the critical angle reflect and continue to propagate in the core.

The information carrying capacity, or bandwidth, of fiber relates to the spreading or dispersion of light pulses. A pulse of light broadens as it travels along a fiber. If the pulse spreads such that the last portions of one pulse arrive after the first portions of the following pulse, then intersymbol interference occurs and the receiver can no longer distinguish individual pulses. Pulse dispersion depends on both pulse width (baud rate) and distance.

Light is a form of electromagnetic energy similar to radio waves, but at a much higher frequency (shorter wavelength). The following equation shows the relationship between frequency, f, and wavelength, L:

$$L = \frac{v}{f}$$

where v is the velocity of the wave (3×10^8 meters/second in free space). Figure 6-10 shows the electric and magnetic fields for a wave propagating in the z direction. Note that the direction of propagation of the wave and the directions of the magnetic and electric fields all form right angles (orthogonal). Maxwell's equations govern the propagation of electromagnetic waves. When a guide such as an optical fiber confines electromagnetic waves, the solution to these equations leads to *modes.* In essence, a mode represents a path which a light ray can follow as it travels along a fiber. The number of modes supported by a fiber relates to the core diameter; the larger the diameter, the greater the number of modes which propagate along the waveguide. *Multimode fibers* (Figure 6-11) refer to optical waveguides which support many different modes of propagation. Optical fibers sufficiently thin and with the appropriate refractive indices support only a single mode of propagation in the core and are called *single mode* fibers. Dispersion increases as the number of modes increases, as shown in Figure 6-12.

Graded-index multimode fiber reduces dispersion by having an index of refraction highest on the fiber axis and lowest at the core-cladding interface. Since light travels more slowly along the denser core axis, this fiber design allows waves traveling different length paths to have approximately the same axial speed, thereby reducing dispersion caused by multiple modes.

Two basic design parameters limit the length of a fiber optic link: the previous discussed dispersion and *attenuation*. Attenuation (loss of light energy) may result from:

- *absorption,* where propagating light interacts with impurities in the silica glass,
- *scattering,* where geometric imperfections in the fiber cause light to be redirected out of the fiber, or
- *microbends,* which may occur during fiber or cable manufacture and *macrobends* which can result from improper installation practice (e.g., exceeding the minimum bending radius).

In general, single mode fiber supports wider bandwidth and has lower attenuation than multimode fiber, allowing longer cable runs. Currently, multimode fiber finds application mostly for point-to-point data communications applications and accounts for only 5-10% of the total stock manufactured by fiber vendors.

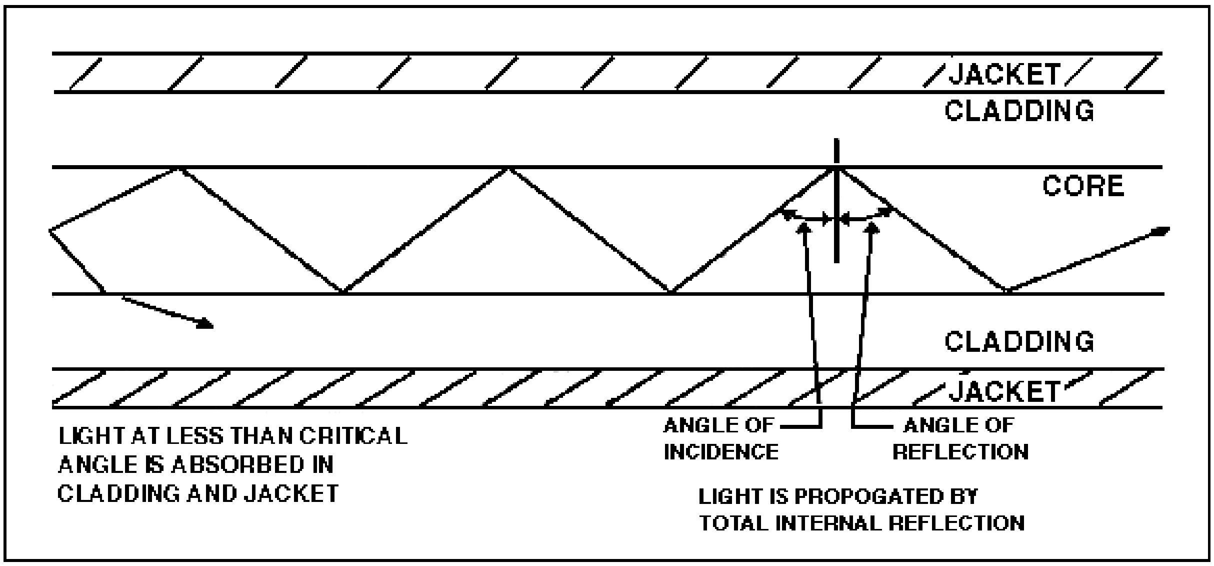


Figure 6-9 Light Propagation in Optical Fiber

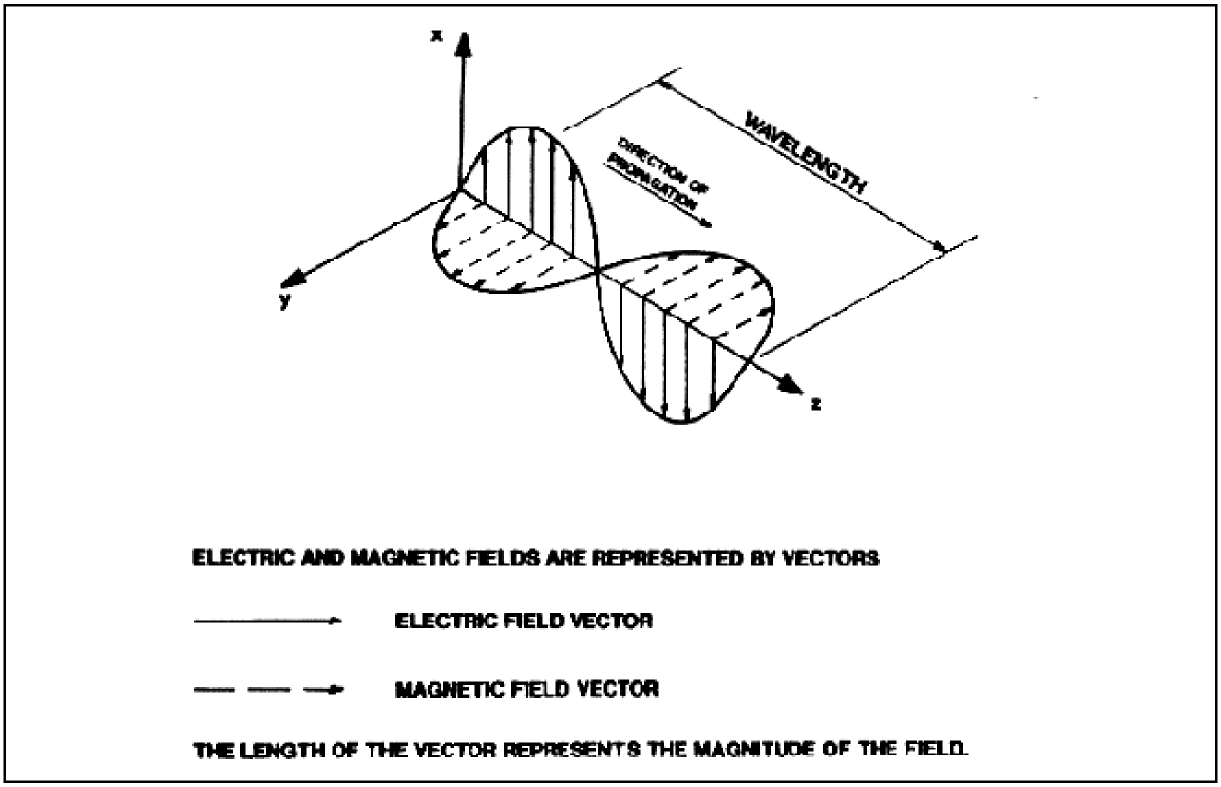


Figure 6-10 Representation of Electromagnetic Wave

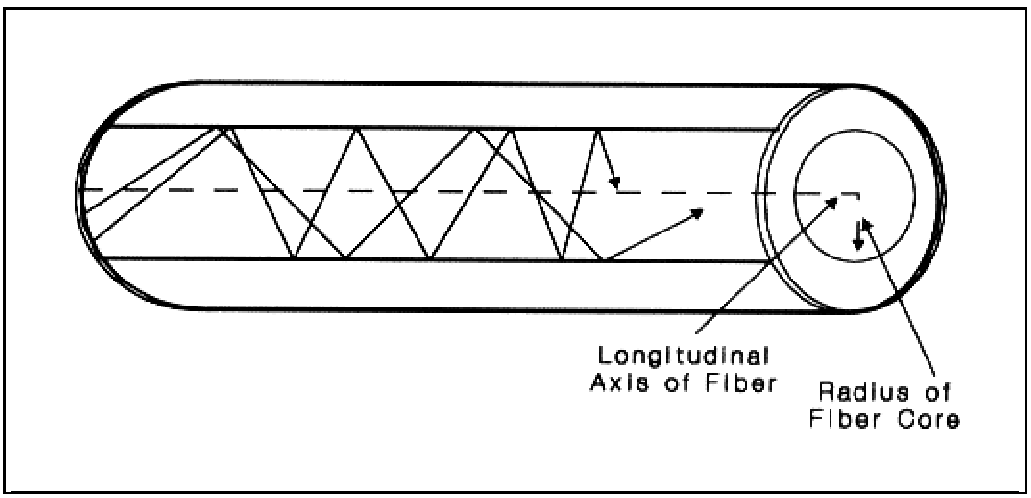


Figure 6-11 Propagation in Multimode Fiber

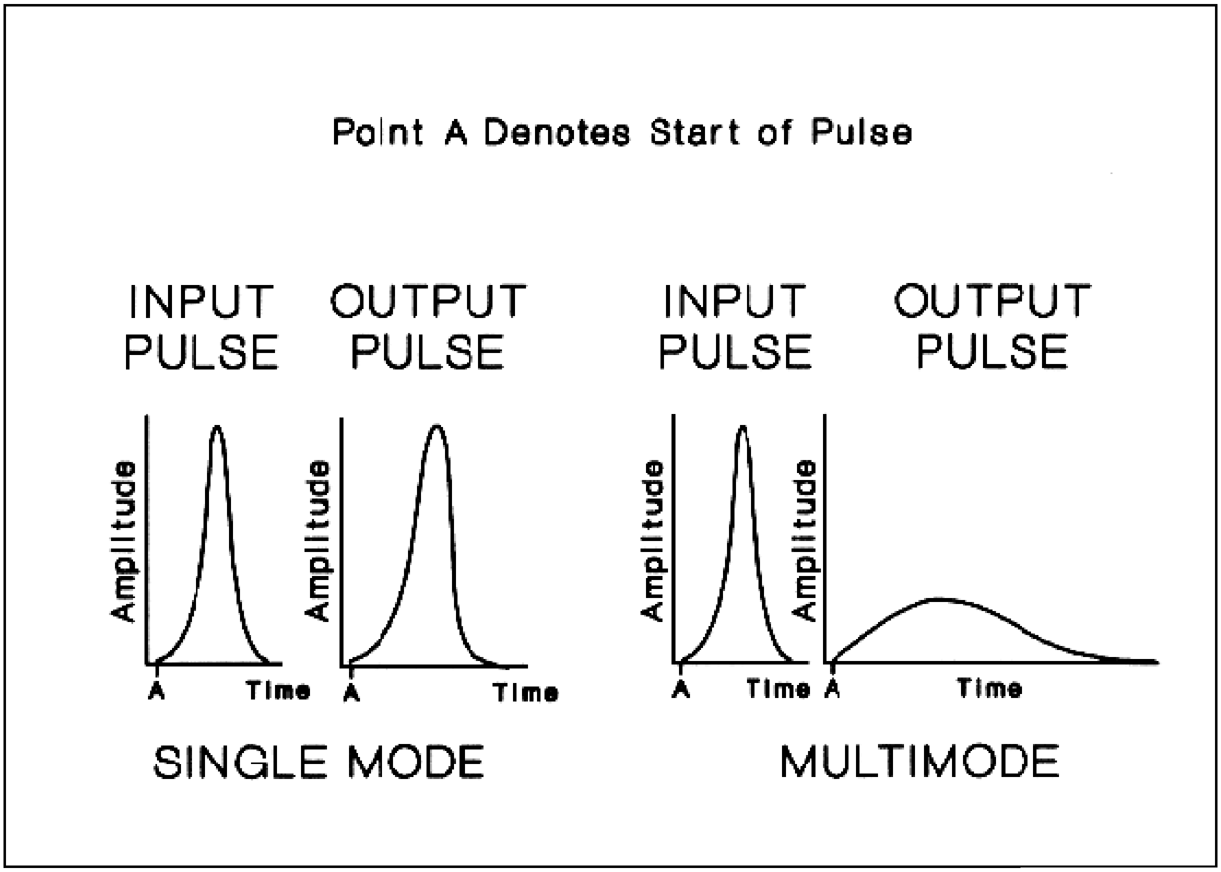


Figure 6-12 Response of Single Mode and Multimode Fibers to Input Pulses

Cable Options

A wide variety of fiber cable options exist to meet specific application requirements, as shown in Table 6-7 (22, 23). Dimensions of the fiber cable depend on the selected options, but the cable diameter will generally prove less than the 0.69 inches shown in Table 6-8 (23).

Fiber optic cable performance depends primarily on the fiber type (single mode versus multimode) and the operating wavelength. For most practical applications, single mode fiber links are power limited, meaning link length becomes limited primarily by the capabilities of:

- the light source,
- light detector, and
- fiber attenuation.

Hence, the maximum attenuation (e.g., 0.35 db/km) at a particular operating wavelength (e.g., 1310 nm) typically characterizes single mode fiber performance.

Depending on the baud rate transmitted, multimode fiber links may be limited by attenuation (e.g., 2 db/km) or by dispersion (individual pulses eventually overlap). Typical multimode fibers have a bandwidth of 400 MHz-km at a wavelength of 1300 nm. Such a fiber can sustain a baud rate of 400 MHz over a distance of 1 km but only 100 MHz when transmitting over a distance of 4 km. Traffic control systems which use multimode fiber at the low baud rates typical of distribution system channels or for small signal control systems will typically be limited by attenuation considerations.

For purposes of illustration, Tables 6-9 and 6-10 present performance parameters and 1992 list price data for representative single and multimode cable. Note the relatively small unit cost difference for comparable single and multimode fiber cables. This price data shows multimode fiber as more expensive for cables with 24 or more fibers.

Single mode fiber is strongly recommended over multimode fiber for any communications link which serves as, or could evolve to, part of a backbone network. For non-backbone data links with significant equipment costs, equipment compatible with both multimode and single mode fiber should be considered.

In general, fiber manufacturers and distributors will work with customers to help them understand the various cable options and select the appropriate fiber optic cable for a given application. Table 6-11 provides an example of specifications typically used for single and multimode fiber.

A splice permanently joins two or more optical fibers. In uncontrolled environments, installers encase splices in a closure system designed to offer environmental protection and mechanical support. As shown in Table 6-12, splicing techniques vary in terms of performance and splice time. To date, traffic control system communications has most commonly used fusion splicing. Fusion splicing was introduced as one of the first splicing techniques and, at the time, produced substantially better performance. Within the past few years, new techniques (e.g., rotary mechanical splice, CSL splice) have proved less labor intensive and, in some cases, provide performance on par with fusion splices. Recent procurements for freeway traffic management systems (e.g., San Antonio) have specified system performance parameters rather than a specific splicing technique.

Non-permanent connections of individual fibers in controlled environments use connectors together with distribution systems. Average connector loss ranges from 0.35 dB to 0.7 dB depending on the type of connector and fiber. Relatively inexpensive interconnection cabinets can accommodate small fiber counts, terminating 12-48 fibers in a single cabinet. Distributing frames and modular distribution shelves typically accommodate large fiber counts, where a single shelf may terminate up to 144 fibers.

Fiber Cable Parameter	Sample Options
Type	Single mode (8.3 micron core), multimode (50 micron core), multimode (62.5 micron core)
Count	From 1 to 216 fibers in a single cable
Sheath	Crossply metallic/nonmetallic, rodent protection, express entry metallica/nonmetallic/rodent, oversheath
Core	Ribbon with air or filled core bundle with air or filled core
Operating Wavelength	825 nm, 850 nm, 670 nm, 1300nm, 850/1300nm, 870/1300 nm for multimode 1310 nm, 1550nm, 1310/1550 nm for single mode fiber
Maximum Tensile Rating	2700N (600 lbs.), 1300N (300 lbs.)

Table 6-7 Fiber Cable Options

Description	Diameter
Multimedia 50 Micron Core Filled Bundle Cable (LIGHTPACK) with Steel Reinforced Crossply Sheath	.42 inch for 4-48 Fibers .49 inch for 50-96 Fibers
Multimode 62.5 Micron Core Filled Bundle Cable (LIGHTPACK) with Steel Reinforced Crossply Sheath	.42 inch for 4-48 Fibers .49 inch for 50-96 Fibers
Multimode 62.5 Micron Core Ribbon Cable (AccuRibbon) with Stelel Reinforced Crossply Sheath	.49 inch for 12-96 Fibers .59 inch for 108-144 Fibers
Single Mode 8.3 Micron Core Filled bundle Cable (LIGHTPACK) with steel Reinforced Crossply Sheath	.42 inch for 4-48 Fibers .49 inch for 50-96 Fibers
Single Mode 8.3 Micron Core Ribbon Cable (AccuRibbon) with Steel Reinforced Crossply Sheath	.49 in for 12-96 Fiber .59 inch for 106-215 Fibers
Single Mode 8.3 Micro Core Ribbon Cable (AccuRibbon) with Lightguide Express Entry Sheath	.59 inch for 12-96 Fibers .69 inch for 108-216 Fibers

Table 6-8 Fiber Cable Dimensions

Number of Fibers	Maximum Loss (1310 nm)	Maximum Loss (1550 nm)	Cable Diameter (inches)	Unit Price (100 feet) ($)
4	0.35 dB/km	0.23 dB/km	0.49	113.88
12	0.35 dB/km	0.23 dB/km	0.49	172.38
24	0.35 dB/km	0.23 dB/km	0.49	200.52
30	0.35 dB/km	0.23 dB/km	0.49	318.24
48	0.35 dB/km	0.23 dB/km	0.49	402.18
60	0.35 dB/km	0.23 dB/km	0.49	592.8
216	0.35 dB/km	0.23 dB/km	0.49	2,061.54

Table 6-9 Representative Single Mode Fiber Performance and Price

Prices represent 1992 costs and vary with other characteristics of cable

Numbers of Fibers	Maximum Loss (160 MHz-km at 850 nm)	Maximum Loss (500 MHz-km at 1300 nm)	Cable Diameter (inches)	Unit Price (100 feet) ($)
4	3.75 dB/km	1.00 dB/km	0.49	84.00
12	3.75 dB/km	1.00 dB/km	0.49	148.80
24	3.75 dB/km	1.00 dB/km	0.49	265.20
30	3.75 dB/km	1.00 dB/km	0.49	323.40
48	3.75 dB/km	1.00 dB/km	0.49	498.60
60	3.75 dB/km	1.00 dB/km	0.59	615.00

Table 6-10 Representative Multimode Fiber Performance and Price
Prices represent 1992 costs and cary with other characteristics of cable.

- Fibers shall meet the following specifications

Specification	Single Mode Fiber	Multimode Fiber
Core Diameter	8.3 microns	62.5 microns
Maximum Core Non-Circularity	6.0%	6.0%
Maximum Core Eccentricity	1.0 micron	1.0 micron
Maximum Attenuation		
At 850 nm (160 MHz-km)	n/a	3.75 db/km
At 1300 nm (500 MHz-km)	n/a	1.00 db/km
At 1310 nm	0.35 db/km	n/a
At 1550 nm	0.23 db/km	n/a
Cladding Diameter	125 +/-2 microns	125 +/-2 microns
Cladding Design	Depressed	Not Applicable
Maximum Cladding Non-Circularity	2.0%	2.0%
Outer Coating	AT&T D-LUX 100 or approved equal	AT&T D-LUX 100 or approved equal
Outer Coating Diameter	250 microns	250 microns

- The cable shall meet the following specifications:

Crush Resistance (EIA RS-455041 test)	262N/cm
Impact Resistance (EIA RS-455-25 test)	500 impacts
Cyclic Flex (RS-455-104 test)	500 cycles
Twist Resistance (EIA RS-455-85 test)	150 cycles
Maximum Tensile Load	
- During Installation	600 lbs.
- Long Term	135 lbs.

- The cable shall be approved by Underwriters Laboratories and shall cable markings at two foot intervals on the outer sheath indicating the type of cable, number of fibers, and distance from end.

- The cable sheath shall be high density polyethylene..

- The cable shall be of a design the facilities sheath entry in midspan.

- The sheath shall be filled with a non-hygroscopic, water blocking compound to prevent water penetration.

Table 6-11 Example of Fiber Specifications

Technique	Average Splice Time	Average Splice Loss
Fusion	10 minutes	0.09 dB
Rotary Mechanical (with testset)	5-10 minutes	0.05 dB (single mode) .10 dB (mutimode)
Rotary Mechanical (without testset)	5-10 minutes	0.20 dB (single mode) 0.25 multimode)
CSL LightSlice System	2-3 minutes	0.20 dB
Array (splice 12 fibers at once)	2 miutes per fiber	0.40 dB (single mode) 0.15 dB (multimode)
Raid Ribbon (Splice 12 fibers at once)	2 minutes per fiber approved equal	0.40 dB (single mode) 0.25 dB (multimode)

Table 6-12 Splicing Techniques (Ref. 23)

Interconnection costs vary considerably based on:

- application requirements (e.g., number of fibers),
- local labor rates, and
- the splicing technique used.

Materials for a fusion splice contribute negligibly to cost; however, the associated Equipment is expensive. Material cost for a mechanical splice ranges from $8 - $25, while A closure system costs between $250 - $1000. Interconnection cabinets for 12 to 24 single Mode fibers costs approximately $400 and $750, respectively. Multiple cabinets can Terminate a moderate quantity of fiber, but large counts (e.g., more than 100-150 fibers) Require a distributing frame.

Fiber optic cable designs allow:

- aerial installation,

- direct burial, or
- pulling through a conduit.

Most recent traffic control system designs call for fiber cable installed in conduit.

Fiber cable pulling costs depend primarily on pull distances and local labor rates. Pull distances of up to two miles can prove possible. However, typical installations require an average of four handholes or manholes each mile, with more pull locations in applications with hilly terrain or numerous overpasses. The cost to pull cable through conduit often approximates $1 per foot. The designer should prepare a cable pulling plan to account for the cable's maximum tensile load rating.

Data Communications Equipment

Transmitters and Receivers

Fiber optic communications equipment transmits and receives optical signals, converting electrical energy into optical energy and vice versa. The *Light Emitting Diode* (LED) and *Injection Laser Diode* (ILD) have become the two most common light (photon) sources for fiber optic communications systems. ILDs operate much more efficiently than LEDs in terms of the percentage of optical energy coupled into the core of the fiber, while LEDs cost much less.

Two photodiodes, PIN and Avalanche PhotoDiode (APD) have become the most commonly used receivers ("photon counters"). The terminology PIN derives from the semiconductor construction of the device where an intrinsic (I) material lies between the p-n junction of the diode. In general, the PIN costs less but provides slower response time than the APD. See Freeman (24), for example, on the relative merits of the two photodiodes given a set of conditions such as temperature or wavelength.

Modems, Multiplexers, and Repeaters

A variety of fiber optic communications equipment sees use for traffic control applications. For example, modems can transmit data over a dedicated pair of fibers (e.g., between a controller and the traffic operations center), while multiplexers transmit voice, data, and/or video over a fiber backbone network. Most traffic control applications require a mixture of the types of equipment described below. Ultimately, the designer must make several trade-offs (e.g., use more fiber or deploy more multiplexer equipment) before arriving at the final network configuration.

Fiber optic modems convert an electrical signal (e.g., RS-232C) to an optical signal and vice versa, allowing full duplex data communications over one or two fibers. Relatively inexpensive (e.g., $400) fiber modems support data rates up to 19.2 kb/s over a few kilometers, with much higher data rates and/or longer distances also possible. In traffic control applications, fiber modems typically provide a point-to-point connection between a remote data device and the operations center or a communications hub which multiplexes the data and transports it to the operations center.

As previously discussed, the bandwidth of a fiber relates to the link distance. Thus, the maximum repeater spacing in fiber optic networks depends on 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 prove common in fiber networks. With the control area of systems generally within a 24 to 30 km radius, fiber systems can provide excellent unrepeated performance over an entire control area.

Fiber optic repeaters differ from other types in that they do not amplify the optical signal but rather convert it to its original electrical form and then convert it back to an optical signal. Optical signals require this regeneration because pulse dispersion would not be corrected by amplification alone. In some cases, however, system design can address pulse dispersion.

Fiber optic repeaters are sometimes called *regenerators.* New amplification technologies may replace regeneration, however.

If a fiber has multiple drops in series as typically used in small or moderate size traffic signal systems, common practice uses drop/insert units. These units perform the following functions:

- 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
- retransmit the optical signal.

This process also regenerates the signal. In a daisy-chain multiple drop configuration however, any failure of a drop/insert unit results in the loss of every drop beyond the unit. However, units which contain a passive transfer feature can be used to avoid this type of failure.

Table 6-13 describes the types of fiber optics systems commonly used for several traffic control system applications.

Example

Figure 6-13 shows a node for a freeway fiber optic communication system. The distribution system at this node contains a transmitter and receiver which connect to drop/insert (DI) units in the field. The DI unit at Controller No. 1 detects the received signal from the node and electrically sends it to the controller at that location. It also retransmits it to downstream controllers at the specified transmitter power level. The DI unit also receives a signal from the DI unit at Controller No. 2. At some point during the polling cycle, it will add data to the bit stream. It then retransmits the composite signal to the node. The characteristics of the design follow:

- All controllers on the same communication channel operating at a baud rate of 9.6 Kbps.
- Two glass 62.5/125 fiber cables (cables with 62.5 micron core and 125 micron cladding cable diameters).
  - Attenuation of 6 dB per km at 850 nm.
  - Bandwidth-length product of 100 MHz-km at 850 nm.
- Transmitter
  - Provides power at 850 nm launched into 62.5/125 cable ranging from -15 dBM to -20 dBM.
- Receiver
  - Sensitivity is -36 dBM at an error rate of 10^{-9} when connected to 62.5/125 cable
  - Dynamic range of 25 dB.

Application for Traffic Control Systems	Most Applicable Type of Fiber Optic Communication System
Backbone and Trunking Communications Systems	Single mode systems with injection laser diodes used because of longer distance transmission capabilities required. Single mode systems provide higher data rate capabilities.
Distribution Communications Systems	Multimode systems with light emitting diodes usually provide sufficient performance for distributing systems and, where applicable, used to obtain lower cost transmitters, receivers, splices and possible fiber cable.
Communication Systems for Small Closed Loop Traffic Signal Systems	Depending on the distance between controllers, multimode communication systems using regenerative techniques at the intersection are feasible and several manufacturers supply.

Table 6-13 Commom Applications of Fiber Optics Communication Systems to Traffic Control Systems

The design proceeds as follows:

A. Dispersion Check

Check the bandwidth for the longest link. Since the range for the longest link is 0.69 km, the maximum operating bandwidth is

$$BW = \frac{100\ (106)}{0.69} = 144.9MHz$$

Since the planned baud rate is only 9.6 Kbps, no bandwidth limitation is present for this design.

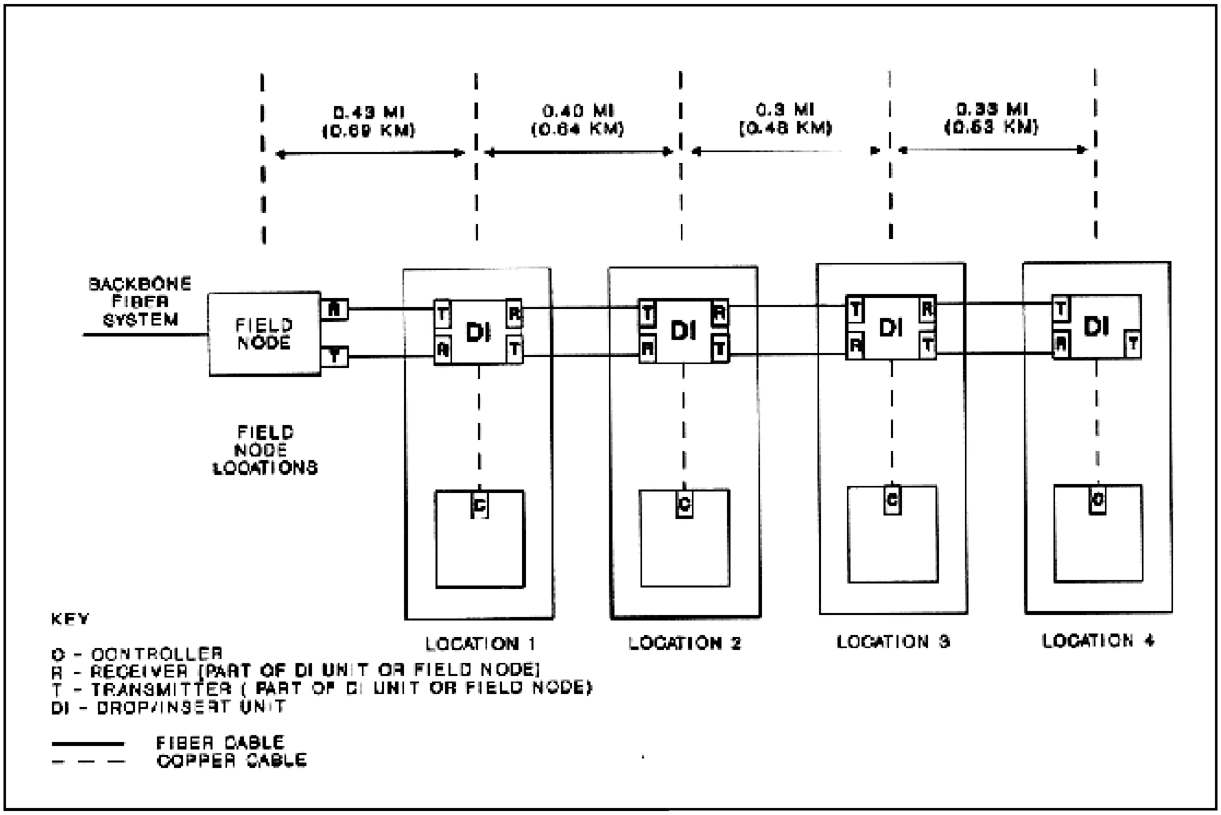


Figure 6-13 Geometric Configuration for Example

B. Power Budget analysis

Compute the power budgets for the longest and shortest links to check both the power margin and receiver dynamic range. Consider the component tolerances and compute the minimum power margin for the longest link and the maximum power margin for the shortest link. Table 6-14 shows the power budgets.

A 9.9 dB power margin, which is satisfactory, is obtained for the longest link case. For the shortest link case, the 15.9 dB power margin is within the 25 dB dynamic range defined by the receiver specification. The design is therefore satisfactory.

Standards

Beginning in 1988, the ANSI T1 standard body defined optical telecommunications interface standards for North America. All the optical transmission systems installed prior to 1988 were proprietary and commonly referred to as asynchronous lightwave transmission systems. The post-1988 set of domestic optical standards are commonly called Synchronous Optical Network (SONET) in ANSI T1 and Synchronous Digital Hierarchy (SDH) in CCITT, which sets international standards for telecommunications.

The SONET standards define transmission capacity, optical interconnects and internal formatted signals in terms of Optical Carrier type N (OC-n) where N specifies capacity in terms of electrical DS3 equivalents (see Table 6-22 for the electrical Digital Signal Hierarchy presented later in this chapter). For example, an OC-3 interconnect specifies a bit rate of 155.52 MB/s and can carry any combination of the same or lower bit rate channels having 3 DS3 equivalent capacity. Therefore, an OC-3 signal can comprise three DS3s, 84 DS1s, 1 DS3 and 56 DS1s, etc. Table 6-15 lists the standard interconnect rates and equivalent channel capacity as defined by ANSI T1 SONET (25).

	Minimum Power for Longest Link	Maximum Power for Shortest Link
Power launched	- 20 dBM	- 15 dBM
Receiver sensitivity for BER 10^{-9}	- 36 dBM	- 36 dBM
Power budget	16 dB	21 dB
Losses at transmitter connector	- 1 dB	- 0.5 dB
Cable attenuation (0.69 x 6)	- 4.1 dB	- 4.1 dB
Losses at receiver connector	- 1 dB	- 0.5 dB
Total Loss	6.1 dB	5.1 dB
Power Margin	9.9 dB	15.9 dB

Table 6-14 Power Budgets for Example

Multiplexing

Most fiber communication uses Time Division Multiplexing. Fiber applications typically implement TDM on a bit-by-bit basis as opposed to the message-by-message technique used in twisted-pair systems. Multiplexers combine many low- to medium-speed digital data channels into high-speed channels, e.g., T1 (1.544 Mbps) or T2 (6.312 Mbps). In many cases, the operation of these multiplexers remains totally transparent to the end user.

Channel	Bit Rate	Equivalent Capacity
OC-48	2.48832 Gb/s	48 DS3
OC-36 *	1.86624 Gb/s	36 DS3
OC-24	1244.06 Mb/s	24 DS3
OC-18 *	933.12 Mb/s	18 DS3
OC-12	622.08 Mb/s	12 DS3
OC-9 *	466.56 Mb/s	9 DS3
OC-3	155.52 Mb/s	3 DS3
OC-1 *	51.84 Mb/s	1 DS3
STS-N +	N (x) 51.84 Mb/s	N (x) DS3

Table 6-15 North American Sychronous Optical Network (SONET) Standards

The following paragraphs describe a number of multiplexer types. Whereas a large traffic system might use all of these, a smaller system would typically use only a subset.

- *Access Multiplexers* - An Access Multiplexer provides low speed interfaces (channel units) to support voice and data services required by traffic control devices. Twenty-four (24) low speed channels multiplex to a higher speed interface (e.g., DS-1), used as the input signal to a DS2 or Digital Backbone Multiplexer. An access multiplexer designed for the roadside environment costs approximately $10,000.

- *DS2 Multiplexer* - A DS2 Multiplexer provides service and protection optics for termination of up to 4 DS1 circuits and supports point-to-point optical spans up to 13 miles. Some traffic control applications can use this multiplexer as part of a secondary communications hub which provides a moderate capacity fiber link to a primary communications hub. This equipment typically costs $12,000 per unit (16).

- *Digital Backbone Multiplexers* - SONET OC-3 multiplexers meet requirements for a high capacity digital fiber backbone to transmit voice, data, and/or video. Suppliers can provide OC-3 Multiplexers for the traffic environment for location at primary communications hubs (e.g., roadside cabinets). SONET OC-3 multiplexers support optical spans up to 30 miles with point-to-point, linear drop, add drop, or self healing fiber ring configurations. Depending on the equipment configuration and features, OC-3 multiplexers range from $30,000 to $45,000 per unit.

  Since a SONET Multiplexer typically provides DS-1 and DS-3 circuit terminations, an Access Multiplexer would provide the direct interface to devices such as controllers, sensors, and telephones. Analog video signals would need digitizing prior to transport over a digital fiber backbone together with voice and data (see Chapter 4).

- *Analog Backbone Multiplexers* - Certain traffic control applications sometimes use Frequency Modulation (FM) Multiplexers, especially for transporting video signals on a fiber backbone. Currently available equipment allows transmission of up to 16 analog video signals on one single mode fiber (26). In this system, the analog FM video system operates in parallel with a digital backbone that transports voice and data. This equipment costs approximately $7,000 for the FM transmitter, and $3,100 for each modulator and receiver. Thus, an analog FM multiplexer supporting six (6) cameras would cost approximately $25,600 ($7,000 + 6 x $3,100).

Examples

This section describes nine traffic control systems (TCS) which use fiber optics wholly or in part and represent a diverse cross-section of the current state-of-the-practice.

The systems represent designs from different time periods. Five TCS are currently operational with the first beginning operations in 1984. Some TCS are currently being implemented, with others in the final stage of design. They support a wide range of applications such as:

- vehicle detection,
- traffic signal control,
- ramp meter control,
- lane control,
- changeable message sign (CMS) control,
- closed circuit TV (CCTV),
- voice communications,
- highway advisory radio (HAR),
- equipment status monitoring.

See Table 6-16 for a summary of applications supported by each TCS.

The following paragraphs briefly describe each of the nine TCS, and compare communication networks with respect to:

- network topology,
- media
- transmission systems.

Finally, some general conclusions are drawn and projected trends discussed.

- *Highway 401 (Toronto)* - The first phase of Toronto's Freeway Traffic Management System, which covers 9.6 miles (16 km) of Highway 401, became operational in 1990. A phased expansion is planned for Highway 401 and the Queensway, but this discussion only considers the first phase of the project. TCS applications provided for Highway 401 include vehicle detection, CCTV, changeable message signs, voice communications, ramp metering (future), lane control signals (future), and highway advisory radio (future) (27, 6).
- *Shirley Highway Extension (Virginia)* - The Shirley Highway Extension provides a 20 mile extension to an existing TCS which uses a coaxial cable communication system. The original TCS became operational in 1985, and supports the following applications: vehicle detection, changeable message signs, ramp metering, and CCTV. The Shirley Highway Extension became operational in 1990 and supports nine CCTV cameras (28).
- *I-70 Hanging Lake Tunnel (Colorado)* - Hanging Lake Tunnel is approximately 1 mile and contains a separate passage for eastbound and westbound traffic. The TCS, currently under construction, supports vehicle detection, changeable message signs, dynamic signals, and remote terminal units for power and process equipment (7).
- *Hanshin Expressway (Japan)* - The Hanshin Expressway refers to a network of roads operated by the Hanshin Expressway Public Corporation. As of July 1990, the Hanshin Expressway approximates 91 miles and serves the cities of Osaka and Kobe. Additional routes are currently under construction. The Hanshin Expressway TCS, which first became operational in 1984, currently has three control centers and supports the following applications: vehicle detection, changeable message signs, CCTV, and HAR (29, 30).
- *ATSAC (Los Angeles)* - The first phase of the Los Angeles Automated Traffic Surveillance and Control (ATSAC) System became operational in June 1984, encompassing 4 square miles and controlling 118 intersections with 396 detectors. Currently ATSAC controls more than 650 signalized intersections. Los Angeles initiated a ten year implementation plan in 1988, with the ultimate goal to have the City's 4000 signalized intersections within ATSAC by 1998. TCS applications supported by ATSAC include vehicle detection, intersection control signals, and CCTV (31).
- *George Massey Tunnel (British Columbia)* - The George Massey Tunnel TCS is operational and currently supports a six camera CCTV system. Plans for future applications include vehicle detection, ramp metering, changeable message signs, and lane control signals (32).
- *Gulf Freeway, North Freeway and US 290 (Houston)* - Some parts of the Houston Freeway Management System are currently under construction, with others in the design phase. The system will eventually cover approximately 350 miles and address the needs of Metro, State, City and County authorities by supporting the following applications: intersection control signals, lane control signs, dynamic signs (wrong way), changeable message signs, vehicle detection, parking lot ramp metering, CCTV, service telephones, HAR, and equipment status (33).
- *Surveillance, Control, and Driver Information (Seattle)* - The Surveillance, Control and Driver Information (SC&DI) system for Washington State District One (Seattle) is currently under design. When complete, the system will include approximately 279 miles of arterial roads and freeways. The system will support the following TCS applications: ramp metering, vehicle detection, changeable message signs, CCTV, HAR, gates for

reversible lanes, and emergency telephone service (26).

- *Freeway Management System (San Antonio)* - The San Antonio Freeway Management System is currently under design. The first phase covers approximately 27 miles of freeway, with the total system expected to cover approximately 192 miles. The system will support the following TCS applications: vehicle detection, lane control signals, changeable message signs, CCTV, and emergency telephone service (34).

Applications	Selected Traffic Control Systems								
	Hwy 401	Shirley Hwy	I-70 Tunnel	Hanshin Expwy	ATSAC	Massey Tunnel	Houston	Seattle	San Antonio
Vehicle Detection (counts, speed)	O	O	P	O	O	P	P	P	P
Changeable Message Signs	O	O	P	O		P	P	P	P
Dynamic Signals (lane control)	P		P			P	P		P
Intersection Control Signals					O		P		
Ramp Metering	P	O				P	P	P	
Gates for Reversible Lanes		O						P	
Closed Circuit TV	O	O		O	O	O	P	P	P
Telephone Service	O						P	P	P
Highway Advisory Radio	P			O			P	P	
Equipment Status (power)			P				P		

O = OPERATIONAL P = PLANNED

Table 6-16 Applications Supported by Nine Traffic Control Systems

Network Topology

The nine TCS use four topologies for backbone and distribution communications networks, as illustrated in Figure 6-14.

The Backbone Communications Network refers to a high capacity trunk which transmits data from multiple devices using some form of multiplexing. The Distribution Communications Network provides a dedicated transmission link to one device, or multiple devices which share the same link using an access technique such as polling and can take the following forms:

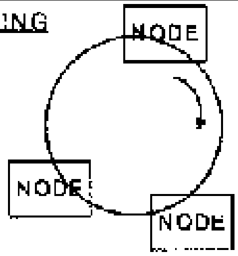
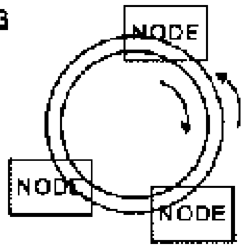
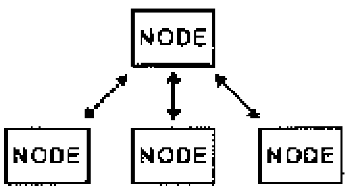
	BACKBONE NETWORK	DISTRIBUTION NETWORK
UNPROTECTED RING 	HANSHIN EXPWY (DATA)	
PROTECTED RING 	HIGHWAY 401 (DATA) I-70 TUNNEL SEATTLE	
LINEAR DROP 	HOUSTON SEATTLE SAN ANTONIO SHIRLEY HWY EXTENSION	HWY 401 (CONTROLLERS) SEATTLE
STAR 	HIGHWAY 401 (VIDEO) ATSAC HOUSTON SAN ANTONIO (INITIAL INSTALLATION, ULTIMATE CONFIGURATION WILL BE PROTECTED RING)	HIGHWAY 401 SHIRLEY HWY EXTENSION I-70 TUNNEL HANSHIN (DATA, VIDEO) ATSAC MASSEY TUNNEL HOUSTON SEATTLE SAN ANTONIO

Figure 6-14 Traffic Control System Communications Network Topologies

- **Unprotected Ring** - Each node (i.e., communications hub or TCS equipment) connected to two others by a uni-directional transmission link, creating a "closed" loop.

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

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

- **Star** - Communication links emanated from a source node (e.g., traffic control center) to multiple secondary nodes (e.g., communication hub or TCS equipment).

Most of the nine systems use a combination of network topologies. The Seattle TCS plans to use a protected ring for the majority of the backbone network, but a linear arrangement where the road network does not support a ring topology. Houston plans to use a star topology for backbone communications between central and satellite hubs, and a linear backbone topology between satellite and field hubs. San Antonio uses a star topology but specifies diversely routed backbone media for protection against cable cuts. Hence, the resulting physical topology resembles a protected ring.

As shown in Figure 6-14, approximately half the TCS use a ring topology for the backbone network. Interestingly, neither of the currently operating ring TCS (i.e., I-70 Tunnel, Hanshin Expressway) use this network topology for transmitting CCTV. The Seattle TCS, currently under design, plans to transmit voice, data, and video over a protected ring network.

Houston, Shirley Highway, San Antonio, and ATSAC use linear or star topologies as the primary network topology. In addition, Highway 401 and Seattle augment their ring topologies with a linear or star network. Both TCS which support intersection control signals use a star topology for at least a portion of their communications network, providing one example of how system requirements (e.g., location of controllers) may dictate the backbone network topology.

As for the distribution network, the nine TCS use a star topology. In a few special cases, a linear topology (i.e., daisy chaining) is also used to communicate with selected devices.

Media

Table 6-17 identifies the media used by each TCS for the backbone network and three distribution network applications, voice, data, and video. The following paragraphs explain each application:

- *Backbone Network - Voice, Data, Video*

- All the TCS except the Shirley Highway Extension use single mode or multimode fiber for their backbone communications network. The Shirley Highway Extension uses an existing coaxial cable for backbone communications. Based on the previous definition of backbone network (i.e., transmits multiplexed signals), the George Massey Tunnel CCTV system classifies as a distribution network and does not include a backbone.

- *Distribution Network - Voice*

  The four TCS that support voice applications all use twisted copper pair media for connecting telephones to a communications node on the backbone.

- *Distribution Network - Data*

  Six TCS use twisted copper pair media for connecting data devices or controllers to a communications node on the backbone network, while two TCS (Highway 401, I-70 Tunnel) use multimode fiber. One reason cited for using fiber media for data applications was to extend the distance between a communications node and remote devices.

- *Distribution Network - Video*

  Seven TCS use either single mode or multimode fiber for transmission of video signals to a communications node or directly to the control center. In the distribution network, each camera uses a dedicated fiber with camera controls (pan/tilt/zoom) typically treated as a separate data application and served by twisted pair media.

The San Antonio TCS plans to use coaxial cable to transmit video signals from individual cameras to a communications node. Also, note that the Los Angeles ATSAC, which plans to use fiber for future CCTV applications, currently uses three other types of communication for CCTV: coaxial cable (RG11), conditioned twisted 16-gauge and 22-gauge pairs, and atmospheric lasers for line of sight distances up to 1 km (31).

Applications	Selected Traffic Control Systems								
	Hwy 401	Shirley Hwy	I-70 Tunnel	Hanshin Expwy	ATSAC	Massey Tunnel	Houston	Seattle	San Antonio
Backbone Network - Voice, Data, Video (between nodes)	fiber-sm	coax	fiber-mm	fiber-mm	fiber-mm	n/a	fiber-sm	fiber-sm	fiber-sm
Distribution Network - Voice (device to node)	copper	n/a	n/a	n/a	n/a	n/a	copper	copper	copper
Distribution Network - Data (device/controller to node)	fiber-mm	copper	fiber-mm	copper	copper	n/a	copper	copper	copper
Distribution Network - Video (camera to node)	fiber-mm	fiber-sm	n/a	fiber-mm	coax copper lasers fiber *	fiber-mm	fiber-mm	fiber-mm	coax

Table 6-17 Backbone and Distribution Media Used by Nine Traffic Control System Communication Networks

Transmission Systems

Table 6-18 summarizes the characteristics of transmission systems used for TCS backbone and distribution communications networks. The table considers each TCS in terms of two backbone network applications (Voice & Data, Video) and three distribution network applications (Voice, Data, Video). The table summarizes four types of information in the matrix cells:

- Analog/Digital Signal,
- Transmission Rate,
- Standards,
- Multiplexing Technique.
- Backbone Network - Voice & Data

All TCS that support voice and data applications, except the Shirley Highway system, use a digital fiber backbone network. ATSAC and the not-yet-operational systems (i.e., I-70 Tunnel, Houston, Seattle, San Antonio) all comply with the Digital Signal (DS) hierarchy and/or Synchronous Optical NETwork (SONET) standard. Excluding ATSAC, the operational TCS (i.e., Highway 401, Hanshin Expressway) have backbone networks that provide relatively high data rates (i.e., 25 and 32 Mbps, respectively).

- Backbone Network - Video

A variety of approaches transmit video on the backbone communications network.

Some TCS (i.e., Hanshin Expressway, ATSAC, George Massey Tunnel) do not use a backbone network for transmitting video, instead providing a dedicated analog transmission path from each camera to the control center. Seattle plans Frequency Modulation/Frequency Division Multiplexing (FM/FDM) to transmit up to 16 video signals on a single backbone fiber, with a second fiber allocated if there are more than 16 cameras associated with a communications hub. The Seattle network designers recommend that each communications hub use a separate fiber to transmit video signals to the control center.

The previously mentioned TCS all transmit video and voice/data on separate backbone networks, although in some cases the fibers are provided in the same cable. The San Antonio TCS plans to use DS3 codecs to transform the analog distribution network video signals into a digital signal transmitted over the same backbone network as voice and data. This approach reduces the amount of fiber required in the backbone network and simplifies network management, but requires relatively high transmission rates (e.g., San Antonio specifies 155.52 Mbps).

- Distribution Network - Voice

  All TCS that support voice services use analog transmission over twisted copper pairs between telephones and communications nodes, where a standard DS0 (64 kbps) interface at the communications node provides access to the backbone network.

- Distribution Network - Data

  Transmission rates for distribution network data devices and controllers range from 1.2 to 56 kbps. The two TCS (i.e., Highway 401, I-70 Tunnel) which use fiber media for communicating to data devices transmit information at 9.6 kbps via fiber optic modems. Other TCS use modems or Data Service Units (DSUs) to transmit data over twisted copper pair media.

- Distribution Network - Video

  The eight TCS that support CCTV all transmit analog baseband video signals in the distribution network from cameras to a communication node or the control center. Seven of the eight TCS either use or plan to use fiber as the CCTV transmission medium, while San Antonio plans to use coaxial cable. As previously mentioned, ATSAC currently uses three other types of communication for CCTV.

Applications	Selected Traffic Control Systems								
	Hwy 401	Shirley Hwy	I-70 Tunnel	Hanshin Expwy	ATSAC	Massey Tunnel	Houston	Seattle	San Antonio
Backbone Network - Voice and Data • Analog/Digital Signal • Transmission Rate (Mbps) • Standards	Digital 25 prop.	Analog	Digital 1.544 DS1	Digital 32 prop.	Digital 1,544 DS1	n/a	Digital 1.544 DS1	Digital 1.5,6.3,51 DS1,DS2,OC1	Digital 155 OC3
Backbone Network - Video • Analog/Digital Signal • Multiplexing Technique	Analog yes	Analog FM	n/a	Analog none	Analog none	n/a	currently undefined	Analog FM/FDM	Digital TDM
Distribution - Voice • Analog/Digital Signal	Analog	n/a	n/a	n/a	n/a	n/a	Analog	Analog	Analog
Distribution Network - Data • Transmission Rate (Kbps)	9.6	not specified	9.6	unknown	1.2	n/a	9.6	not specified	2.4 - 5.6
Distribution - Video • Analog/Digital Signal	Analog	Analog	n/a	Analog	Analog	Analog	Analog	Analog	Analog

Table 6-18 Transmission Rates, Interfaces, and Standards Used by Nine Traffic Control Systems

Conclusions

Comparing the nine systems leads to the following conclusions and trends:

- Fiber optic cable seems the media of choice for owned land line communications backbones serving medium and large freeway surveillance systems and large centralized traffic signal systems. Expect that fiber optics will also find use in smaller freeway systems with owned land lines where support of full motion or compressed video is required.

- Some TCS use fiber in the distribution network for data applications. Use of fiber for this application could expand if the bandwidth requirements for data devices/controllers increase, possibly due to new Intelligent Vehicle Highway System (IVHS) devices. However, twisted copper pairs will remain the media of choice for this application, with use of wireless communications increasing over the next few years.

- The TCS communications network designs reflect a concern for network reliability by using:
    - protected ring network topologies,
    - diverse routing of backbone cables,
    - transmission equipment with automatic protection switching,
    - allocation of spare media.

- Some TCS systems use common telephone communications standards such as the electrical Digital Signal hierarchy and SONET. These standards will see increasing use, especially for TCS that serve large areas or must have compatibility with other local TCS to form a regional system.

- Current TCS use a variety of approaches for transporting video on the backbone communications network, including:
    - dedicating fibers from each camera to the control center
    - transmitting analog multiplexed video signals on a video-only backbone,

- transmitting digitized multiplexed video signals on a voice-data-video backbone.

- For TCS that serve a small area (e.g., bridge, tunnel), coaxial cable or dedicated fibers will likely continue serving individual cameras. For TCS that serve a large area, many systems will use an analog multiplexing technique with digitized video becoming increasingly popular based on expected advances in video compression technology.

Leased Line Options

Many traffic control applications use leased lines for communications to field devices. This section provides an overview of leased analog and digital services available from Local Exchange Carriers (LECs), Cable TV Providers, and Metropolitan Area Network Vendors.

Characteristics * (5)

A leased communications network provides an alternative to jurisdiction-owned cable. Developing the configuration and cost of a leased communications system necessitates working closely with representatives of the provider. These representatives should include engineering, sales, and data transmission personnel. The designer should advise the provider as to:

- data characteristics
- data rates and bandwidth required,
- desired quality,
- operational aspects of the system (e.g., once-per-second/dial-up communications, full/half-duplex, etc.), and
- field locations (e.g., controller/ramp meter cabinets) included in the system.

All parties should clearly define and understand the following information:

- Characteristics of the leased channels and equipment restrictions. This includes:
  - 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 provider to furnish service to the field locations and capability for expansion.
- Estimated time to provide service.
- Location of the nearest access point to the provider's cable from each field cabinet, and the division of work between the provider and 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 provider's lines from controller equipment. Telephone company termination equipment usually requires a separate access door or separate cabinet mounted on the side of traffic control cabinet.
- Rules regarding leased circuit terminations at the central facility, including any equipment which the jurisdiction must furnish.
- Complete understanding of the 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 provider and of the jurisdiction. Maintenance policies of the provider, including response time and method for determining charges if fault is determined in the jurisdiction's equipment after the provider maintenance has been called for and furnished.
- After obtaining the above information, the designer can develop leased network configurations to obtain cost estimates for the trade-off analysis. In addition to the provider's fees and charges, the cost of leased alternatives must also include the construction of connection facilities (e.g., conduit laterals) between the provider's termination point and the controller/ramp meter cabinets, and the cost of any special hardware required to interface with the provider's circuits.

Local Exchange Carriers

Local Exchange Carriers include the seven Regional Bell Operating Companies (RBOCs) and hundreds of smaller independent telephone companies that provide "local" telephone service. By law these companies can only provide service within a designated area called a Local Access and Transport Area (LATA), which may correspond to a metropolitan area, a region in a state, or even an entire state. Long distance carriers such as AT&T, MCI, and Sprint handle communications between LATAs (i.e., inter-LATA), with the LEC providing access from the customer premises to the long distance carrier point of presence.

Most traffic control applications require communications within a single LATA (i.e., intra-LATA), meaning solely the LEC provides leased communications services. The availability of specific services and their corresponding tariffs vary across the country since each state regulates its LECs. The following sections describe LEC provided leased communications services appropriate for traffic control applications.

Voice Grade Line

Many traffic control applications such as signal control and vehicle detection use low speed modems (e.g., 1200 baud) for communications over voice grade circuits.

Tariffs filed with the appropriate state regulatory agency specify the price for private lines within a state. Typically, tariffs may include:

- a one-time charge for installing the private line channel,
- a monthly charge for each termination,
- a monthly charge based on airline mileage for the length of the local or interoffice channel,
- a monthly charge for optional features (e.g., line conditioning).

Table 6-19 shows some illustrative pricing data from current tariffs to estimate the lease cost of a voice grade channel circuit. For example, in the State of New Jersey, a full duplex circuit between a traffic operations center and traffic signal where the same central offices serves both terminations would cost $76.00 per month (i.e., 2 x $38.00) with an installation fee of $143.00. The provider charges an additional $14.02 per month if different central offices in the same exchange serve the terminations.

Table 6-20 provides examples of tariff charges for interoffice service.

Digital Line Options

- Private Line Data Service

- The LECs also offer digital private line data service, providing for the duplex transmission of digital signals using digital facilities. Synchronous speeds of 2.4, 4.8, 9.6 or 56 Kbits per second can serve to communicate to field devices or maintenance shops. Potential applications for these services include communication between traffic control centers.

- Similar to voice grade lines, tariffs filed with the appropriate state regulatory agency specify the price for digital private line data service. Table 6-21 provides several examples of pricing data from current tariffs. In general, digital private line tariffs include a nonrecurring installation charge and monthly charge for each digital access line, and a monthly charge based on mileage for interoffice channels.

- For example, a New Jersey Bell 2.4 kbps private line digital circuit, with both stations served by the same central office, costs $323/month ($161.50 x 2) with an installation charge of $300 ($150 x 2). The interoffice channel monthly charge ($30.25 plus $0.25 per airline mile) adds to the $323/month with the circuit end-points served by different central offices.

State	Channel Type	Type 3002 Channel (2 Channels Per Circuit)	
		Non-Recurring Charge	Monthly Charge
California	Half Duplex Full Duplex	$ 358.00 $ 358.00	$ 13.46 $ 22.61
Colorado	Half Duplex Full Duplex	$ 110.00 $ 110.00	$ 10.89 $ 21.80
Connecticut	Half Duplex Full Duplex	$ 118.31 $ 118.31	$ 11.43 $ 16.79
Illinois	Half Duplex Full Duplex	$ 253.93 $ 253.93	$ 15.73 $ 18.07
Massachusetts	Half Duplex Full Duplex	$ 205.25 $ 205.25	$ 23.18 $ 26.57
Nevada	Half Duplex Full Duplex	N/A N/A	$ 35.50 $ 35.50
New Jersey	Half Duplex Full Duplex	$ 135.00 $ 143.00	$ 38.00 $ 38.00

Table 6-19 Illustrative Tariffs for Private Line Local Channels **Note(6)**

- The LECs also make available higher capacity digital transmission channels such as fractional T1 and T1 (i.e., 1.544 Mbps). These facilities might transmit coded video or link traffic operations centers. The Pennsylvania DOT, for example, currently plans to lease such lines to transmit coded video from several cameras in the Philadelphia area to a control center more than 15 miles distant. In New Jersey, the T1 tariff is:

  - $215 per month per local distribution channel (2 local channels per circuit),
  - $166 per month for an interoffice channel, and
  - $326-$539 installation charge for each local channel.

  The T1 tariff in Pennsylvania is:

- $319 per month per local channel,
- $660 installation charge per termination,
- $38 per mile for interoffice channels.

INTEROFFICE CHANNEL (Distance measured in airline miles)	
NEW JERSEY BELL	• $14.02/month if terminations in same exchange but different offices • $11.67/month for first mile and $3.35/month for additional miles if terminations in different exchanges
ILLINOIS BELL	• $20.70/month for first 1/4 mile and $.40/month for additional 1/4 miles for distances less than 12 miles • $31.10/month for first mile and $1.70/month for additional miles for distances of 12 or or more miles
PACIFIC BELL	• $0.53/month for first 3 miles for intraexchange, intradistrict area and increasingly smaller charges for additional miles • $5.23/month for first 10 miles for interchange, interdistrict area and increasingly smaller charges for additional miles
INSTALLATION (One time charge)	
NEW JERSEY BELL	• $135.00 to $143.00 when terminations are in the same exchange and central office • $248.00 to $252.00 when terminations are in the same exchange and different central offices • $252.00 to $289.00 when terminations are in different exchanges
PACIFIC BELL	• $358.00 plus unspecified mileage based one-time charge

Table 6-20 Examples of Interoffice Tariff Charges

State-Service Name	Data Rate (Kbps)	Digital Access Channel Termination		InterOffice Channel Monthly Charge	
		Non-Recurring Charge	Monthly Charge	Fixed	Per Airline Mile
Arizona - Digicom I	2.4 4.8 9.6 56	$ 500.00 $ 500.00 $ 500.00 $ 500.00	$ 87.75 $ 89.12 $ 107.77 $ 275.93	$70-$117 $70-$143 $70-$166 $70-$325	0-$1.40 0-$1.56 0-$1.95 0-$10.40
Colorado - Dataphone Digital Service	2.4 4.8 9.6 56	$ 106.80 $ 106.80 $ 106.80 $ 106.80	$ 67.61 $ 96.15 $ 159.67 $ 287.27	$ 45.00 $ 90.00 $ 180.00 $ 560.00	$ 0.30 $ 0.55 $ 0.90 $ 4.00
Connecticut - Digital Data Service	2.4 4.8 9.6 56	$ 520.55 $ 520.55 $ 520.55 $ 591.53	$ 113.58 $ 113.58 $ 113.58 $ 260.29	N/A N/A N/A N/A	$ 3.55 $ 3.55 $ 3.55 $ 4.50
District of Columbia - Digital Data Service	2.4 4.8 9.6 56	$ 55.13 $ 55.13 $ 55.13 $ 135.51	$ 97.61 $ 131.12 $ 174.18 $ 322.09	N/A N/A N/A N/A	N/A N/A N/A N/A
Florida - Dataphone Digital Service	2.4 4.8 9.6 56	$ 93.00 $ 93.00 $ 93.00 $ 93.00	$ 67.50 $ 80.00 $ 142.50 $ 244.65	$ 62.50 $ 93.75 $ 156.25 $ 593.75	$ 0.95 $ 1.25 $ 1.55 $ 5.65
Michigan - Dataphone Digital Service	2.4 4.8 9.6 56	$ 65.56 $ 65.56 $ 65.56 $ 98.34	$ 73.48 $ 96.81 $ 129.15 $ 268.08	$ 48.29 $ 50.53 $ 77.49 $ 168.46	$ 0.40 $ 0.45 $ 0.75 $ 3.37
New Jersey - Digital Data Service	2.4 4.8 9.6 56	$ 150.00 $ 150.00 $ 150.00 $ 150.00	$ 161.50 $ 192.30 $ 249.41 $ 287.23	$ 30.25 $ 32.90 $ 47.11 $ 75.00	$ 0.25 $ 0.40 $ 0.62 $ 3.10
New York - Digipath Digital Service	2.4 4.8 9.6 56	$ 443.63 $ 443.63 $ 443.63 $ 443.63	$ 113.22 $ 139.67 $ 176.70 $ 271.93	$ 28.80 $ 37.70 $ 56.57 $ 82.90	$ 0.13 $ 0.24 $ 0.48 $ 2.40

Table 6-21 Illustrative Tariffs for Digital Private Line Services **Note(7)**

- Telecommunication Standards for High Data Rate Channels

  The American National Standards Institute (ANSI) T1 standards organization currently defines electrical telecommunications standards for North America. ANSI T1 standards specify:

  - network facility interface points,
  - transmission speeds,
  - signal formats, and
  - standard vendor interconnect specifications.

Table 6-22 provides a condensed view of the North American electrical digital hierarchy illustrating standard interconnect rates or channels used by telecommunications exchange carriers. These specifications form the basis for the majority of North American public and private telecommunications networks.

"T1" service within the network refers to a Digital Signal Type 1 (DS1) formatted signal and can carry 24 Digital Signal Type 0 (DS0) voice channels, 24 DS0A data channels, or a combination of voice and data. DS0/DS0A formatted signals provide voice and low speed data services, typically carried on a 2-wire or 4-wire twisted pair circuit for distances up to two miles from a switch or point of origin. Twisted pair media can also transport DS1 signals between communications hubs. Twisted pair media typically do not carry higher rate channels (e.g., DS2, DS3), generally a higher bandwidth transport media such as fiber, microwave, etc. carry these channels.

The T1 protocol uses a timing reference scheme. If timing synchronization is lost, the information recovery time can reach 50 milliseconds although normally lower. The traffic control system design must accommodate this possibility.

Channel	Bit Rate	Composition
DS3	44.736 Mb/s	28 DS1 Equivalent Capacity
DS2	6.312 Mb/s	4 DS1 Equivalent Capacity
DS1C	3.152 Mb/s	2 DS1 Equivalent Capacity
DS1	1.544 Mb/s	24 DS0 Equivalent Capacity
DS0	64 Kb/s	DS0, DS0A, or DS0B Rate Only
DS0A *	64 Kb/s	2.4, 4.8, 9.6, 19.2 or 56 Kb/s, or 56 Kb/s carried on a single DS0
DS0B *	64 Kb/s	20 (2.4 Kb/s), 10 (4.8 Kb/s), or 5 (9.6 Kb/s) multiplexed onto a single DS0

Table 6-22 North American Electrical Digital Hierarchy Standards ***Note(8)***

- Integrated Services Digital Network

The Integrated Services Digital Network (ISDN) provides support for voice and non-voice applications using a limited set of standardized facilities. The following types of channels construct any ISDN access link:

- B channel (64 kbps): used to carry digital voice or data
- D channel (16 or 64 kbps): carries signaling information and packet data
- H channel (384, 1536, and 1920 kbps): used for high speed applications such as fast facsimile

The ISDN Basic Rate Interface (BRI) consists of two full duplex B channels and a full duplex 16 kbps D channel, and targets most individual users. The ISDN Primary Rate Interface (PRI) comprises 23 B channels and one 64 kbps D channel in the United States. PRI targets users with greater capacity requirements, such as an office with a digital PBX (35). For a complete technical description of ISDN, see reference (36).

As shown in Table 6-23, current and projected deployment of ISDN varies considerably depending on the region of the country (37). Bellcore or the local exchange carrier can provide more detailed information on specific services supported (e.g., voice, voice/data) and ISDN deployment plans for a particular city. (38).

To evaluate ISDN cost, consider:

- terminal equipment,
- installation, and
- monthly service costs.

RBOC	% Lines with Access to ISDN	
	1991	1994
Ameritech	16	87
Bell Atlantic	36	90
BellSouth	15	52
NYNEX	10	27 in 1993
Pacific Bell	24	40-50
Southwestern Bell	8	32
US West	20	51

Table 6-23 Current and Projected ISDN Deployment

A recent review of ISDN equipment reported prices for PC adapter boards ranging from $1000 to $2000. ISDN installation and service costs vary by RBOC and state and are generally provided on an individual case basis. As an example, Ameritech cites the approximate BRI installation and monthly service charges for Centrex and business line users as $250 and $29, respectively. BRI installation and monthly service charges for Pacific Bell Centrex business and residential users approximate $150 and $17.50-$29.50, respectively.

Cable TV Providers * (9)

Although fiber optics has largely supplanted coaxial cable for new large scale traffic systems, community antenna television (CATV) may still find use for traffic system communications to avoid the cost of owned land lines or telephone line rental charges.

CATV may prove a reasonable option if:

- franchise agreements allow government use of CATV cable or,
- the cable company offers communication channels at favorable rates, and

- technical requirements (routing, bandwidth, fidelity and reliability) prove satisfactory.

However, channel limitations will probably preclude significant levels of video surveillance. For example, traffic control systems in Overland Park, Kansas, Grand Rapids, Michigan, Paterson, New Jersey, Casper, Wyoming, London, Ontario, and Brampton, Ontario all use communication facilities provided by the CATV system operator. For these systems, 1-3 outbound channels and 2-4 inbound channels provide communications to intersection control units (39). In some cases, CATV implementation did not prove successful. In Arlington, Virginia, for example, due to noise problems in the CATV system, a traffic control system never became operational, and the agency replaced it with a twisted pair cable network.

Data transmission techniques used for CATV networks prove very similar to those discussed in the previous section on coaxial cable. Some constraints may exist 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 distributes uniformly 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 approximate those in dedicated cable systems, except the CATV franchise handles them. If a choice of frequencies exists, examining the channels with a spectrum analyzer can indicate which channels will least likely suffer from excessive noise and interference.

Fiber optic transmission technology is currently available to CATV providers and some providers have plans to convert their networks. The CATV technology is generally compatible with traffic control system requirements; however, the feasibility of utilizing this technology must be studied for each system.

Applications

Because of their similarity in media and design, CATV networks appear appropriate for nearly all applications previously discussed for dedicated coaxial cable systems. However, CATV represents both a shared resource and a leased medium, which makes it unique in certain respects. These differences result in advantages and disadvantages, as summarized in Table 6-24.

Note, 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 depends on its exact language. Franchise agreements which indicate that the franchise "must comply with 47 CFR 76.254" cannot be enforced while those 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 the CATV company will make available channels for traffic control.

Design Considerations

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

- Review franchise agreements to assure available upstream and downstream channels; and adequate frequency allocation. Feasibility testing of the CATV network may prove worthwhile. The CATV company, should assure cooperation and assist implementation of communication links to controller cabinets and the central signal control facility.

- Develop acceptance test criteria for the CATV communication network and invoke in an agreement between the system owner and CATV company. Incorporate these criteria in the systems specifications. (This assigns responsibility and requires the appropriate party to make corrections if the system does not operate properly). Clarify maintenance responsibilities and stipulate response time for repair.

- Obtain a firm commitment from the franchise to the support and maintenance necessary for reliable communications.

Advantages

- A single 6 MHz channel adequate for data transmission.
- Network already in place.
- Design effort and initial installation cost much lower than a dedicated coax system.
- Franchise agreement may provide for government use of CATV cable and bandwidth at reduced rates or free, reducing recurring costs.
- A second separate coax institutional network (I-net) may exist for the express purpose of providing bidirectional services to commercial subscribers.
- I-nets generally provide good levels of service to subscribers.

Disadvantages

- Most CATV networks designed and installed with emphasis on downstream transmission of video signals to cable subscribers.
- Video channels take up most available bandwidth.
- Bandwidth available to traffic control may be very narrow, ranging from a single 6 MHz channel to 4 or 5 channels.
- A single 6 MHz channel does not support full motion video transmission in addition to data communications.
- Frequencies of available channels often least desirable in susceptibility to noise and interference.
- Quality of video signal required for CATV considerably less than required for data. (Noise which does not adversely affect video (e.g., lines on a TV picture) may interfere with data transmission.)
- CATV subscriber facilities sometimes concentrated in residential areas.
- Service to the central business district (CBD) and industrial areas sparse or non-existent.
- Area of coverage and network layout may not coincide with traffic signal locations.
- Traffic control system may have to compete with other public section I-net users for more desirable channels.

Table 6-24 Advantages and Disadvantages of CATV

<u>Maintenance</u>

As in other leased facilities, external parties handle maintenance. In CATV this can prove 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 critical to CATV operation. Therefore, for a problem not affecting the majority of subscribers, the operator may not provide expedient service and repair. On the other hand, some CATV franchisees have proved conscientious in the maintenance of their system for data transmission.

Alternative Metropolitan Area Network Vendors

Similar to the increased competition which emerged in the 1980's for long distance, Local Exchange Carriers (LECs) now face increasing competition from alternative local communications providers. These metropolitan area network vendors have deployed or are deploying high capacity fiber networks that run throughout high volume communications areas (e.g., downtown business districts). Today, there exist a number of alternate access providers (see Table 6-25) that expect to operate in 46 of the 75 largest cities in the U.S. by the early 1990's.

Alternative local transport providers allow customers to obtain direct access to long distance carriers or implement point to point links. For example, two office buildings located near Metropolitan Area Network nodes may lease a DS1 circuit. A recent agreement in New York allows one alternative access vendor to also supply circuits to the LEC central office, thereby providing access to local switched services (40). Other vendors are working to obtain similar agreements with the LECs.

Most alternative access vendors offer high capacity DS1 and DS3 circuits. In addition, some vendors supply voice grade, digital data service, and/or fractional T1 circuits. Depending on the alternative access vendor, prices for these services may approximate the LEC tariff (see Table 6-19) or discounted as much as 10-15%.

Traffic control applications may use alternative fiber network vendors in specialized circumstances. For instance, a metropolitan traffic control application requiring high capacity leased links between traffic control centers might benefit by using an alternative access provider, assuming the network serves the desired locations. On the other hand, an alternative access vendor may not provide service for low capacity data links to scattered locations as required for many traffic control applications.

Future Directions

Fiber To The Curb/Home

The Local Exchange Carriers (LECs) continue to evaluate the deployment of fiber in the local loop as a replacement or complement to copper twisted pairs. With the additional bandwidth provided by fiber, the LEC network could deliver high bandwidth information services (e.g., cable TV) to customers. To date, the LECs have performed several "fiber to the curb/home" trials, but have not committed to deployment. Fiber to the curb/home could impact design of communications for traffic control systems which require wide bandwidth to field locations.

ACC Corp. Rochester, NY	Intermedia Communications of Florida, Inc. Miami, FL	Metropolitan Fiber Systems, Inc. Philadelphia, PA
Associated Communications of Los Angeles Los Angeles, CA	Intermedia Communications of Florida, Inc. Orlando, FL	Metropolitan Fiber Systems, Inc. Pittsburgh, PA
Atlantic Communications Enterprises Atlantic City, NJ	Intermedia Communications of Florida, Inc. Tampa, FL	Metropolitan Fiber Systems, Inc. San Francisco, CA
Bay Area Teleport Alameda, CA	Kansas City FiberNet Kansas City, MO	MTEL Digital Services, Inc. Irvine, CA
City Signal, Inc. Kalamazoo, MI	Linkatel Communications, Inc. Carlsbad, CA	MWR Telecom, Inc. Des Moines, IA
Comtech Network Systems Group Baldwin, MO	LOCATE New York, NY	New England Digital Distribution, Inc. Boston, MA
Diginet Communications, Inc. Chicago, IL	Metrex Corp. Atlanta, GA	Penn Access Corp. Pittsburgh, PA
Diginet Communications, Inc. Milwaukee, WI	MetroComm, Inc. Columbus, OH	Phonoscope Communications, Inc. Houston, TX
Digital Direct, Inc. Dallas, TX	Metropolitan Fiber Systems, Inc. Baltimore, MD	Privacom, Inc. Charlotte, NC
Digital Direct, Inc. Seattle, WA	Metropolitan Fiber Systems, Inc. Boston, MA	Teleport Communications Group Boston, MA
Eastern TeleLogic Corp. King of Prussia, PA	Metropolitan Fiber Systems, Inc. Chicago, Il	Teleport Communications Group Chicago, IL.
Electric Lightwave, Inc. Portland, OR	Metropolitan Fiber Systems, Inc. Dallas, TX	Teleport Communications Group Dallas, TX
Electric Lightwave, Inc. Seattle, WA	Metropolitan Fiber Systems, Inc. Houston, TX	Teleport Communications Group Houston, TX
FiberNet, Inc. Rochester, NY	Metropolitan Fiber Systems, Inc. Los Angeles, CA	Teleport Communications Group Los Angeles, CA
Indiana Digital Access Indianapolis, IN	Metropolitan Fiber Systems, Inc. Minneapolis, MN	Teleport Communications Group New York, NY
Institutional Communications Corp. McLean, VA	Metropolitan Fiber Systems, Inc. New York, NY	Teleport Communications Group San Francisco, CA

Table 6-25 Selected Metropolitan Area Network Vendors (Ref. 70)

Competition In the Loop

Just as long distance communications and metropolitan area networks have become competitive over the past 10 years, the local loop (i.e., the link between a house and the local central office) may also open to competition. In particular, there has been much discussion about the ability of cable TV operators to also provide voice communications and interactive information services. Conversely, the Local Exchange Carriers are working to eliminate regulatory barriers which prevent them from providing information services directly to customers. The LECs have already performed several trials in conjunction with cable TV operators which deliver cable TV to home via fiber optic cables (41).

With respect to traffic control applications, increased competition in the local loop may offer a wider range of communication services available at prices which reflect the level of competition.

Endnotes

1 (Popup)
Major portions of this section were excerpted from Reference 20.

2 (Popup)
Major portions of this section were excerpted from Reference 20.

3 (Popup)
Major portions of this section were excerpted from Reference 20.

4 (Popup)
Major portions of this section were excerpted from Reference 20.

5 (Popup)
Major portions of this section were excerpted from Reference 20.

6 (Popup)
Additional costs for interoffice channels, CPE equipment, etc., are not included, meaning the data represents a minimum cost rather than a total circuit cost. At least two channel terminations per circuit are required.

7 (Popup)
The monthly charge reported in the table for digital access lines assumes the stations are within the normal baseband serving area. Charges for stations outside this area are generally more and often include a mileage sensitive component. Two channel terminations are required per circuit.

8 (Popup)
Transmission for these rates for distances beyond 12,500 feet normally requires a DS1 or higher multiplexer and a transmission system.

9 (Popup)
Major portions of this section were excerpted from Reference 20.

CHAPTER 7 - WIRELESS ALTERNATIVES

Figure 7-1 Microwave Transmission

Introduction

Although land line communications have predominated in traffic control systems, recent technological advances make wireless communications increasingly attractive.

In addition to traditional wireless media such as radio frequency and microwave, traffic system designers now look to cellular networks, satellite transmission, packet radio, spread spectrum radio and other data communications options.

Need

The transportation professional needs to become familiar with wireless alternatives, and understand their characteristics, applications, advantages and disadvantages, and application to traffic control.

The designer must also become aware of the regulatory issues which govern the use of wireless communications.

Purpose

This chapter describes wireless technologies, services and regulatory issues relevant to traffic data communications. It covers the following media:

- Owned
  - area radio networks
  - terrestrial microwave links
  - spread spectrum radio
- Commercial

- cellular radio
- packet radio
- satellite

Organization

Table 7-1 summarizes the organization of this chapter which addresses each of the leading wireless communications alternatives and relevant regulations.

Owned Radio Communications

Existing and planned traffic control systems use the following types of owned radio communication technologies:

- Area Radio Networks (ARN)
- Terrestrial Microwave Links
- Spread Spectrum Radio

Table 7-2 summarizes the major characteristics of these technologies and Table 7-3 presents advantages and disadvantages of radio communications. Subsequent paragraphs describe design considerations in radio communications and details of the major technology alternatives.

Section Title	Purpose	Topics
Owned Radio Communications	Description of Alternatives	• Area Radio Networks • Terrestrial Microwave Links • Spread Spectrum Radio – Direct Sequence – Frequency Hopping
Commercial Wireless Network Services	Description of Alternatives	• Cellular Radio – Architecture – Service Coverage and Cost – Data Transmission – Traffic Control System Applicatons • Packet Radio – Architecture – Service Descriptions – Traffic Control System Applications • Satellite – Architecture – Satellite Service Economics
Regulatory Issues	NTIA and FCC Requirements	• Spectrum allocations • Private land mobile radio service • Private operational fixed microwave service • Part 15 devices not requiring a license • Antenna tower regulations

Table 7-1 Organization of Chapter 7

Design Considerations

The designer must account for *fading* in wireless communication system power budgets. Fading represents variation of received signal power and results from two principal causes, *multipath transmission* and *power fading*:

- Multipath Transmission

  This type of fading results from interference between a direct wave and another wave, usually a reflected wave. The ground or atmospheric sheets or layers may cause this reflection. Direct path interference may also occur, caused by surface layers of strong refractive index gradients or horizontally distributed changes in the refractive index. Multipath fading may display fades in excess of 30 dB for periods of seconds or minutes (24).

- Power Fading

  Absorption by rain or water vapor causes an increase in loss through the atmosphere. This loss becomes severe at 11 GHz and higher frequencies, but behaves unpredictably and must be treated statistically (42).

  Fading results in periods of reduced signal strength, and in this sense radio systems provide a lower level of service reliability than landline systems. Traffic systems require an adequate backup mode for these situations, as well as for other failures. Time based coordination can provide satisfactory backup, for example.

Radio based communication equipment may have *turnaround times* which become significant fractions of the communication time period during a polling cycle. In selecting particular equipment or class of equipment, the designer should verify compatibility with the polling protocol. In some cases the manufacturer must modify standard products not specifically designed for traffic applications.

Owned Radio Communications	Characteristics
Area Radio Networks (ARN)	• Operates in 150 MHz to 960 MHz bands • Requires FCC license • Can control groups of traffic signals or other devices requiring relatively low data rates
Terrestrial Microwave Link	• Operates in 926 MHz to 40 GHz bands • Requires FCC license • Can transmit data, voice, video, between two points • Can in some cases control groups of traffic signals • Can be used for point to point trunk
Spread Spectrum Radio	• Does not require FCC license in 902 MHz to 928 MHz band • Can transmit data and compressed video

Table 7-2 Owned Radio Communications

Advantages

- No need for physical medium since signal propagates through atmosphere.
- No cost of major land line installations and maintenance.
- Used to span natural barriers or provide communications link between points where rights-of-way are not available.
- Flexible implementation.
- Commercial off-the-shelf equipment available.
- Used in a number of traffic control systems.

Disadvantages

- Relatively complex design (compared to land line communications systems) since the local operating enviroment (e.g., terrain, potential sources of interference, available frequencies, etc.) must be investigated and taken into account as part of design process. (However, a variety of theoretical models can be used to predict radio wave propagation for a given set of conditions.)
- Limited choices of operating frequencies based on regulatory issues.
- Path line of sight constraints (e.g., in the microwave region of 900 MHz and above, line of sight to the receiving antenna(s) generally required). Propagation relationships govern the actual clearance required of obstacles and adjacent structures.
- Fading considerations.
- Turnaround time considerations.
- Limited bandwidth.
- Requires external antennas and cable.
- May require repeaters.

Table 7-3 Advantages and Disadvantages of Radio Communications Systems

Area Radio Networks (ARN)

Area radio networks refer to systems that broadcast signals to an area rather than a specific location. ARN can operate traffic controllers as well as provide voice communications with highway maintenance vehicles. Table 7-4 summarizes the advantages and disadvantages of area radio networks applied to traffic control systems.

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

Table 7-4 Advantages and Disadvantages of Area Radio Networks (ARN)

Area radio signals radiate uniformly in all directions, unlike point-to-point microwave links. As the signal propagates it may:

- "bend" slightly over changes in the ground surface
- reflect off buildings or other obstacles
- penetrate into buildings.

Scattering and reflection allow the signal to propagate into built up areas although these effects reduce signal strength. Terrain barriers may limit the feasibility of this technology.

Table 7-5 lists frequency bands available to highway maintenance applications for Private Land Mobile Radio Service (i.e., area networks). Typically, one frequency pair is allocated for an application, meaning all the application transmitters must share the transmit and receive channels. Thus, for voice communications all receivers tune to the same broadcast and users respond only to messages directed to them.

Similar to voice communications, data applications need a protocol which allows multiple devices to share the same communications channel. One approach *polls* all the remote devices, thereby giving a device exclusive use of the transmit channel for a short period of time. Another approach packetizes data and then transmits it using a *multiple access contention technique*. The latter compensates for potential collisions when two transmitters attempt to use the same channel at the same time (see Chapter 4).

Frequency Band (MHz)	Class of Station
33-47	Base or Mobile
72-76	Operational Fixed
150-170	Base or Mobile
169-172	Mobile
450-470	Fixed
470-512	Base or Mobile
806-824	Mobile
851-869	Base or Mobile
928 and above	Operational Fixed, Base or Mobile
929-930	Base Only
1427-1435	Operational Fixed, Base or Mobile
2450-2500	Base or Mobile

Table 7-5 Frequencies Allocated for Highway Maintenance Under Part 90

Area radio networks for traffic systems have used both polling and contention techniques.

Data channels generally have a bandwidth of 25 KHz, sufficient to support a 9.6K bits/second data rate signal.

<u>Example</u>

The traffic control system in Lancaster, California (43) represents an interesting example of both area radio and terrestrial microwave as shown in Figure 7-2.

Features of this system include:

- A central control architecture in combination with Type 170 controllers.
- Some intersections connected to the control center using twisted wire pairs.
- Remote intersections organized into two ARNs.
- ARN also used for data communication with mobile work stations.
- A terrestrial microwave link used for communication between the control center and shop.

- Radio controlled traffic signal channels connected from the control center to the radio room by conventional modems.
- A 1200 bps polled signal fed to the radio transceiver which communicates with a transceiver at the local controller.
- An RS-232C serial port on the local transceiver connected to the 170 controller's serial port connector.
- Basic polling interval of 30 seconds.
- Radio modems to provide a simple data transfer, i.e., the Type 170 and traffic operations center software to provide all message checking and polling controls.
- Modems of this type including antenna and wiring typically cost under $5000.
- Channel specifications follow:

CCU Channel	Outbound Frequency	Inbound Frequency	Power
11	458.6375 MHz	453.6375 MHz	2W
12	458.9375 MHz	453.9375 MHz	2W

Example of Power Budget for Area Radio Network

An area radio network communications link from a traffic operations center to freeway traffic management system controllers has the following parameters:

- Antennas - Traffic operations center antenna located on roof 100 feet above the ground. Antennas at field controllers 20 feet above ground. Line of sight established between field and traffic operations center antenna.
- Gain of both control center and field antennas of unity (0 dB).
- Transmitter power = 2 watts
- Distance to furthest controller = five miles
- Frequency = 480 MHz
- Receiver sensitivity for BER of 10^{-6} = -115 dBM
- Line losses at antenna

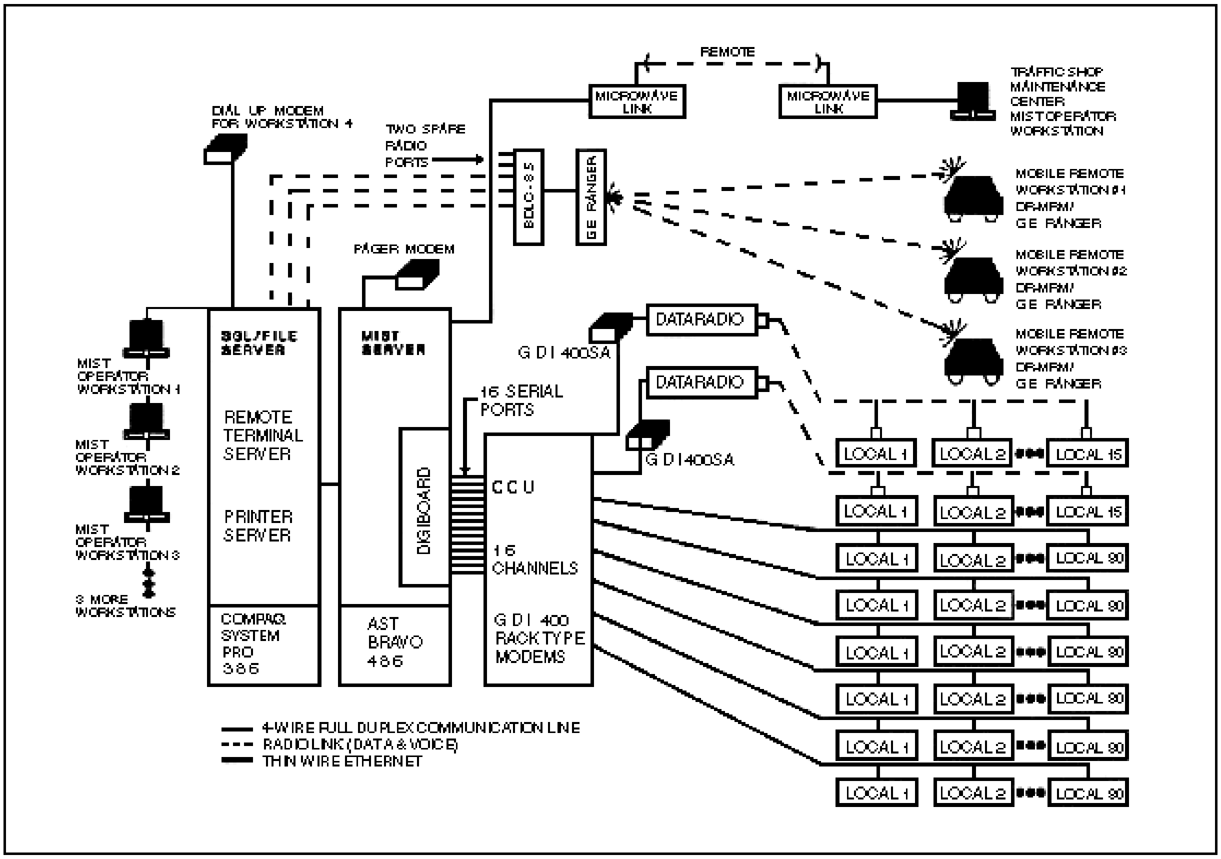


Figure 7-2 Lancaster Traffic Signal System Configuration

Table 7-6 shows a power budget for this example. This represents a simplified power budget to illustrate the general design process. The design of radio communication systems often proves more complex than land line systems and may require special expertise. For example, it may require consideration of additional factors including:

- bending,
- clearance of obstacles,
- propagation over bodies of water, and
- weather effects.

If preliminary study shows radio a meaningful candidate, an engineer with the necessary expertise should perform a more detailed study.

Terrestrial Microwave Links

Point-to-point traffic control applications have used *terrestrial microwave* links primarily as a communications trunk between offices and/or remote work centers (e.g., maintenance building) carrying voice and data as in Figure 7-2. In some cases, microwave links communicate with traffic signal controllers or transmit video information. Table 7-7 presents some advantages and disadvantages of terrestrial microwave links.

Transmitter Power	+33 dBM
Receiver Sensitivity	-115 dBM

Power Budget	148 dB
Transmission Losses	
- Line loss at traffic operations center antenna	-1 dB
- Traffic operations center antenna gain	0 dB
- Free space loss (see Note 1)	-104.2 dB
- Fading loss (see Note 2)	-33 dB
- Field controller antenna gain	0 dB
- Line loss at field controller	-1 dB
TOTAL Loss	139.2 dB
Power Margin	8.8 dB

Table 7-6 Power Budget for Area Radio Network

Note 1(1) ***Note 2(2)***

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

Table 7-7 Advantages and Disadvantages of Terrestrial Microwave Links

Microwave signals radiate through the atmosphere along a *line-of-sight path* between transmitting and receiving antennae. Both technical and frequency utilization requirements dictate highly directional microwave frequency antennas. As discussed later in this chapter, the FCC makes several frequencies available for Private Operational Fixed Microwave Service ranging from 928 MHz to 40 GHz (see Table 7-8). Since microwave radio uses simplex transmission, a frequency pair allows transmission in both directions at the same time.

The designer may have little choice regarding the operating frequency available for license from the FCC. Since operating frequency may significantly impact microwave system design and performance, the designer should investigate frequency availability before selecting microwave radio as the communications medium for a particular traffic control application.

Frequency Band (MHz)	Maximum Authorized Bandwidth
928 - 929	12.5, 25 kHz
932 - 932.5	12.5 kHz
932.5 - 935	25, 50, 100, 200 kHz
941 - 941.5	25, 50, 100, 200 kHz
941.5 - 944	25, 50, 100, 200 kHz
952 - 960	25, 50, 100, 200 kHz
1850 - 1990	5, 10, MHz
2130 - 2150	800, 1600 MHz
2150 - 2160	10 MHz
2180 - 2200	800, 1600 kHz
2450 - 2500	625, 800 kHz
2500 - 2690	125 kHz, 6 MHz
6425 - 6525	25 MHz
6525 - 6575	5, 10 MHz
6575 - 6625	5, 10 MHz
6625 - 6875	5, 10 MHz
10,550 - 10,680	5 MHz
12,200 - 12,500	10, 20 MHz
12,500 - 12,700	10, 20 MHz
12,700 - 13,200	not specified
13,200 - 13,250	25 MHz
17,700 - 18,580	80MHz
18,580 - 18,820	20 MHz
18,820 - 18,920	10 MHz
18,920 - 19,160	20 MHz
19,160 - 19,620	10 MHz
19,260 - 19,700	80 MHz
21,200 - 22,000	up to 100 MHz
22,000 - 23,600	up to 100 MHz
31,000 - 31,300	25, 50 MHz
38,600 - 40,000	up to 50 MHz

Table 7-8 Frequencies Allocated for Private Operational Fixed Microwave Service Under Part 94

The FCC is currently investigating the possibility of reallocating selected frequency bands to new services (e.g., Personal Communications Service), including the 2 GHz band sometimes used for traffic control applications. One proposal calls for a 10-15 year transition period, after which all current users except public safety agencies (i.e., highway maintenance) would be demoted from their status as primary users. The proposal restricts all users from expanding their current 2 GHz networks (44).

Microwave systems use both analog and digital transmission techniques. Analog systems typically use frequency modulation (FM), thereby allowing the allocated bandwidth to comprise multiple voice, data and/or video channels. Digital microwave systems use modulation techniques including:

- Amplitude Shift Keying (ASK),
- Frequency Shift Keying (FSK), and
- Phase Shift Keying (PSK).

The most appropriate technique for a given application depends on several factors:

- spectral efficiency requirements
- performance requirements
- economics which depends on equipment complexity

See Reference (24) for a detailed explanation of these tradeoffs as well as a thorough discussion of line-of-sight microwave systems.

Cost Components ($)	Frequency (GHz)			
	2	6	18	23
License and Installation	50,000	25,000	7,000	3,000
Towers	75,000	75,000	2,000	2,000
Antenna	100,000	150,000	18,000	15,000
Total Costs ($)	250,000	250,000	27,000	20,000

Table 7-9 Private Microwave Costs

Table 7-8 shows the channel bandwidth available at different frequencies. Above 11 GHz, atmospheric effects may limit the usefulness of microwave and the designer must carefully evaluate this factor.

Reference (45) describes several factors to consider as part of a microwave communications cost analysis. Operating frequency has direct impact on system cost in that higher frequencies require smaller antennas. More specifically, the larger antenna usually required by 2 GHz and 6 GHz systems:

- costs more
- proves more difficult to install
- requires a stronger tower structure since it receives tons of force from high wind.

Table 7-9 reports some system cost data at various operating frequencies taking these factors into account.

Microwave radio systems can use a variety of other analog or digital equipment depending on the particular application. For example, an access multiplexer can combine several voice and data channels for transmission by the radio system. Similarly, a higher capacity multiplexer can combine DS1 signals for transmission by a DS3 microwave radio system. (See Chapter 6 for

DS1 and DS3 definitions).

Example

The Illinois State Toll Highway Authority currently uses a 2 GHz microwave radio system for voice and data communications between operations centers such as headquarters, toll plazas, and maintenance locations. The authority plans to update the current analog system to a digital system operating at 6 GHz on the backbone and 18 GHz on spurs. Also, the Authority may deploy fiber to provide additional communications capacity for new applications (e.g., video surveillance, electronic toll collection). In this case, the Authority may use both microwave and fiber to provide a redundant communications path for selected applications (18).

Under some circumstances, the designer may select microwave to directly control traffic signals. For example, at least one manufacturer provides a modem operating in the 31 GHz band (for which no FCC network license is required) which replaces the standard modem in the Model 170 controller. The arrangement implements point to point operation between controllers in a daisy chain fashion. Such applications are, however, limited by:

- network geometry
- line-of-sight
- atmospheric conditions.

Spread Spectrum Radio (SSR)

The military initially developed *spread spectrum radio* techniques during World War II to resist enemy radio interception and jamming. These same techniques found commercial application in 1985 when the FCC opened the 902/928, 2400/2483.5, and 5725/5850 MHz frequency bands to spread spectrum.

Spread spectrum refers to a communications technology that spreads a signal bandwidth over a wide range of frequencies at the transmitter, then compresses the signal to the original frequency range at the receiver. For example, the transmitter spreads a 1 watt 100 KHz bandwidth signal over a 100 MHz band using a technique that the receiver knows in advance, thereby allowing the receiver to collect the original signal. This is an application of *code division multiplexing* (CDM).

Figure 7-3 (46) illustrates the difference between a conventional radio and spread spectrum signal. The receiver can successfully decode a spread spectrum signal even if the noise level exceeds the signal level. The bandwidth of a spread spectrum signal (which carries the same data rate as a conventional signal) exceeds by many times a conventional signal's bandwidth. Therefore, the spread spectrum transmitter can repeat the signal many times over or otherwise encode it, all within the spread spectrum signal bandwidth. This results in a "processing gain" which appears as a factor in the power budget.

Since each network works with a different code, different networks in the same location can use the same band. Table 7-10 presents the advantages and disadvantages of spread spectrum radio.

The two main spread spectrum techniques are called *direct sequence* and *frequency hopping*:

- Direct sequence spectrum spreading - a very wide baseband digital signal modulates the original baseband signal, and the wideband signal's amplitude continually changes between two states (+1 and -1).

- Frequency hopping - a transmitter repeatedly changes the carrier frequency from one to another, transmitting for a very short duration (e.g., 1/15,000 second) on a few hundred or thousand different frequencies.

Unlike the other radio technologies described, SSR can resist the effects of multipath interference (46). Line-of-sight restrictions generally apply; however, some level of "bending" around obstacles occurs in the 902-928 MHz band.

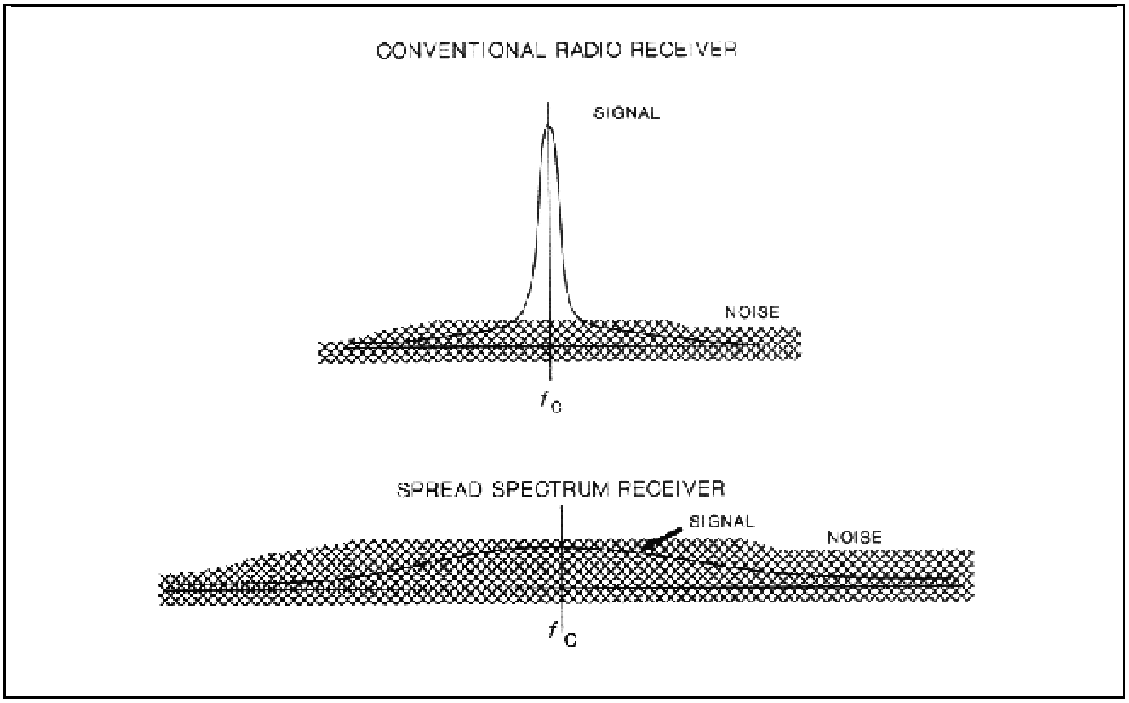


Figure 7-3 Frequency Spectra of Conventional Radio and Spread Spectrum Radio

A variety of trials have been performed or are underway to test spread spectrum systems when operating together with other communications systems. As previously mentioned, spread spectrum inherently proves "noise resistant" since the power of the noise signal diminishes greatly when the receiver recreates the original narrow band signal. Conversely, the interference generated by spread spectrum radio may prove unacceptable to some systems which use the same frequencies (e.g., broadcast TV), but may be imperceptible in other cases (e.g., FM radio, voice communications).

Advantages

- Very flexible installation
- Does not require cable installation and maintenance
- Does not require FCC channel use approval in 902-928 MHz band
- Works extremely well in a high noise environment
- Currently in use for many industrial process control appliances
- Uses low transmitter power
- Can be used in a mixed system of wired or radio interconnected controllers
- No land line interconnect requirement
- Relatively low equipment cost
- Potential for broad range of traffic control system applicaions

Disadvantages
• New technology for traffic control and traffic surveillance application • Uncertain range (0.3 - 6 miles); function of area topography • Higher bandwidth than radio fixed frequency tranceivers • Requires external antenna and cable • Requires more sophisticated equipment and specialized technicians • Unprotected channel space

Table 7-10 Advantages and Disadvantages of Spread Spectrum Radio

Work underway to "prove in" spread spectrum for the next generation digital cellular system (see next section) represents a possible widespread application of the technology. In addition, the FCC continues to support spread spectrum and other technologies which offer the potential for maximizing spectrum utilization. For a more detailed discussion of spread spectrum, see Reference (47).

The most useful application of SSR to date has used the 902-928 MHz band for which the owner requires no facilities license from the FCC. Part 15, paragraph 15.227 contains SSR's current major constraints:

- Maximum peak output power: 1 watt
- Maximum effective radiated power: 4 watts
- Maximum antenna height: no restriction
- Minimum processing gain:
  - Frequency hop 17 db
  - Direct sequence 10 db
  - Hybrid 17 db
- Device cannot interfere with licensed services.
- Must accept interference from licensed services and other Part 15 devices.

For traffic control system applications, SSR's range approximates 0.5 mile to several miles and depending on the application, may require repeaters. Commercial equipment currently supports data rates of approximately 200 KBPS. This will satisfy most data requirements for field equipment and support "low end" coded video transmission.

Cost approximates $3,000 or less per field unit (exclusive of traffic cabinet enclosures, etc.) for equipment of the type described above.

At this writing, some organizations have specified SSR for traffic control applications and several equipment manufacturers have indicated interest in supporting that market.

Potential applications include:

- Communications between a field master and local controllers in closed loop systems.
- Communications from a point in the field to field controllers. Leased land lines can accomplish communications between the field point and control center.

The technology is currently being tested in a traffic control research project which packages the spread spectrum radio with an in-pavement sensor, allowing wireless communications between roadway controller and buried sensor over a distance of approximately 500 feet (48).

Commercial Wireless Network Services

The communication services market is currently in a state of rapid change, with increasing emphasis on digital services and data transmission. The following sections discuss several currently available services.

Cellular Radio

Only a few small scale and/or short term traffic control applications have used *cellular radio service*. However, recent announcements regarding new data services on the existing analog cellular network may increase the applicability of this medium to traffic control. Table 7-11 summarizes advantages and disadvantages of cellular radio communications for traffic control. The following sections describe:

- cellular radio architecture,
- service considerations such as coverage and cost,
- near-term data transmission options and,
- a traffic control application.

Advantages
• May prove cost effective for infrequent communications • Eliminates need to connect to Telco service point or provide owned land line • Effective for controlling portable changeable message signs • May prove effective for temporary installations • Cellular modems available off-the-shelf • Network covers 93% of U.S. population
Disadvantages
• "Airtime" cost excessive for continuous communication service • Only two providers in any one area • Actual data throughout reduced due to protocol overhead • Remote areas may not have service

Table 7-11 Advantages and Disadvantages of Cellular Radio

Architecture

The FCC has divided the United States into 734 service areas and licensed two cellular system operators for each area. Current US cellular service, referred to as Advanced Mobile Phone Service (AMPS), uses two frequencies per call (transmit and receive) and analog transmission in a 30 kHz channel between mobile unit and base station. The FCC has allocated a total of 666 channels in the 800 MHz band shared by the two service providers for a particular area.

Cellular radio maximizes frequency utilization by reusing the same frequencies in "cells" physically separated by a distance called the mean reuse distance, thereby minimizing interference among users of the same frequency. Figure 7-4 presents a simplified view of a cellular system, showing each service area divided into a number of cells served by relatively low power transmitters. Each cell connects to a Mobile Switching Office that connects to the Public Switched Telephone Network (i.e., Local Exchange Carrier). As users move outside the range of a particular cell site, they get "handed off" to another cell site and the call continues without interruption. 1 (3)

Carrier	Service Areas	Service Activation Fee	Monthly Service Charges	Per Minute Airtime Charges
McCaw Cellular Communications	Denver, Colorado Springs, etc.	$25	$25	$.55/Peak $.27/Off Peak
Cellular Communications, Inc.	Cleveland, Columbus, Dayton, etc.	$95	$29.95	$.35/Peak $.20/Off Peak
Cellular One-Southwestern Bell	Chicago, Springfield, Champaign, etc.	$35	$30 (includes 50 minutes of airtime)	$.33/Peak $.19/Off Peak
Bell Atlantic Mobile Communications	Philadelphia, Washington DC, etc.	Included in cost	$44 (Philadelphia)	$.50/Peak $.30/Off Peak
NYNEX Mobile Communications	Buffalo	Included in cost	$15	$.35/Peak $.25/Off Peak
Cellular One-McCaw	San Francisco, San Jose	$25	$37.50 to $45	$.45/Peak $.20/Off Peak

Table 7-12 Cellular Service Costs

<u>Service Coverage and Cost</u>

Cellular radio service was introduced in 1983 and in less than 10 years has grown into an industry with over 6 million subscribers.

Either the amount of land mass or the percentage of population with access to cellular service can measure service coverage. Of the 734 cellular markets, 306 provide service to metropolitan areas and 428 cover rural service areas (49). Since the FCC has licensed two operators in each market, operators may eventually deploy a total of 1468 systems. In terms of population, a 1990 report stated that cellular service covered 84% of the United States population, with 93% coverage expected in 1991 (50).

The cost for cellular "airtime" varies widely depending on the particular service plan selected and the area of the country. Table 7-12 (49) summarizes service fees reported by several cellular system operators, although each operator may also offer other service plans with alternative pricing. The table shows that monthly service charges range from $15-$45 dollars. "Airtime" may cost as little as $0.19 per minute during off-peak hours or as much as $0.55 per minute during peak hours.

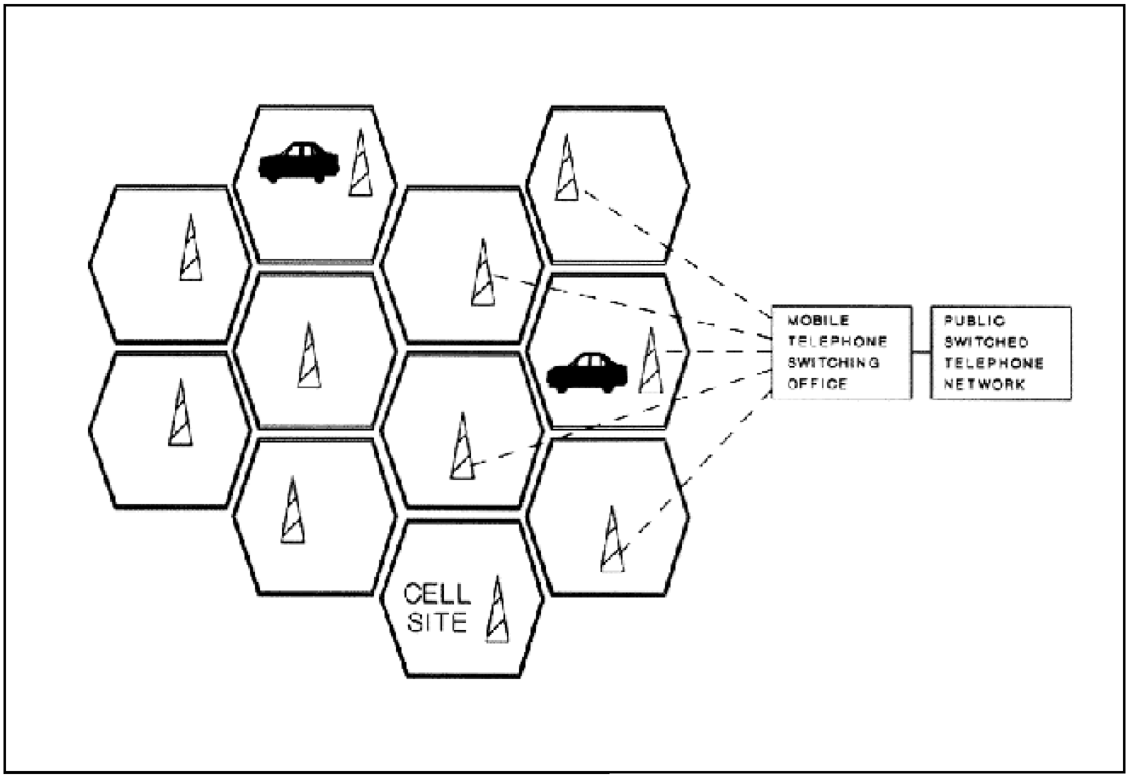


Table 7-4 Cellular Radio System Architecture

Data Transmission

Cellular radio systems were originally conceived to provide voice services only and today, not surprisingly, almost all cellular calls serve voice communications. Initial attempts to "add-on" data services met with some problems, including the lack of a standard interface to connect external data equipment to mobile phones. Initial attempts to use standard "wireline" modems for cellular largely proved unsuccessful because the modem protocols did not account for the cellular radio network's unique features. For example, fading, handoffs, and "blank and burst signaling" would result in many requests for a repeat transmission, reducing data throughput significantly (51).

Subsequently, modems with protocols designed specifically for cellular radio have been developed and tested successfully in a wide range of applications, providing data communications to taxis, police, field engineers, and commercial fleets. Cellular models generally cost $900-$1,200, although some low speed modems range between $500-$600. The higher cost class of cellular modems supports raw data rates up to 14.4 Kbits per second while the lower cost modems typically support 1.2 Kbits per second data rates (51). Note that actual data throughput diminishes 30-50% due to protocol overhead.

To reduce data transmission cost, cellular operators and equipment vendors are developing packet switched data capability (52, 53, 54).

Traffic Control System Applications

The current tariff structure based on connect time remains too expensive for applications requiring continuous communication service. Certain applications which require communication at relatively infrequent intervals may prove good candidates, particularly if owned land line service is unavailable and the cost to access telephone service appears high. Cellular radio service may also prove a good candidate for temporary installations.

Packet Radio

Unlike cellular radio, *packet radio* services were designed for data transmission rather than voice communications. Based on the developments discussed in the previous section, the line between packet radio and cellular radio begins to blur as cellular radio implements features supporting both voice communications and packet data. This section describes:

- the architecture used by the two largest commercial data-only packet radio services,
- the features of these services, and
- traffic control system applications.

Table 7-13 shows advantages and disadvantages of packet radio service.

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

Table 7-13 Advantages and Disadvantages of Packet Radio Service

<u>Architecture</u>

Packet radio services communicate with user terminals over one or more frequency pairs in the 800 and 900 MHz bands via radio base stations and antennae typically deployed on the tops of multi-story buildings or towers. Each base station, which may serve a coverage radius of 10-20 miles, connects to a backbone communications network that routes packets to the specified destination. Packet radio services may also provide access to applications such as messaging and database access.

Unlike cellular radio, multiple remote terminals use the same frequency pair for transmitting and receiving data. A multiple access protocol such as the slotted ALOHA algorithm reduces the probability of collisions between transmissions from remote terminals. (Chapter 4). With slotted ALOHA, the base station uses a local "system channel" to define free time slots during which remote terminals may transmit information. Remote terminals select one of these time slots at random, transmit the data packet, and then listen for an acknowledgment from the base station during the next cycle. If the remote terminal does not receive acknowledgment, it repeats the transmission using the same procedure.

The packet radio architecture and pricing plan adapts best to transmitting short bursty messages, and not for file transfers (i.e., more than 1-2 pages of text) or continuous communications between two end points. Typically, it takes a few seconds to deliver a packet.

(55, 56, 57).

Feature	ARDIS	MOBITEX
# of Channels	1 - 3	10 - 30
Channel Width	25 KHz	12.5 KHz (Mobitex)
RF Protocol	Proprietary	Open
Coverage	400 Cities	50 Cities (by year end 1992)
Raw Data Rate	4.8 kbits/sec 19.2 kbits/sec (planned)	8 kbits/sec 19.2 kbits/sec (planned)
Pricing - Signup Fee	$50 per terminal	$50 per terminal
Pricing - Monthly (per terminal)	$32 minimum offset against: $.08/packet (prime time) or $.05/packet (off time) plus $.04 per 100 characters	$25 per month plus usage charge ranging from: $.03 per 1 byte status message $.125 per 512 byte message
Modem and Terminal	$1000 - $2000 Proprietary interface	$1000 - $2000 Open interface

Table 7-14 ARDIS and MOBITEX Packet Radio Service Summary

<u>Service Descriptions</u>

The two major packet radio services currently available in the United States are Advanced Radio Data Information Services (ARDIS) and MOBITEX. Table 7-14 summarizes key aspects of the services.

<u>Traffic Control System Applications</u>

As with cellular radio service, packet radio service remains too expensive for controllers requiring continuous communication (polling intervals in the range of a few minutes or less). Packet radio services may find use for applications described for cellular radio (see Table 7-11).

Satellite

The current generation of satellite equipment and services has generally not proved cost effective for communications "local" in nature, typically required by traffic control applications. Designers should consider satellite communications for traffic control systems spanning large distances (e.g. regional). Table 7-15 summarizes advantages and disadvantages of satellite communications. A description of satellite service architecture and economics follows:

Advantages
• Cost of circuits independent of their length
• Cost effective for long-haul circuits
• Downlink signals can be received over a wide area (e.g., cable TV)

• Uplink signals can originate over a wide area • Flexible for "quick setup" or mobile applications
Disadvantages
• Not proven cost effective for local type communcations (not long haul) • Limited number of service providers • Channel leasing costs subject to increases

Table 7-15 Advantages and Disadvantages of Satellite Communications

Architecture

As shown in Figure 7-5, satellite communications architecture uses earth stations to transmit and receive data via a geosynchronous (i.e., appears to remain in a fixed position in space) satellite positioned approximately 22,300 miles above earth. Specifically, an earth station:

- modulates the baseband signal to the appropriate power and transmission frequency, then
- radiates the signal to the satellite.

The satellite:

- shifts the received signal's frequency
- amplifies it, then
- reradiates the signal back to earth where it can be received by earth stations in the coverage area.

The FCC allocates the following frequencies for fixed service satellite communications:

- C band (i.e., 5.925-6.425 GHz uplink and 3.700-4.200 GHz downlink), and
- Ku band (i.e., 14.0-14.5 GHz uplink and 11.7-12.2 GHz downlink).

Similar to other radio systems, the characteristics of these frequency bands differ markedly with respect to:

- propagation effects,
- equipment performance, and
- FCC regulations.

Availability of desirable frequencies becomes an issue in some geographic areas. However, satellite communications economics remain the primary reason that has thus far inhibited this communications medium from application to most traffic control systems (58).

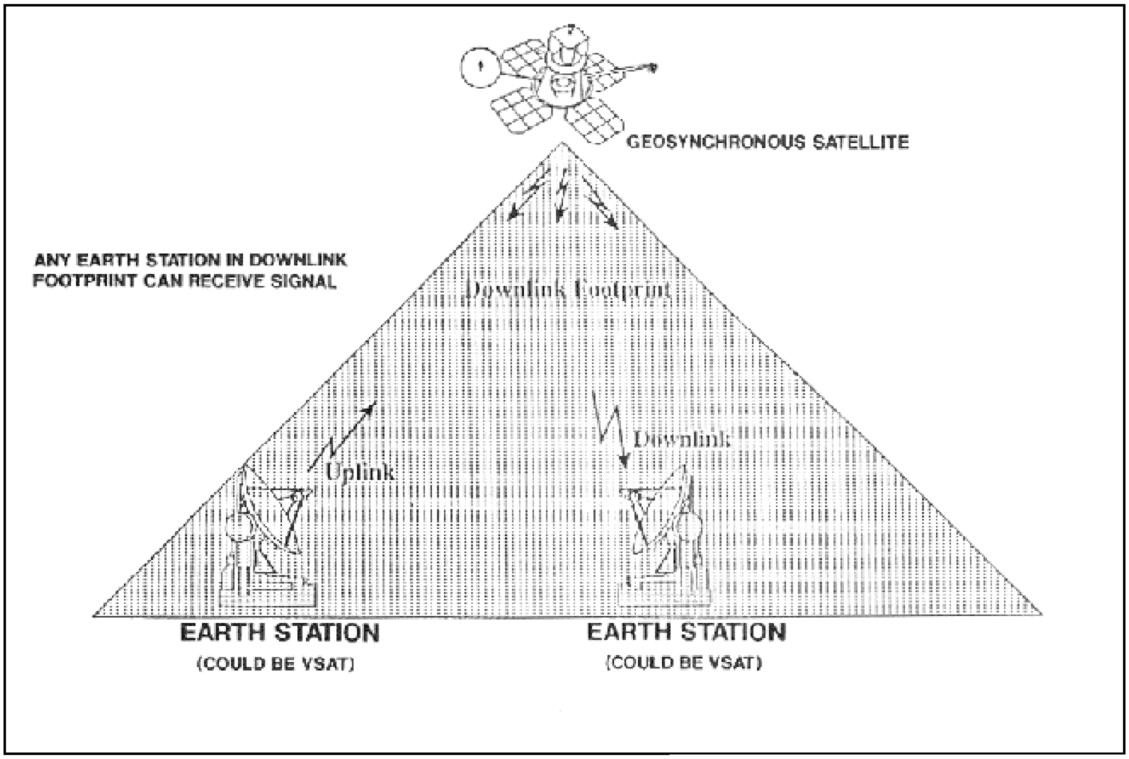


Figure 7-5 Satellite Communications Architecture

Satellite Service Economics

Morgan and Rouffet (59) performed a comparison of satellite service and several wireline services for leasing a 56 kbit/second circuit over 5 years. Although both satellite and wireline services have changed somewhat since the study was performed in 1986, the data remains useful in understanding the economics of satellite service for long haul and medium distance circuits. As shown in Figure 7-6, satellite services cost the same for the 195 mile and 2443 mile circuits. In comparison to wireline options, satellite services cost the most for the 195 mile circuit but proved less expensive than 2 of the 3 wireline options for the 2443 mile circuit.

Regulatory Issues

The National Telecommunications and Information Administration (NTIA) and Federal Communications Commission (FCC) govern the use of radio frequency (RF) spectrum in the United States. In particular, NTIA regulates the Federal Government's use of RF spectrum while the FCC allocates spectrum use for non-federal sector applications including traffic control. The following sections describe FCC regulatory procedures that apply when using wireless communications for traffic control applications.

Spectrum Allocations

RF is internationally recognized as that part of the electromagnetic spectrum below 3000 GHz. However, telecommunications rarely use the 300-3000 GHz band, and most radio communications systems operate below 40 GHz (60).

- Fixed
- Fixed Satellite
- Broadcasting
- Broadcasting Satellite
- Meteorological Aids
- Inter-Satellite

- Mobile
- Mobile Satellite
- Land Mobile
- Land Mobile Satellite
- Aeronautical Mobile
- Aeronautical Mobile satellite
- Maritime Mobile
- Maritime Mobile Satellite

- Amateur
- Amateur Satellite
- Radionavigation
- Aeronautical Radionavigation
- Maritime Radionavigation
- Radionavigation Satellite
- Earth Exploration Satellite
- Meteorological Satellite

- Radiolocation
- Standard Frequency and Time Signal
- Standard Frequency and Time Signal Satellite
- Space Operation
- Space Research
- Radio Astronomy

Table 7-17 FCC Radio Services

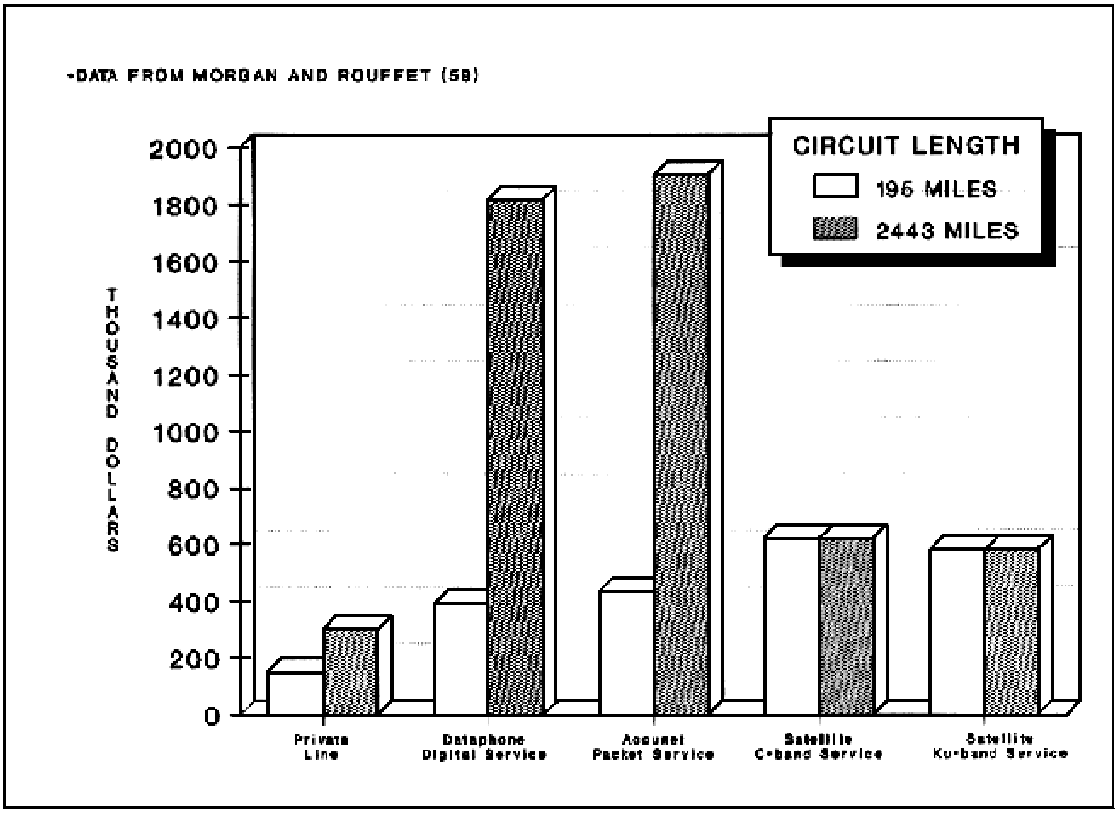


Figure 7-6 Cost for Satellite and Wireless 56kb/s Leased Circuit Over 5 Years (1986)

Frequency Band Name	Frequency	Applications
Very Low Frequency (VLF)	3 kHz-30 kHz	Very long-range point-point communications (over 1000 nautical miles)
Low Frequency (LF)	30 kHz-300 kHz	Long- and medium-range point-point communications; radionavigation aids; aeronautical mobile
Medium Frequency (MF)	300 kHz-3 MHz	Medium- and short-range communication. AM broadcasting; aeronautical mobile, radionavigation, marine radiophone, Loran; international distress, disaster; amateur
High Frequency (HF)	3 MHz - 30 MHz	Medium- and long-range communication. International broadcasting; International point-point; air-ground; ship-shore; space research; amateur, citizens, radio astronomy
Very High Frequency (VHF)	30 MHz - 300 MHz	Short-range line-of-sight communication; over--horizon "scatter" communication. VHF television, FM broadcasting; space tracking and telemetry, satellites; aeronautical distress; worldwide radionavigation; land mobile; amateur; radio astronomy
Ultra High Frequency (UHF)	300 MHz - 3 GHz	Short-range communication; microwave relay; over-horizon "scatter" communication. UHF television, instructional TV; land mobile; weather satellites, meteorological aids; space tracking and telemetry; radar; worldwide aeronautical radionavigation; amateur, citizens; radio astronomy
Super High Frequency (SHF)	3 GHz - 30 MHz	Microwave relay; deep space, space research, telemetry, communications satellites; radar; aeronautical radionavigation; meteorological aids; amateur, citizens; radio astronomy
Extra High Frequency (EHF)	30 GHz - 300 GHz	Microwave relay; space research; radar; radionavigation; amateur, experimental; radio astronomy
None	300 GHz - 3000 GHz	Unallocated radio spectrum

Table 7-16 International Telecommunications Union Frequency Band Names

The International Telecommunications Union has defined eight frequency band classifications (e.g., Very High Frequency, Ultra High Frequency) commonly used when discussing the RF spectrum. As shown in Table 7-16, the FCC may allocate spectrum for a class of applications in one or more of these frequency bands. To facilitate frequency assignments, the FCC has defined a set of *radio services* shown in Table 7-17 and allocated frequency bands to each of these services.

The FCC Code of Federal Regulations defines specific regulations and frequency assignments for each radio service (61). Private communications for traffic control systems generally classifies as a *Private Land Mobile Radio Service* or a *Private Operational Fixed Microwave Service*. FCC Part 15, which defines specifications for devices which may operate without a license, contains regulations for spread spectrum communications.

In 1986 the FCC established frequency coordination procedures for Private Land Mobile Radio Services. Certified coordinators have been identified for each of the different application areas, with the American Association of State Highway and Transportation Officials (AASHTO) coordinating frequencies for the Highway Maintenance Radio Service. The certified frequency coordinator must approve all applications for radio station or system licenses prior to submission to the FCC. Appendix A (62) contains information provided by AASHTO regarding Highway Maintenance Radio Frequencies Coordination Procedures.

FCC Form 574 must be completed for Private Land Mobile Radio Services and submitted to the FCC after the appropriate frequency coordinator has approved the application. FCC Form 402 must be completed for Private Operational Fixed microwave Radio Service applications. This service does not require preliminary frequency coordination.

The FCC also regulates commercial wireless services, as described previously. Reference 61 also describes regulations for commercial services.

Private Land Mobile Radio Service

Private Land Mobile Radio Service, defined by the FCC as "mobile service between base stations and land mobile stations, or between land mobile stations", may be licensed and used for Public Safety, Special Emergency, Industrial, Land Transportation, and Radio Location Radio Services. Traffic control applications are considered *Public Safety Services*, which further subdivides into the following service categories: Local Government, Police, Fire, *Highway Maintenance*, and Forestry-Conservation (62).

The FCC eligibility requirements for Highway Maintenance Radio service states as follows:

"Any territory, possession, state, county, city, town, and similar governmental entity is eligible to hold authorizations in the Highway Maintenance Radio Service to operate stations for transmission of communications essential to official highway activities of the licensee".

Table 7-5 (from Reference 61, Part 90) shows frequencies allocated by the FCC for assignment to stations in the Highway Maintenance Radio Services. Although the FCC allocates some frequencies over 928 MHz, their use for operational fixed stations is regulated under Private Operational Fixed Microwave Service (see next paragraph).

Private Operational Fixed Microwave Service

Private Operational Fixed Microwave Service refers to operational-fixed radio facilities licensed and operated in the microwave spectrum above 928 MHz. Traffic control applications which meet the eligibility requirements stated in the previous section for Highway Maintenance Radio also become eligible for Private Operational Fixed Microwave Service. Table 7-8 shows specific frequencies allocated by the FCC for this service in Reference 61, Part 94.

Part 15 Devices Not Requiring a License

Part 15 of the FCC regulations defines conditions under which an intentional, unintentional, or incidental radiator may operate without an individual license. Spread spectrum devices may operate within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. These bands, sometimes called "junk" bands, see a variety of applications with minimal FCC protection from interference. However, spread spectrum communications use techniques to reduce interference, as described previously in this chapter.

Antenna Tower Regulations

Part 17 of the FCC Rules and Regulations give requirements for construction, marking, and lighting of antenna towers. In addition to these requirements, the designer must consider the impact of construction of a new antenna tower. Local residents may react to visual and other potential environmental impacts of the tower. In some cases it may prove possible to use an existing tower or alternate location (e.g., tall building) for mounting antennae.

Endnotes

1 (Popup)
Calculate free space loss from the following equation (24):

$$L_{dB} = 36.58 + 20 \log_{10} D + 20 \log_{10} f$$

where D is the distance between antennas in statute miles and
f is the frequency in megahertz.

2 (Popup)
This is a generally representative value from data provided in Ref. 24.

3 (Popup)
Users may hear a "click" during voice conversations when handoffs occur. Depending on availability of channels in adjacent cell site, the system may drop the call.

CHAPTER 8 - RELIABILITY, MAINTAINABILITY, AND EXPANDABILITY

Figure 8-1 Installing Communications Cable

Introduction

For effective operation of a traffic control system, the communications system must function with minimal downtime. Lessons learned from existing systems demonstrate that agencies can implement reliable, maintainable and expandable communication systems using proper design and construction practices.

Need

Reliability, maintainability and expandability in a communications system can best be achieved by incorporating these factors throughout the design process. Therefore, the transportation professional must understand the principles which lead to a reliable, maintainable and expandable communications system.

Purpose

This chapter provides the user with information on communication system operational experience, and guidance on the design of systems to reduce the impact of communications failures and to enhance maintainability and expandability.

Organization

Table 8-1 summarizes the organization of this chapter.

Section Title	Purpose	Topics
Operational Experience	Summarizes lessons learned from operating communications system	• Construction and lightning damage • Owned vs. leased lines • Limitations to expansion
Enhancing Reliability	Summarizes design and construction techniques to improve reliability	• Failure reports • System responses • Design techniques • Installation techniques
Enhancing Maintainability	Summarizes design and construction techniques to improve maintainability	• Technology selection • Maintenance plan • Documentation • Standards • Test equipment
Enhancing Expandability	Summarizes design techniques to improve expandability	• Expansion requirements • Design techniques • Spare capacity options

Table 8-1 Organization of Chapter 8

Operational Experience

In the communications system design, the designer should consider lessons learned from operational traffic control systems. A number of operating agencies have provided data for the purpose of assessing operational, maintenance and expansion issues related to communications. Table 8-2 provides comparative information from several agencies.

This, as well as information from other agencies, indicate that:

- Most line failures result from *construction activity* damage.
- *Owned TWP* lines provide a higher quality of service and have fewer service interruptions than leased lines.
- The quality of traffic communications equipment generally proves satisfactory; most equipment failures result from *lightning* induced damage.
- Where the jurisdiction's *own forces* rather than contractors installed communication lines, installation quality proved higher and more maintenance free.
- Investment in *preventive maintenance* has a high payoff in the maintenance of service quality and prevention of deterioration. This proves particularly true with higher technology media such as coaxial cable.
- Limitations to *expansion* of central architecture systems largely result from three factors:
  - Communications equipment becoming sole source from a single manufacturer or no longer available.
  - Expansion locations on arterials not physically contiguous to the central system.
  - Inconvenience of cable plant physical expansion.

- Two solutions to overcome limitations to expansion include:
  - Use a closed loop system for the new intersections.
  - Extend the central computer system by means of leased lines or radio communications.

Jurisdiction	Amarillo, TX (Ref. 71)	Clearwater, FL (Ref. 72)	Greensboro, NC (Ref. 73)
Number of Intersections under System Control	86 CBD 69 Arterial	72	247
Type of System	Central computer in CBD. Closed loop type masters on arterials.	Central computer	Central computer
Type of Communications Medium	Owned TWP	Owned TWP	Owned TWP
Year of Initial Service or Major Upgrade	1975	1980	1975
Multiplexing	TDM	TDM	TDM
Significant Communications Outages	1/week	99% on line	15/week
Line Failures	Data not comparable	Low, only due to construction	9/year
Communication Equipment Failures	Failures only due to lightning	Failures only due to lightning	36,000 Hr MTBF
Maintenance Effort	CBD cable plant maintenance excessive	Preventive maintenance mostly	Moderately high
Expansion Problems	Cable plant limitations	None Currently upgrading to MTCS. **Note:** Using TV on TWP	▪ Central system capacity ▪ Sole source communication unit out of production. Major upgrade currently underway

Jurisdiction	Minneapolis, MN (Ref. 74)	Monroe County, NY (Ref. 75)	Toronto, Ontario (Ref. 76)
Number of Intersections under System Control	712	348	1,590
Type of System	Central computer	Central computer	Central computer
Type of Communications Medium	Owned TWP	Owned Coaxial	Leased Voice Grade
Year of Initial Service or Major Upgrade	1976	1985	1980
Multiplexing	TDM/FDM	TDM/FDM	No multiplex, FSK used for transmission
Significant Communications Outages	3/week	Data not comparable	Data not comparable
Line Failures	1/month, due to construction	Low, only due to construction	10/week
Communication Equipment Failures	500,000 Hr MTBF	Problems mostly due to connections which loosen	44,500 Hr MTBF
Maintenance Effort	Minimal	Preventive maintenance important to prevent loss of signal strength on coaxial cable. Preventive maintenance effort high but worth it.	Line maintenance high
Expansion Problems	Limited by hardware availability	Expansion areas not close to present cable plant. Conduit connections to new areas expensive.	Non-standard equipment hinders expansion. Currently redesigning to eliminate limitations.

Table 8-2 Information from Operating Agencies on Communications Operations and Maintenance

Enhancing Reliability

Failure Reports

Most computer traffic systems report field device failures which, in many cases, include communication failures. A reported communication failure may result from an equipment failure or uncorrected errors during several consecutive polls. Multiple failures on a channel usually result from a line break or a communications equipment failure in the control center.

In some cases the system configuration may not permit the isolation of a communication system failure from the failure of other equipment such as a controller.

System Responses

Under conditions of communication failure, the controller normally reverts to another mode of operation such as:

- Local isolated operation, or
- Backup coordination.

Current system designs typically use time based coordination as a backup for loss of communications. In older systems, a number of which remain operational, coordinated timing dials in the field controllers achieve backup coordination (65), with dial synchronization usually accomplished prior to failure of the communication system. In some instances a parallel set of cables coordinates the timing dials.

Design Techniques

The following commonly used design techniques can provide a reliable communications system:

- Redundant backbones
- Limitation on number of controllers on one communication channel
- Additional power margin
- Improved cabinet design
- Adequate lightning protection

The following paragraphs describe these techniques:

Redundant Backbones

Backbone systems see use in large fiber optics based communication systems (Chapter 6). Some of these systems use a redundant backbone configuration such as the protected ring shown in Figure 6-14. To be truly redundant often requires the use of a separate conduit in a separate trench or other supporting structure (redundancy at this level is expensive). In some cases the geographic layout of the system proves sufficiently rich in interconnecting links so that each controller may be accessed from two different directions, eliminating the need for redundant trenches and conduits.

Limitation of Number of Controllers on One Channel

Multiplex techniques usually support large numbers of controllers on a single fiber or spread spectrum radio channel. However, in this implementation the failure of one channel can result in loss of a large portion of, or even an entire system. The agency may reduce exposure by limiting either the number of controllers or the fraction of a system assigned to a single channel.

Additional Power Margin

Chapter 2 discusses the concept of power margin. While systems may provide satisfactory performance when initially installed, components may age and cable connections become impaired. While preventive maintenance can offset these factors, initial system design with extra power margin permits some component degradation without adverse effects on performance.

Improved Cabinet Design

In some cases, environmental conditions contribute to communications equipment degradation or malfunction. Examples include:

- Excessive temperature due to inadequately ventilated cabinets
- Location of equipment at a cabinet hot spot
- Exposure to moisture.

Design should preclude these conditions.

Adequate Lightning Protection

Lightning has proven a major contributing cause of communication equipment and line failure. Appendix C discusses lightning protection.

Cable Installation Issues Relating to Reliability and Maintainability

Failure to conform to proper installation procedures commonly causes communication system failure or unreliable performance. Common problem areas include:

- Improperly implemented fiber optic cable and coaxial cable connections.
- Maximum cable pulling tension exceeded.
- Use of tighter cable bending radii than recommended by manufacturer.
- Improper splices.

Installation personnel should receive appropriate training for these items prior to starting installation. Construction inspection personnel should also be made aware of the importance of these items.

There are three basic methods of installing a cable to interconnect a traffic control system. The following paragraphs discuss these methods:

- Cable in Conduit

  Cable installed in conduit generally proves the most secure and requires the least maintenance if adequately protected by timely mark-outs and a tight permitting process. This method installs cable in conduit (either galvanized steel or PVC) approximately two feet below the surface, depending on State specifications. Junction boxes provided at regular intervals aid in cable pulling and maintenance. The junction box type varies with state standards, but generally consists of a concrete structure buried in the ground with a cast iron cover capable of carrying wheel loads. Spacing also depends on State specifications and the conduit layout. The designer should provide more frequent pullboxes if the conduit runs have bends, particularly if sharp. For instance, PVC conduit should not have bends greater than 22% because pulling long runs of cable through such a bend can actually cut the conduit. Instead, install a pullbox. States commonly specify maximum spacings of 150 to 300 feet for relatively straight conduit runs.

The conduit and approximately two feet of earth covering protect the cable. In some cases, a plastic tape approximately 4 inches wide and carrying a warning is installed six (6) inches over the conduit to warn excavators. To provide for further structural protection of the cable, the conduit is sometimes encased in concrete. The additional concrete protection is more typical of high voltage cable systems where piercing the cable may be life threatening and is not cost effective except in special situations.

Potential damage from excavation or the installation of signs posts, guide rail posts or utility poles presents the principal danger to cable. Where possible, reduce the chance of damage by placing conduit in existing grass medians to minimize excavation due to new driveways, the installation of utility poles and most roadside signage. Since any excavation within the highway rights-of-way normally requires permits, the agency can notify permittees and adequately protect the cable system. The maintaining agency generally provides field mark-outs of the cable system in accordance with OSHA regulations prior to any excavation in the cable vicinity. This mark-out requirement represents an additional agency maintenance responsibility, although probably the only significant additional responsibility involved in the maintenance of a cable in conduit interconnect system. The maintaining agency must coordinate and cooperate with other utilities in the area to assure proper notifications. Telephone and power companies often set up a single telephone number for excavators to call to request mark-outs. Agencies maintaining traffic control systems should join with area utility companies in such a notification system.

Cost represents the principal drawback to a cable in conduit system. Conduit can cost from $3.00 to $10.00 per foot more to install than direct burial cable and from $10.00 to $20.00 per foot more to install than aerial cable, depending on local conditions and cable size.

- Direct Burial

  Burying interconnect cable directly in the ground using special direct burial cable can result in a considerable savings. Direct burial cable has an extra insulating jacket to protect the communication pairs or fibers. Direct burial cable eliminates the conduit and junction box costs and, depending on the terrain and make up of the surface area, can make excavation cheaper. For long straight cable runs with few surface obstructions, a specialized cable installation machine can plow cable directly into the ground. Do not specify plowed cable installation for locations where the soil contains large rocks, which can nick the cable during installation. Cable plowing proves most appropriate for long continuous runs with no obstructions, roadways, driveways or sidewalks in the path of the plow. The disadvantage of direct burial cable includes greater susceptibility to damage than cable protected by conduit. Further, it can prove more difficult to maintain and repair.

  Generally, do not use direct burial cable unless a system exists for good control of excavations through the permitting process and roadside development in the area of the cable installation is minimal. For instance, direct burial cable would suit an installation alongside freeways and parkways with control access and few, if any, installed utilities. Installation of signs and guiderail or highway construction sponsored by the highway agency presents the principal danger to the cable. Direct burial cable generally does not suit arterials with frequent driveways and substantial overhead or underground utility systems present. A grassed arterial median may prove one possible exception. Do not install direct burial cable under pavement or sidewalks which make the cable inaccessible.

With buried cable systems, either direct burial or cable in conduit, the key to reliability lies in the maintaining agency's control of excavations, and sign post, guiderail and utility pole installation in the vicinity of the cable system. The maintaining agency must develop a successful notification system and provide timely mark-outs when notified. Through the permitting process, the agency must review all construction work and incorporate cable protection into the plans. In addition, the agency must make sure that all of its own operating arms remain aware of the system and take the proper precautions, as an agency's own construction or maintenance activities often disrupt cable systems.

- Aerial Mounting

The third cable installation method is aerial installation on existing utility poles. This normally proves the least expensive method of installation, often only 25% of the cost of cable installed in a conduit and junction box system. However, aerially supported interconnect cable normally has a yearly rental fee charged by the owner of the utility pole for permission to maintain the attachment. In addition, relocation fees often must be paid to the various utilities already attached to the pole to establish adequate vertical clearances on the pole. The charges are termed "make ready" costs.

In addition to significant cost savings for aerial installation, excavation will less likely damage the cable causing loss of system communication. Further, if cable damage occurs no excavation is needed to perform the required repairs. However, aerial installation has two drawbacks:

- Slow deterioration due to exposure to the sun's ultraviolet rays; however, the cable should not deteriorate to the point of necessary replacement for at least 15 years. Cable installed in conduit should last considerably longer.

- Annual rental or attachment fee paid to the owner of the utility pole. The agency generally negotiates this fee with the utility companies on an area-wide basis. In some locations, this may necessitate enabling legislation at the State or local level to authorize a blanket agreement. In the negotiations, point out that the utility companies benefit from their ability to install poles, cable and conduit in the public rights-of-way; in return the utility should eliminate or reduce the fee.

With the installation of cable on utility poles, maintenance costs continue, some reimbursable, some not. These expenses result from:

- Reattachment of the cable to new utility poles because a vehicular accident destroys the original pole,

- Relocation due to highway construction or a new development, or

- Replacement for utility maintenance reasons.

Even though motor vehicle accidents sometimes destroy utility poles, damage rarely occurs to the cable.

When comparing cable installed in conduit versus installed aerially, the difference in initial construction costs appears most striking. Yearly maintenance costs for the two systems should prove comparable. The aerial system has the additional yearly pole rental fee and because of the deterioration of the cable in the air, the agency will have to replace aerial cable once to match the twenty to twenty-five year life of the cable installed in conduit. These additional costs do not, however, match the additional construction costs inherent in the underground cabling system. In addition, the aerial cable can prove less susceptible to damage easier to repair.

Enhancing Maintainability

The acquisition of a traffic control system represents a significant investment and implies a commitment by the operating agency to support and maintain the system. A number of steps should be taken during the system design and acquisition phase to assure the maintainability of the system as well as develop the agency's ability to maintain the system. The agency should consider the following steps:

- Make a critical evaluation of the agency's capability to provide timely maintenance for communication equipment and communication lines. The agency may prefer less complex technology or leased communication channels rather than a system the agency cannot adequately support.
- Establish a maintenance plan well in advance of system installation. Maintenance technicians should receive training from the contractor during system installation, and the specifications should include this requirement.
- Specify documentation which includes communication line connections and controller and field device channel communication assignments.
- Specify communications equipment and system designs which use common standards. The inability to support communications equipment and expand traffic systems because of the unavailability of compatible equipment has proved common. With non-standard equipment, procure an adequate number of spare communication modules for use well into the future. Also consider the acquisition of sufficient numbers of specialized parts which may become unavailable (e.g., custom integrated circuitry).
- Obtain the appropriate quantity and type of communication test equipment.
- Coordinate with utilities which use the right-of-way for their facilities so that construction or maintenance activities do not present a threat to the communication cable and conduit.

Enhancing Expandability

In many cases spare twisted wire pairs or fibers in a cable address the issue of system expansion. While useful, this often fails to provide the required functionality.

The designer should consider this issue thoroughly during system design. System expansion categories include:

- Expansion of system function at a controller site. Examples of expansions include the later addition of devices such as blankout signs, lane control signals and overheight detectors.
- Addition of new controllers within present project limits.
- Expansion of the system to sites contiguous to the present project.
- Expansion of the system to sites not contiguous to the present project.

Although the requirements for future expansion are not fully known during initial system design, in many cases the jurisdiction's geography, coupled with a knowledge of desired functionality improvements allows planning for system expansion.

Table 8-3 identifies several techniques to consider during the design of a communication system and the relationship to expansion requirements.

Techniques for Consideration in Communication System Design to Facilitate Future Expansion	Expansion of Function at Controller Site	New Controllers Within Present Project Limits	Expansion to Site Contiguous to Present Project Limits	Expansion to Non-Contiguous Sites
1. Provision of spare function or bit capacity within present communication protocol	✓			
2. Provision of spare controller capacity on polled communications protocol		✓		
3. Provision of spare channel capacity in cable		✓	✓	
4. Provision of trunked cable capacity in conduit			✓	
5. Addition of spare ports or port expansion capability to central computer complex		✓	✓	✓
6. Addition of communications server to central computer complex		✓	✓	✓
7. Acquisition of area radio channels from other agencies in jurisdiction whose need has diminished or terminated				✓

Table 8-3 Relationship of Communications Expansion Tecniques to Expansion Requirement

CHAPTER 9 - STANDARDS

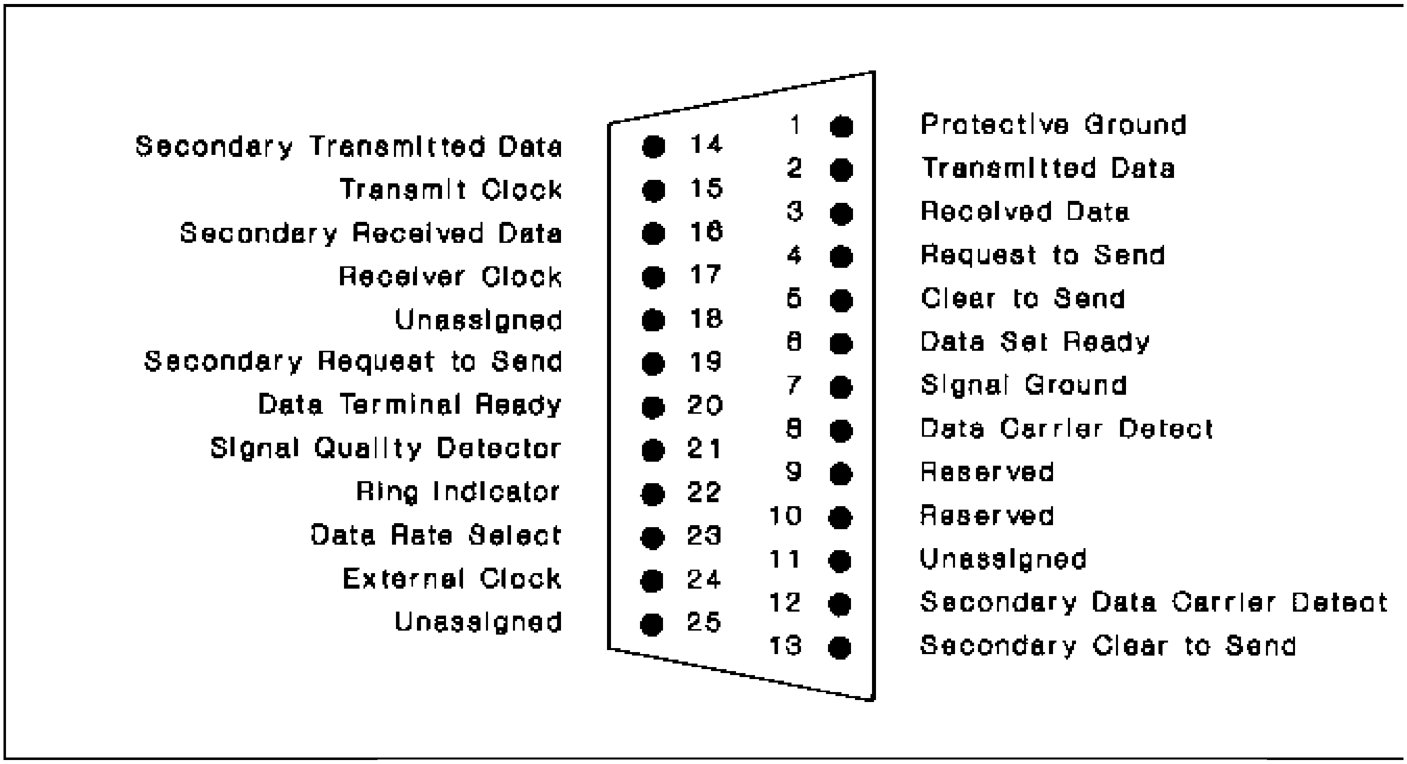


Figure 9-1 RS 232 Standard

Introduction

The previous section emphasized the need to consider the "ilities" in the design process, i.e., reliability, maintainability and expandability. The use of standards provides another avenue for enhancing these factors. Attention to standards becomes critical as traffic control systems increasingly form the basic infrastructure for IVHS.

Need

Chapter 10 discusses the problems encountered in expanding systems well after initial installation. Many of these systems use communications and controller equipment which do not conform to standard equipment interfaces and protocols. Expansion is not feasible for some of these systems as the manufacturer no longer supports the equipment.

Reference (63) describes an FHWA sponsored project to develop communication standards for traffic control systems. The project developed a standard for a remote control unit for the NEMA TS1 controller by defining physical and electrical interfaces. Since the standard did not define message and polling protocols, however, it failed to achieve interchangeability among equipment provided by different manufacturers.

Although Reference 39 rejects the need for additional standards, their importance has been more recently recognized.(64) The popularity of the Type 170 controller family, a step towards open architecture, further illustrates the advantages of communications and control equipment standardization. Without standards, the designer and jurisdiction effectively lose control after award of the installation contract.

Purpose

The transportation professional must recognize the importance of standards during the design process. The designer must prepare specifications in sufficient detail to assure the desired level of standardization of field equipment functions and communication interfaces and protocols.

Therefore, this section provides guidance in the selection and imposition of standards during design of the communications system.

Organization

Table 9-1 summarizes the organization of this chapter.

Section Title	Purpose	Topics
Relevant Standards	Summarizes standards applicable in traffic control systems communications	Standards for: • serial data interface • modems • voiceband channels • digital signals • fiber optics • integrated services • compressed video • local area network
Incorporation of Standards	Discusses the role of standards in traffic control systems design	Advantages and disadvantages of standards

Table 9-1 Organization of Chapter 9

Relevant Standards

This section describes the use of standards for various aspects of system design.

Serial Data Interface

Serial data interfaces connect various field devices such as controllers to communications equipment (e.g., modems, radio transmitter/receivers).

- RS232 - The Electronic Industries Association (EIA)

  The RS232 standard has proven the most common standard in the U.S. for serial data transfer, with most current traffic equipment compatible with the C level revision (1969). The D level revision issued in January 1987 will grow in use with time. (The EIA will drop its use of the term RS, and the RS232 standard will become EIA 232.)

  Although commonly used, this standard only applies to distances of 50 feet or less and transmission rates of approximately 20 KBPS.

- RS 422, RS 423 and RS 449

RS 449 serves as a mechanical and functional specification containing two subspecifications, RS 422 and RS 423 which specify electrical interfaces. RS 422 specifies a balanced electrical interface and can transmit at higher rates and over longer distances than RS 423, the unbalanced interface.

RS 423 provides for data transmission up to 4000 feet at 1.2 KBPS and at rates of 100 KBPS at 40 foot distances. RS 422 provides for data transmission of 100 KBPS at 4000 feet and 10 MBPS at 40 feet.

Twisted Wire Pair Modem

Traffic control systems mostly use modems designed for telephone channels and agency owned twisted wire pairs. Chapter 6 and Table 6-5 identify common modem standards.

Voiceband Private Line Channels

FCC Tariff No. 260 established the criteria for leased telephone lines prior to AT&T divestiture. Reference (66) describes the relevant technical considerations. The 3002 channel represents a voiceband data channel applied to this tariff. The agency can lease it in an unconditioned or conditioned configuration. Conditioned lines provide greater levels of control than unconditioned lines over distortion and signal to noise ratio.

Although Tariff No. 260 no longer applies to the local exchange carriers, most local telephone companies still provide service comparable to a 3002 channel.

Digital Signal Hierarchy

Chapter 6 and Table 6-22 discuss transmission standards for data rates of 64 BPS and above.

Fiber Optics Transmission

Chapter 6 discusses the SONET fiber optics system standard: the T1 equivalent for fiber optics in North America.

Integrated Services Digital Network (ISDN)

Chapter 6 describes channel standards for ISDN services provided by communication service suppliers.

Compressed Video

Chapter 4 discusses the current video compression codec standard.

Local Area Networks

IEEE makes available a series of local area network (LAN) standards which deal with networks whose physical dimensions generally prove smaller than most traffic control systems. Therefore, these standards do not directly apply to communication with field devices; thus this handbook does not include LAN standards.

Incorporation of Standards

The previous section identified communication standards most useful for traffic system communication.

As indicated previously in Needs, the specification of standards for system design provides the operating agency with certain advantages. However, a requirement for incorporating standards may also have disadvantages. The following paragraphs discuss pros and cons.

Advantages

Spares and Compatible Equipment

Chapter 8 indicates the lack of compatible communications equipment for system expansion and difficulty in procuring spares have become major limitations in a number of traffic systems. Use of communication equipment designed to commonly used standards coupled with the functional isolation of this equipment from other traffic system components facilitates procurement of spares and compatible equipment for future expansion.

Use of Mixed Communication Technologies and Media

Requirements to expand traffic control system operation to locations not contiguous to the existing system and not accessible by land lines have become increasingly common. The design of traffic systems with communication standards supported by a number of different media and technologies can facilitate this type of expansion.

Compatibility with Test Equipment

The use of non-standard interfaces, protocols and data rates may limit the use of certain types of test equipment.

Training and Support Materials Not Provided by Manufacturer

A significant body of technical literature exists which describes the function and operation of communication ports and modems designed to common communication standards. This material often provides a useful supplement to the manuals supplied by the contractor and can usefully serve engineers, technicians and software maintenance personnel.

Disadvantages

System Architecture Incompatibilities

Certain system architectures, such as closed loop systems supplied by manufacturers for NEMA controllers, do not use standards to effect the functional isolation of the communication equipment and the associated software. Other factors, such as ease of procurement and grooming for operation, prove more important to the agencies which select this type of system architecture.

Possibility of Higher System Cost

Communication standards do not specifically target traffic control system applications so data rates and modem standards do not necessarily reflect optimum selections for traffic control systems. Non-standard modems and protocols sometimes permit a more highly optimized system than use of a standard. This may result in lower system cost.

Figure 9-2 provides an example of this situation in which the system requires relatively short communication lines. The 3100 BPS data rate provides a capacity increase of 158% over the commonly used 1200 BPS modems and an increase of 29% over the 2400 BPS standard modem less commonly used for traffic control systems. To achieve the identical functional capability with the use of standards would have required the use of additional cable and RCU's.

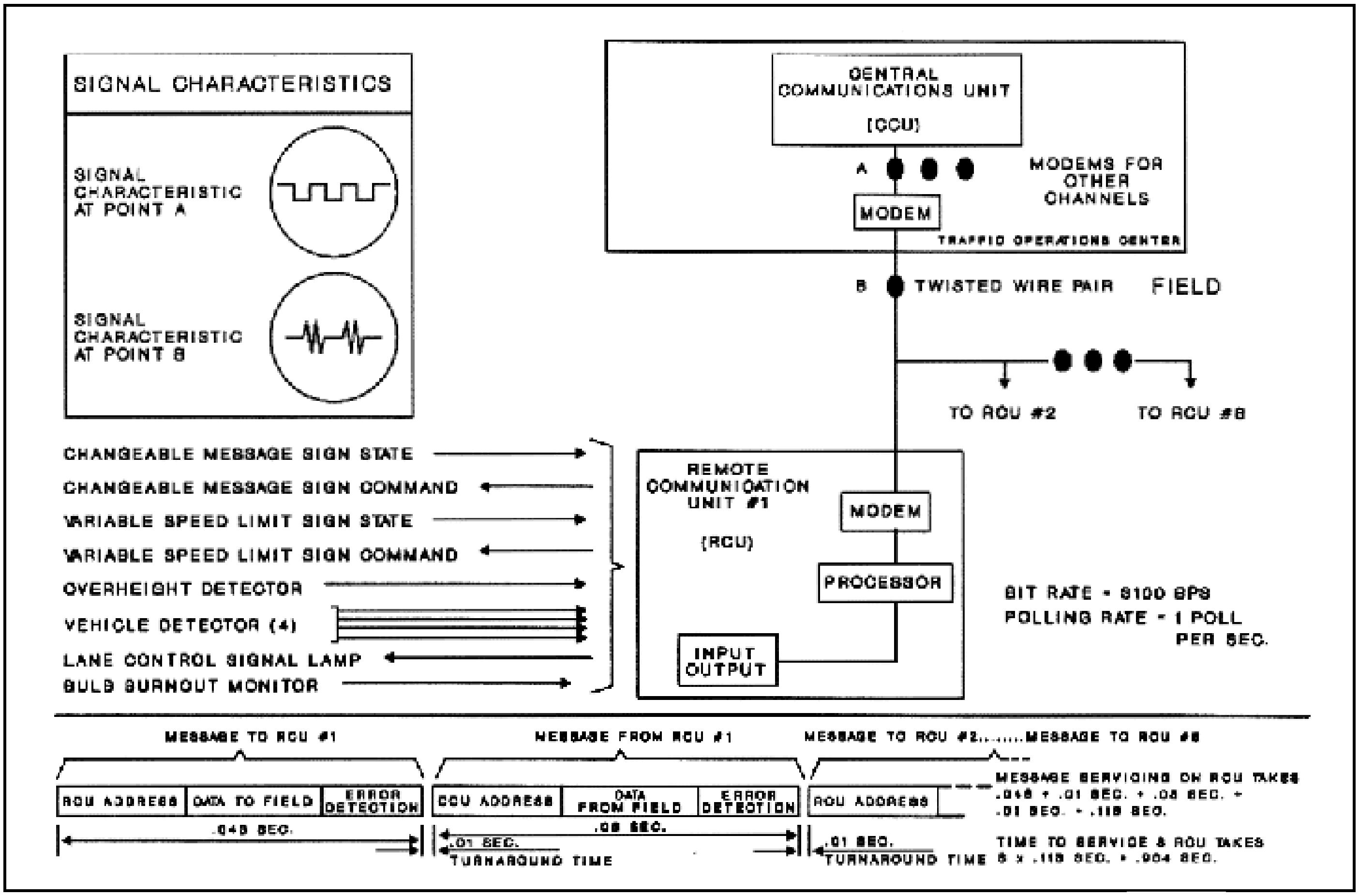


Figure 9-2 TDM Communications Scheme for Elizabeth River Tunnel (Norfolk, Virginia)

CHAPTER 10 - INSTITUTIONAL AND LOCAL ISSUES

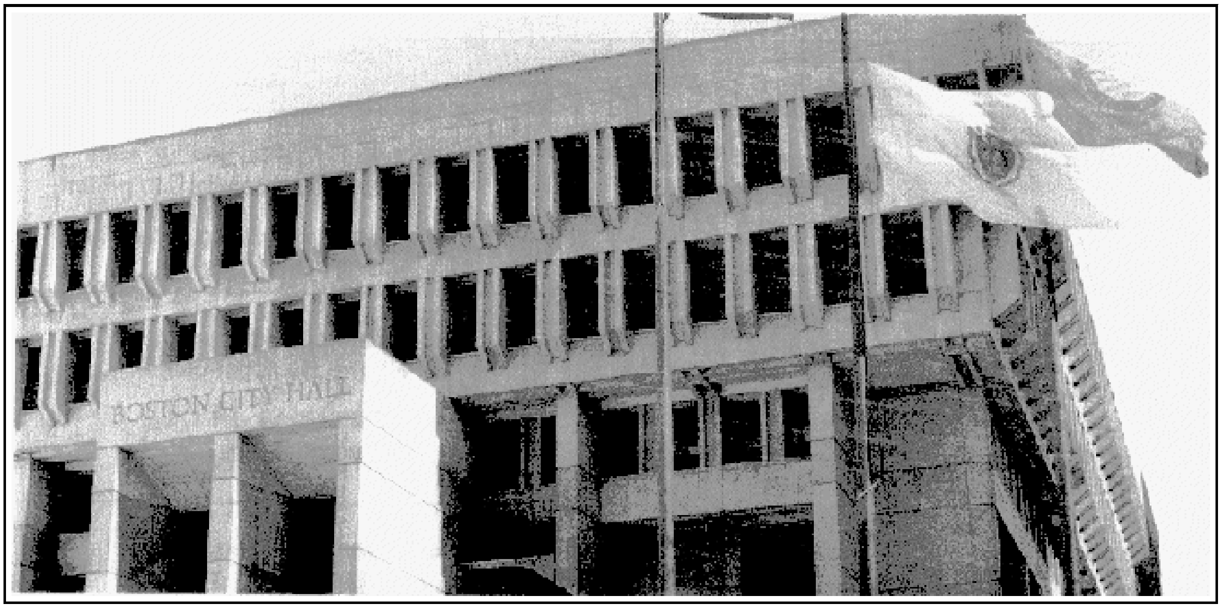


Figure 10-1 Boston City Hall

Introduction

Institutional and local issues often strongly influence decisions on the selection of a communications system. These issues can prove equally as important as technical evaluations.

Need

The transportation professional needs to identify those site-specific issues likely to affect a communications design trade-off and understand how to evaluate these factors.

Purpose

This chapter identifies some important institutional and local factors which impact a communications system. This makes the designer aware of these issues and encourages their consideration in communications system planning.

Organization

Table 10-1 summarizes the organization of this chapter.

Existing Equipment

The selection of a communications system often becomes interdependent with system architecture selection. Usable cable, conduit and intersection control equipment already in place may influence both system architecture and communications design. Since the conduit/cable often proves the major cost of the entire traffic system, a plan which uses existing equipment can become the least expensive and most obvious course.

Section Title	Purpose	Topics
Existing Equipment	Summarizes the role of existing equipment in selecting system architecture	• Existing cable, conduit and intersection control equipment • Testing of existing cable plant
User Preference	Summarizes the role of agency equipment preferences	• Existing investment in intersection controllers • NEMA vs. Model 170 preferences
Franchises	Summarizes the potential of using power/telephone/CATV franchises	• Franchise agreements • Fees • Maintenance responsibilities
Maintenance Capability	Discusses role of agency maintenance capability in system selection	• Maintenance level for newer technologies • Agency options
Reliability	Discusses design constraints arising from reliability considerations	• Preferences for cable based systems, owned media and minimal disruption due to single point failures
Standardization	Discusses importance of standards relative to other design issues	• Expansion capability • Use of existing equipment
Risk	Discusses acceptance of some degree of technical risk	• Potential cost reduction • Improved features • New technology evaluation • Risk mitigation

Table 10-1 Organization of Chapter 10

During the planning phase, designers should require electrical tests of existing cable to determine its suitability for a new system. If the plan includes replacing cable in existing conduit, system installation must include replacement of any damaged conduit. Plans and specifications should provide for this contingency.

User Preference

The jurisdiction's past investment in intersection controllers or desire to maintain a consistent policy in the use of either NEMA or Model 170 Controllers may also play a significant part in defining the system architecture and communication system. (67)

Franchises

Power and telephone company franchises may provide the municipality with a cost saving approach to obtain conduit or pole rights. In some cases, the municipality had exercised these rights exercised for fire alarm interconnect and then abandoned them, thus providing opportunities for traffic control system use. Similarly, CATV franchise awards may make a number of channels available for community service. However, the physical design of the CATV system (see Chapter 6) may limit the use of this capability.

If the designer seriously considers CATV prior to a final commitment to this service, he or she must make arrangements with the CATV facility with respect to:

- fees,
- maintenance responsibilities, and
- maintenance response times.

Maintenance Capability

As indicated in Chapter 8, communication performance often relates to maintenance quality, including preventive maintenance. The increasing sophistication of the newer communications media such as data radio and fiber optics may require a level of maintenance experience and capability which the municipality does not have and cannot easily acquire. (68) The municipality may opt for:

- simpler technology maintainable with in-house forces;
- contract maintenance; or
- leased line service to reduce the need for in-house forces.

Reliability

Jurisdictions may choose to place constraints on the communication system design to increase reliability or prevent the simultaneous loss of communication to large groups of controllers. Examples of such constraints include:

- rejection of radio based technologies,
- preference for owned communications media over leased media, and
- avoidance of communication designs containing points of single failure which disrupt communication to large numbers of controllers.

Standardization

Chapter 8 discusses the problems encountered in maintaining and expanding communication systems well after initial installation. Many of these systems use communications equipment which does not conform to standard equipment interfaces and protocols. Expansion may not prove feasible for some of these systems as the manufacturer no longer supports the equipment.

Chapter 9 identifies communication standards. The user should determine the relative importance of standardization vis-a-vis other issues such as system architecture and retention of existing equipment. The designer should include desired standards in the plans and specifications.

Risk

Although a risk free traffic system communications design appears desirable, some situations warrant acceptance of design risk. Risk may appear either due to lack of fully proven communications technology for the intended application or because service interruptions may occur in certain technologies. Each traffic organization must evaluate:

- the level of risk,
- whether the organization can assume risk, and
- whether potential benefits outweigh the risk.

Reasons for possible assumption of risk include:

- Significant reduction of installation and operating cost.

For example, certain technologies, such as radio, may incur periods of service outage. Although analyses can estimate outage frequencies, actual experience may differ from these estimates.

- Obtaining features otherwise unachievable or impractical to achieve.
- Evaluation of new technology.

A portion of a system may evaluate communication technologies relatively new to traffic control. Sometimes the agency does this as a first step to a wider deployment of the technology. After the evaluation, however, operation and maintenance of the system usually represents a continuing investment by the jurisdiction.

When an agency opts to pursue communication alternatives containing risk, the following steps can mitigate the risk:

- Design the system with the capability to use an alternate communication approach, if necessary. Standardized communication interfaces can accomplish this.
- Only undertake an alternative containing risk when the interruption of communication on a temporary basis will still result in satisfactory system operation.