Report No. FHWA-RD-78-85

A COMMUNICATIONS TRADE-OFF STUDY FOR COMPUTERIZED TRAFFIC CONTROL

Vol. 1. Final Report

November 1978

Final Report

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Springfield, Virginia 22161

Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report presents information that will be useful in reducing communication system costs of future computerized urban traffic control systems. The report provides this information in the form of tutorial and reference material, cost computation procedures, and an example of a communication subsystem specification. The report consists of two volumes: the main text in Volume 1 and appendixes in Volume 2.

This report is being distributed to FHWA Washington, Region, and Division Offices.

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Charles F. Scheffey
Director, Office of Research

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-78-85	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Communications Trade-off Study for Computerized Traffic Control . Volume 1, Final Report		5. Report Date November 22, 1978 6. Performing Organization Code
7. Author(s) J. Scott, R. Gordon, B. Soicher, J. Dudek, R. Kroeger		8. Performing Organization Report No. GF-3704-1060
9. Performing Organization Name and Address Sperry Systems Management Sperry Rand Corporation Great Neck, New York 11020		10. Work Unit No. (TRAIS) 32L2132 11. Contract or Grant No. DOT-FH-11-9275
12. Sponsoring Agency Name and Address Office of Research and Development Federal Highway Administration U.S. Department of Transportation Washington, DC 20590		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code 1-T-0288

15. Supplementary Notes

FHWA Contract Manager: M. K. Mills (HRS-32)

16. Abstract

The goal of this study is to provide information that will be useful in reducing costs of future computerized urban traffic control systems. The final report provides such information in the form of tutorial and reference material, cost computation procedures, and an example of a communication subsystem specification. The report consists of two volumes, the main text in Volume 1 and appendixes in Volume 2.

Volume 1 of the report covers the following subjects: It discusses the principal functions of a computerized traffic control system, describes the types of data that must be transmitted, provides a brief tutorial overview of the communication methods available for providing such transmission, and shows how to estimate the transmission rate requirements for typical systems. It also describes communication methods applicable to computerized traffic control, examines various types of data transmission techniques, discusses factors affecting communication costs, and describes procedures for computing costs and utility measures, with examples. Volume 1 also contains an example of a specification for a communication system that uses a combination of wire pairs and air path optics as the transmission media.

The appendixes in Volume 2 provide detailed information on various topics relevant to material contained in Volume 1.

17. Key Words Communications, Traffic Control, Computerized Traffic Control	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 245	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

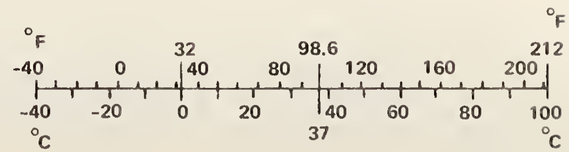
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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FIGURES

FIGURES (Cont.)

TABLES

SECTION 1

INTRODUCTION

This section contains the following material:

- A tabular guide to the report contents.
- A short description of the approach taken in conducting the study.
- The major conclusions of the study.
- Recommendations for future research.

1.1 REPORT SUMMARY

The objective of this report is to provide information that will be useful in reducing costs of future computerized urban traffic-control systems. This information includes tutorial and reference material, as well as examples of cost computations and an example of a communication subsystem specification.

The report consists of two volumes. The first volume contains six sections which provide the basic information to be used in selecting and specifying communications for a traffic control system, and the second volume contains primarily tutorial and reference material.

As an aid in using this report, the information has been subdivided into five separate categories. These are listed in Table 1-1, together with the report location where they are covered, and an indication of the reader background needed to avoid difficulty in following the material.

Material contained in the remaining sections and appendices of the report are briefly summarized as follows:

Section two discusses the principal functions of a computerized urban traffic control system, describes the types of data that must be transmitted, and describes the various communications techniques that may be used for such data transmission.

Section three describes communication methods which are applicable to computerized traffic control, classified in accordance with their transmission medium.

Section four discusses factors affecting communication cost, describes procedures for computing costs and utility measures, and illustrates the procedures with examples of the computations.

TABLE 1-1. REPORT GUIDE

Information category		Location in report	Reader background
Item No.	Description		
1	Tutorial and background information on what a computerized traffic control system does; what its basic communication requirements are; and the general types of communication methods that can meet these requirements.	Vol. 1, Section 2; Vol. 1, Section 5; Vol. 1, Glossary; Vol. 2, Appendix E	Traffic Engineering.
2	Tutorial and reference material on all of the communication methods that were examined during the course of this study.	Vol. 1, Section 3; Vol. 1, Section 5; Vol. 2, Appendices F thru L	Traffic Engineering; some electronics and digital logic training or experience; and understanding of Section 2 of this report (or equivalent).
3	Tutorial and reference material on topics common to more than one communication method.	Vol. 1, Sections 3 and 5 Vol. 2; Appendix B	Same as for Item No. 2 above.
		Vol. 2, Appendices A, C and D	Same as for Item No. 2 above plus control system theory and probability theory.
4	Factors affecting communications cost and utility, plus examples of cost and utility computations.	Vol. 1, Section 4; Vol. 1, Section 5	Traffic Engineering.
5	Example of a specification for the communications subsystem of a computerized traffic control system.	Vol. 1, Section 6	Traffic Engineering and some digital computer training or experience.

Section five contains supplementary material, such as derivations or detailed discussions which are referred to in Sections 2 through 4.

Section six contains an example of a communications system specification for a communications system that uses a combination of wire pairs and air path optics as the transmission media.

The Glossary defines communications terminology in semi-technical language.

The Appendices in Volume 2 provide detailed information on various topics relevant to material contained in Volume 1.

Appendices A through E contain tutorial and reference information that is relevant to more than one communication method.

Appendices F through J provide detailed information on the specific communication methods that are considered in the trade-off analysis.

Appendices K and L provide background information in those communication methods that were examined but which were found not to be generally applicable for full-scale traffic control use at the present time.

1.2 STUDY APPROACH

This study was begun by Sperry Systems Management in June 1977 under contract to the Federal Highway Administration. The study approach specified in this contract included the following tasks:

- Reviewing the characteristics of various existing or planned computerized traffic control systems.
- Preparing function block diagrams for models of three basic processing architectures.
- Examining various communication methods, including transmission media, transmission techniques, and communications hardware considered to be applicable to computerized traffic control.
- Conducting a trade-off analysis of communication methods with examples of each of the three basic processing architectures.
- Preparing a communications system specification.

The review of system characteristics consisted of examining and listing the basic traffic control features and communication-related aspects of fifteen traffic control systems which are either already installed or are in the process of being installed.

The preparation of function block diagrams consisted of showing successive operations on the basic traffic control functions (surveillance, controller monitor, and controller command) as they progressed from one end of the communications link to the other. These diagrams were prepared for models of three processing architectures defined in the contract as "centralized", "hierarchical", and "network".

The examination of communication methods included a literature review and examination of a number of potentially useful techniques. Eight different methods classified by their transmission media were examined in detail, and five of these basic types were selected as being presently applicable to computerized traffic control. In addition, various forms of multiplexing and error control common to more than one method of communication were also studied.

The trade-off analysis included a description of cost computation procedures plus examples of computations for the selected communication configurations as applied to the three basic processing architectures. A utility analysis procedure was also developed in which utility values were applied to the selected configurations, and a graphical presentation of the utility/cost relationships was prepared.

The system specification was written for a hierarchical type system architecture using wire pairs and air-path optics as transmission media.

1-3 CONCLUSIONS

The principal conclusion to be drawn from this study is that there are a number of communication methods suitable for computerized traffic control, and the choice of an optimum method (or combination) for a particular locality depends on local conditions and the traffic control features desired. The viable communications methods include those employing the following transmission media: wire pairs (user-owned or leased), coaxial cable, atmospheric optical spectrum (air-path optics), and optical fibers. Various transmission techniques such as frequency and time-division multiplexing (FDM and TDM) and direct current switching are included among the wire-pair communication methods.

Other methods which were studied employ the following transmission media:

- UHF radio spectrum, which is recommended for future research.
- Power lines, which are considered unsuitable because of data rate limitations and potential technical and jurisdictional problems.
- Baseband microwave radio spectrum, which was rejected for lack of demonstrated communication feasibility.

The influence of distributed processing on communications was examined as part of the study and was shown to permit use of communication methods employing relatively low data rates.

The overall effects of local conditions and other factors on the choice of communication methods (transmission media and techniques) are summarized in Table 1-2. This table may be used as a guide to the order in which various techniques may be considered in making a trade-off for a particular situation.

This report is intended to be used as a guide to selection of potential communication systems offered by prospective suppliers or consultants as part of a traffic control system design. The cost of such a communication system may be estimated by following the procedures and examples given in Sections 4 and 5. The communication system features and capabilities may be estimated through reference to the applicable tutorial material in Sections 2 and 3 as well as the background material provided in Appendices A through H (Volume 2). Finally, the completeness of the design or specification may be checked through reference to the material given in the example specification, Section 6.

1.4 RECOMMENDATIONS FOR FUTURE RESEARCH

1.4.1 General

Radio communications was investigated as a potential candidate for computerized traffic control as part of the study. This investigation indicates that radio communication is technically feasible and potentially low in cost. The study also indicates that, at present, a complete traffic control system using two-way radio communications cannot be assembled from commercially available equipment.

Technological advances that have resulted in lower equipment costs and highly reliable equipment, together with the present high cost of wire installation, are the basis for a recommendation that a development effort be made to establish the feasibility of using radio communication techniques for traffic control in an urban environment. The major problems

TABLE 1-2. FACTORS AFFECTING COMMUNICATION CHOICE

Principal factors favoring usage of communication method	Communications methods							
	User-owned wire; TDM	User-owned wire; FDM	User-owned wire; DCS*	Leased wire; TDM	Leased wire; FDM	Coaxial Cable	Air path optics	Fiber optics cable
1. Simple controller, few detectors		X	X		X	X	X	X
2. Complex controllers, many detectors	X			X		X	X	X
3. Available conduit, poles or cable	X	X	X			X		X
4. Easily trenched surface	X	X	X			X		X
5. Low-cost installation contractor	X	X	X			X	X	X
6. Distributed processing desired	X			X			X	
7. Low-cost leasing rates and interconnection to Telco line				X	X			
8. Line-of-sight paths available							X	
9. System expansion expected	X			X		X	X	X
10. Future TV expected						X		X

NOTE: "X" indicates factor is favorable for communication method.

* Direct current switching

to be solved by a research and development program would be those associated with the availability of the communication equipment and FCC authorization.

1.4.2 Equipment Development Program

The technology for the design and manufacture of radio transmitter and receiving equipment for the 950 megahertz band is well known and many manufacturers are capable of producing this equipment. The development programs would require the design of the central transmitter-receiver and antenna as well as the equipment to be used at each traffic control intersection. The intersection units would require a microprocessor to permit relatively low data rate operation and to detect transmission errors.

The communications portion of the system should have the capability of evaluating various diverse concepts as well as redundant transmission techniques to minimize the effects of any errors introduced. The equipment should also allow measurement of ambient interference levels and determination of range capability and error rate as a function of the transmitter power level. Two different equipment configurations should be designed, one consisting of a central base station with satellite transceivers and the other being a serial microwave repeater relay communications configuration.

A development project to firmly establish the economic feasibility of radio communication techniques for traffic control would proceed through the following phases:

Analysis - an extensive analysis of the communication and data handling task would be combined with a literature search to firmly establish the quantitative values of the equipment parameters involved.

Design - equipment would be specified for use in a particular location based on existing transmitter/receiver and antenna designs used with other licensees such as fire alarm services.

Experimental License - based upon the results of the analysis and the prototype system design, an application for an experimental license would be made to the FCC.

Urban Tests - the prototype system would be installed in a congested urban environment to determine the installation problems involved. The equipment would be operated to determine the information error rate, the equipment reliability and the overall system utility.

Permanent License - based upon the urban test results, an application for a permanent license and frequency assignment would be made to the FCC. When this license and frequency assignment is approved, the entire radio frequency concept would be available for general use for traffic control purposes.

1.4.3 FCC Authorization

The Federal Communications Commission assigns portions of the frequency spectrum to various users for different services and these determinations have resulted in the various volumes of the document entitled "Federal Communication Commission Rules and Regulations" which is available from the Superintendent of Documents, Government Printing

Office, Washington, DC, 20040. In the event that a proposed usage of the frequency spectrum is in conflict with the Rules and Regulations, changes may be made by the FCC if the proposed change is in the public convenience, interest, or necessity.

The broad outlines of the rule-making procedure is given in the FCC Rules and Regulations (Volume 1, Part 1, Subpart C - Rule Making Proceedings). The procedure can be initiated by any interested person who can file a "Petition for Rule Making", or the FCC can initiate the rule-making procedure on its own. Either initial action can result in the issurance of a "Notice of Proposed Rule Making" and Assignment of a "Docket" number, which is published in the Federal Register. All interested persons are afforded the opportunity to comment on the proposed rule making within the stipulated reply interval, which is typically a month or two. Provision is made for the filing of reply comments which permits interested parties to examine the initial filing of others and respond before the Commission's deliberations are completed. Under certain circumstances, petitions for oral argument are entertained by the Commission or permit those filing an opportunity to openly address the Commission of the issues involved. Following consideration of the facts available, the FCC will issue a Report and Order which contains the decision on the issue and the reason for the action. The decided rule will be published in the Federal Register and will ordinarily become effective thirty days afterward and will then be incorporated in the Rules and Regulations. The FCC rule-making procedure also includes a procedure to allow petitions for reconsideration.

The FCC has already assigned frequency channels in the 950 megahertz region for a one-way communications path to be used for traffic control. The assignment of other channels by the FCC for traffic control purposes to be used for return path transmission appears to be a straightforward (albeit lengthy) extension of the frequency assignment process.

SECTION 2

TRAFFIC CONTROL SYSTEM CHARACTERISTICS AND GENERAL COMMUNICATIONS REQUIREMENTS

This section contains information on the following topics:

- Basic functions of computerized traffic control systems.
- Types of information that must be transmitted between various elements of such systems.
- Communication methods that are available for providing the data transmission.
- Definitions of basic data communication terminology.
- Characteristics of the information to be transmitted, and the ways in which it is represented in the communication subsystem.
- Factors affecting data rates and methods of estimating such rates.
- Information flow diagrams showing relationships between communications and information processing.

2-1 INTRODUCTION AND SUMMARY

This section provides background information which describes the data to be transferred within a traffic control system network and summarizes the essential features of communication techniques for transferring such data.

Basic traffic control functions are first summarized, and then the communication subsystems are defined for both central and distributed types of processing architecture.

Various communication methods suitable for general traffic control applications are described next. These include methods employing wire pairs, coaxial cable, fiber optics cable, and air path optics, together with various multiplexing techniques.

Finally, the characteristics of the information to be transmitted and the manner in which the communications system represents the information are described. Communication data rate requirements are included in this discussion, and numerical examples are used to illustrate how such rates may be estimated.

A set of information flow diagrams is also included to aid in analyzing the relationships between the communication subsystem and the information processing elements.

2.2 BASIC TRAFFIC CONTROL SYSTEM FUNCTIONS

The principal function of a computerized traffic control system is to provide optimum area-wide, traffic-responsive signal timing. Secondary functions include:

- Detection and identification of malfunctioning equipment.
- Provision of additional modes of operation, such as time-of-day, day-of-week timing pattern selection.
- Provision of emergency modes of operation such as railroad or fire apparatus pre-empt.
- Real-time display of traffic conditions and traffic signal state.
- Collection of data to be used for validating and/or modifying the various timing patterns.
- Displaying and printing records of traffic conditions as well as system and equipment operational status.

2.2.1 Traffic Responsive Timing

To provide traffic responsive timing patterns, the traffic control system may use any of several computational techniques, of which the most common at the time of this writing is a signature-matching computer program developed by FHWA and designated as UTCS first generation traffic control. This program computes smoothed (filtered) values of current traffic volumes and vehicle occupancy* at various locations throughout the subnetwork, and compares them with values of various traffic-condition signatures stored in the central computer memory. When the current values are within pre-set threshold limits of those for a particular stored traffic signature, the computer selects the corresponding timing pattern and transmits it to the intersection. All of the systems used as examples in this report are assumed to employ this UTCS first generation algorithm for traffic responsive control.

2.2.2 Malfunction Detection

The central computer detects controller malfunctioning by processing controller status (monitor) information transmitted from the intersections, and it detects vehicle-detector malfunctioning by processing the detector data and noting extreme deviations from expected

*Ratio of presence time of all vehicles over a sensor to total time being considered (typically 5 to 15 minutes).

values. Once such malfunctions have been detected, the computer provides an alarm in the form of a visible display or audible signal (or both) to initiate repair activity.

2.2.3 Time-of-day Patterns and Emergency Mode Patterns

The time-of-day signal-timing patterns and emergency mode signal timing patterns are obtained from computer memory as a result of computer time clock or operator input signals, respectively.

2.2.4 Other Secondary Functions

The other secondary functions such as data collection, information display and record printing are derived from the primary sources of information by the central computer.

2.3 COMMUNICATION SUBSYSTEM DEFINITION

2.3.1 General

Data communications are required to link the equipment at the intersections with a central or master computer. The basic intersection equipment consists of a traffic signal controller plus a number of vehicle detectors which serve as the source of information (surveillance information) used for traffic-responsive control. (For examples of typical traffic control systems, refer to Appendix E, which contains a summary of the basic traffic control features and communication-related aspects of fifteen existing traffic control systems. Function block diagrams depicting successive operations on the basic traffic control functions traversing the communication link for three of these systems are shown in Section 5, subsection 5.3.)

Some types of traffic control systems also include a computer at the intersection which performs some of the data processing normally performed by the central computer. The communication requirements of systems which employ this type of "distributed" processing are different from the requirements of systems which do not, and are treated separately in the following discussion. Those systems which <u>do not</u> employ distributed processing are identified as having a "centralized" type of architecture. The types of systems which <u>do</u> employ distributed processing are identified as having either "hierarchical" or "network" type of architecture.

The <u>hierarchical</u> type of processing architecture is defined to be a central computer or microcomputer located in a control center room and connected to "local" microcomputers located in roadside cabinets, usually at the intersections. These local microcomputers process controller and detector data, and provide back-up functions.

The network type of processing architecture is defined to be one in which interconnected roadside microcomputers perform all significant data processing. One of the microcomputers in such a system acts as the "master" controller and performs functions analogous to those of the central computer in the hierarchical system, while the "local" microcomputers provide functions similar to the "locals" of the hierarchical system. Several separate groups of such computers may be located within a particular urban area in a network system (typically single arterials) and may be connected to a control center room primarily for monitoring, for data collection, and for timing pattern modification.

2.3.2 Communications for Centralized Type Architecture

The communication subsystem for a centralized type of traffic control system links the vehicle detectors and traffic controllers directly to the computer at the control center, as shown in the simplified block diagram of Figure 2-1. The communication subsystem includes the transmission "medium" (e.g., wire pairs, coaxial cable, fiber optics cable, or visible spectrum of the atmosphere) as well as communications equipment located at each intersection and at the control center. The communication equipment consists of the following units:

- Transmitters at the intersections which accept the vehicle detector voltage outputs (vehicle presence) and controller monitoring voltage outputs (e.g., A-phase green state, etc.) and convert them to a form suitable for transmission via the particular medium being used.
- Receivers at the control center which receive the vehicle detector and controller monitor signals from the communication medium and change them to a form acceptable to the computer interface circuits.
- Transmitters at the control center which accept the voltage outputs representing traffic signal controller commands from the computer interface circuits and convert them to a form suitable for transmission.
- Receivers at the intersections which receive the traffic signal control information from the communication medium and convert it to a form acceptable to the controller.

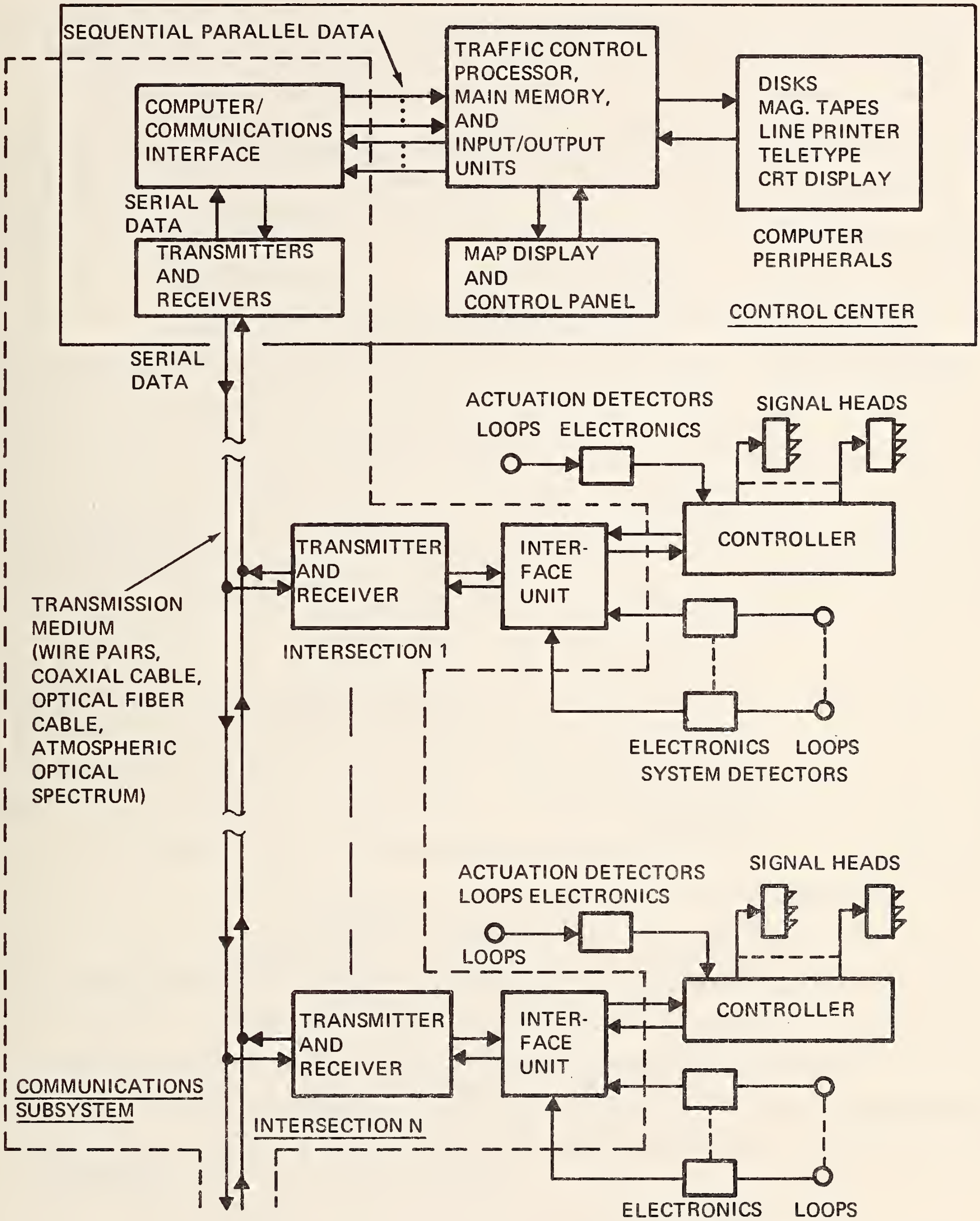


FIGURE 2-1. CENTRAL TYPE ARCHITECTURE BLOCK DIAGRAM

The intersection communication units are normally housed in the intersection cabinet with the traffic signal controller and the detector electronics units. Both the transmitter and receiver functions may be provided by a single physical unit called a modem. *

Distances between cabinets in a typical urban area are 200 to 4,000 feet (60 m to 1.2 km), and maximum distances between the control center and intersection cabinets are typically 10,000 to 50,000 feet (3 to 15 km). These are the distances over which the communications subsystems must transmit data.

2.3.3 Communications for Distributed Processing Architecture

The communication subsystem for a distributed processing type of traffic control system (hierarchical or network type) links the local computers (microcomputers) at the intersections with a central or master computer which provides the area control timing patterns (Figure 2-2). For the network type system, each "master" computer is usually located at an intersection, and is connected by the communication subsystem to a group of "local" intersection computers. The master computers may require additional limited communications (such as dial-up links) to a control center for monitoring, for data collection, or for timing pattern updating purposes (Figure 2-3).

As with the centralized type system, the communication subsystem for distributed computing architectures includes the transmission medium as well as transmitter/receiver units at each intersection and control center. Because the local intersection microcomputers provide some communication functions they are also considered to be part of the communication subsystem as well as part of the traffic control processing system, as indicated by the dashed outline in Figures 2-2 and 2-3.

The transmitter/receiver units (e.g., modems and UARTS) convert data to be transmitted from dc voltage levels to a form suitable for transmission via the selected medium, and convert the received communication signals to a form acceptable to the computers at all locations. The computers, in turn, organize and time the data to be transmitted so that it is recognizable by the computer at the receiving end, and also provide other communication functions as discussed in paragraph 2.5.3 below.

*A "modem" is defined as a unit that transforms serial DC pulses to AC signals (modulates) for transmission, and transforms received AC signals to serial DC pulse data (demodulates). A separate device, often a Universal Asynchronous Receiver/Transmitter (UART) converts the data from parallel to serial (for transmission) and from serial to parallel (on reception) for interfacing with the computer.

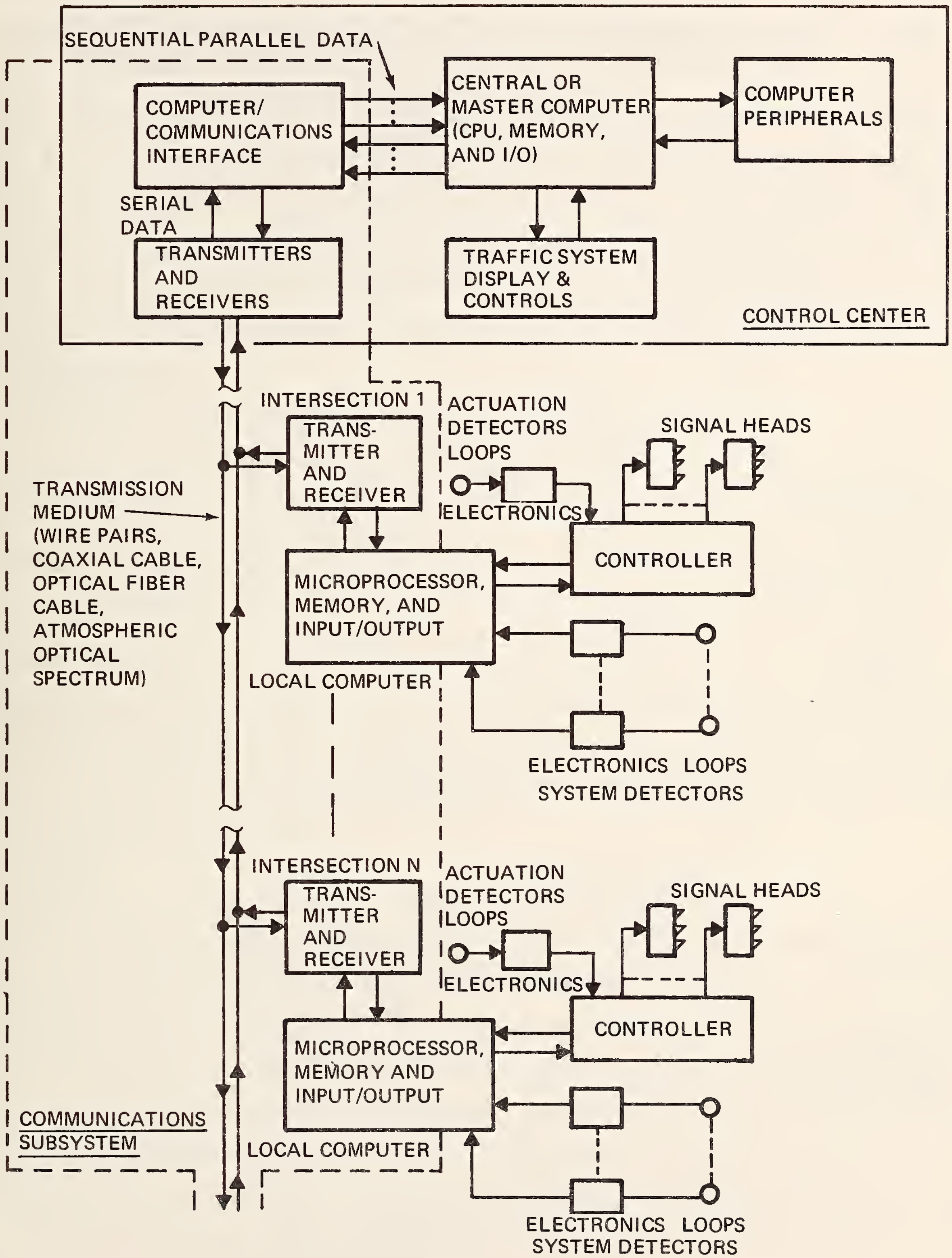


FIGURE 2-2. DISTRIBUTED PROCESSING ARCHITECTURE (HIERARCHICAL TYPE)

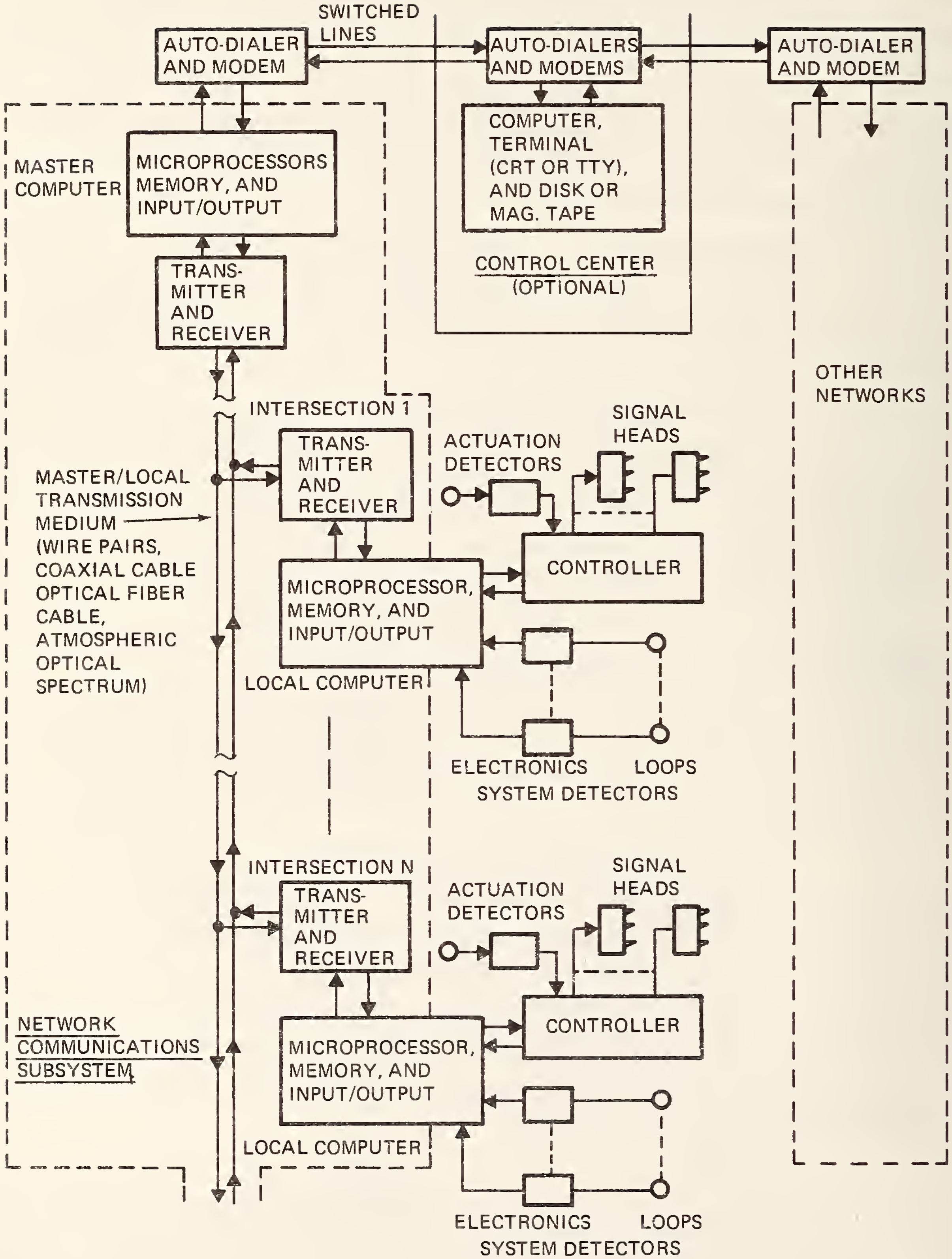


FIGURE 2-3. DISTRIBUTED PROCESSING ARCHITECTURE (NETWORK TYPE)

The transmitter/receiver units and the microcomputer are housed in the intersection cabinet, and the controller and detectors are electrically connected to the microcomputer interface circuits for data transfer.

Typical distances between locations over which data must be transmitted are similar to those for the centralized type system discussed in the previous paragraph.

It should be noted that in a distributed processing type of traffic control system, the basic traffic signal controller functions may be provided by either a separate unit (which could also include a microcomputer) or the same microcomputer that performs the communication and traffic control functions. Thus, with the latter approach, a single microcomputer would provide:

- Communication functions such as data organization.
- System traffic control such as surveillance, monitoring, and controller variable-phase timing.
- Traffic signal controller functions such as preset interval timing and vehicle-actuated phase timing.

2.3.4 Back-up Modes

Communication for both types of processing architecture must provide for an acceptable back-up mode of operation to be employed when either communication or processing fails. Such a mode should be entered automatically whenever a persistent malfunction is detected.

2.4 COMMUNICATION METHODS

2.4.1 General

A number of communication methods, consisting of the transmission medium plus the transmission technique provided by the communication equipment, have been identified as being suitable for general use in urban traffic control systems. These are discussed in the following paragraphs (2.4.2 through 2.4.7).

For a centralized type of system architecture, these methods include combinations of the following media and techniques:

- Transmission media consisting of wire pairs (either user-owned or leased from the telephone company), coaxial cable, or fiber optics cable.

- Transmission techniques* consisting of direct-current switching (DCS), frequency division multiplexing (FDM), or time division multiplexing (TDM).

For a distributed processing type of architecture (hierarchical or network), these communication methods include combinations of the following media and techniques:

- Transmission media consisting of wire pairs (owned or leased), the optical spectrum of the atmosphere (air path optics), coaxial cable, or fiber optics cable.

- Transmission technique* - time division multiplexing (TDM).

Note that coaxial cable and fiber optics cable provide sufficient data handling capacity for any size centralized type system. Therefore, the reduction in quantity of transmitted data provided by distributed processing does not result in a reduction in cost of these media (as it does with other media). However, they are included for distributed processing systems, since they might be used for other reasons such as inclusion of TV surveillance, bandwidth sharing with other agencies, or lower overall system cost resulting from particular local conditions.

Each of the feasible combinations of medium and transmission technique listed above for both the central and distributed type systems is described briefly in the following paragraphs:

2.4.2 Wire Pairs; Direct-Current Switching (DCS)

This communication method typically employs electromechanical relays for transmitting and receiving DC voltages (via wire pairs) representing the two states (presence/absence) of each function such as vehicle detector output, controller "advance" pulse, controller phase monitor signal, etc. The receiving relay essentially replicates the signal being transmitted except for 5 to 10 milliseconds delay attributable primarily to the relay actuation delay.

2.4.3 Wire Pairs; Frequency Division Multiplexing (FDM)

This communication method divides the available bandwidth of the wire medium (usually taken as 300 to 3000 Hz**) into a number of narrow bands (typically 120 Hz each) and allocates a narrow band to each function, such as a single vehicle detector output, etc. The

*These techniques are described, as applicable, in the discussion of communication methods (paragraphs 2.4.2 through 2.4.7).

**The telephone company limits their voiceband private line channels to this frequency band. As a result, most commercial equipment is designed to operate within these limits.

two states of the function being represented, such as vehicle absence or presence, are usually represented by two different frequencies within the narrow (120 Hz) band. For example, in the narrow band centered at 900 Hz, a tone of 870 Hz would represent vehicle absence, while a tone of 930 Hz would represent vehicle presence. These frequencies are called "space" and "mark" respectively, and the technique is called frequency shift keying, or FSK.

A separate FDM transmitter and receiver is required for each function, and, as with the direct current switching technique, the received signal essentially replicates the transmitted signal except for a 5 to 10 millisecond delay (attributable to narrow-band filters in this case). Up to 23 separate functions may be handled on each wire pair, but the number may be limited by distance or wire size.

2.4.4 Wire Pairs; Time Division Multiplexing (TDM)

This communication method divides the time available for data transmission into a sequence of short time intervals (time slots) and typically allocates a time slot to each intersection of a group of 4 to 20 intersections. This group of intersections and the central or master computer are all connected to the same wire pair or set of two wire pairs in what is called a multipoint or multidrop circuit. The central or master computer typically sends controller command data to one intersection and receives all detector and controller monitor data from that intersection within one time slot. It then repeats this process with the next intersection, and so on, until all intersections in the multipoint group have been "polled", at which time the polling of all intersections in the group begins again.

With a centralized type of system architecture, the time slots are typically in the order of 50 milliseconds, and the complete polling cycle (all the group's intersections polled) is one-half to one second in duration. With a distributed processing architecture, the time slots are typically 0.2 seconds to one second in duration, and the polling cycle is in the order of one minute. For both types of systems, all multipoint groups are polled simultaneously, so that all intersections in the system are polled within the same time period as the individual group.

The data transmitted during each time slot is in the form of a time sequence of signals. Each of these signals may have one of two different states (represented by two FSK frequencies) and is used to represent a "bit" of information (binary 1 or 0).* The bits in this serial data stream may represent any one of the following types of two-state information:

- Each bit may represent the presence or absence (1 or 0) of a unique quantity such as Advance, A-phase green, vehicle detected, Skip phase, Flash, etc.
- A series of bits may represent a binary number such as average vehicle occupancy (percent) for a one minute period, or the accumulated number of samples of a detector output voltage for a one second period. The number of serial bits, n, can represent a count between zero and $2^n - 1$. Thus, for example, a string of seven bits can represent a count of up to 127 sample pulses.
- A series of bits may represent the "address" of an intersection being polled, where each intersection responds to its unique address.
- One or more bits may constitute an error detecting code which is used to validate the accuracy of a transmitted "message".

The number of intersections that can be handled by each wire pair (or dual pair) is a function of distance and equipment limitations, and typically varies from 4 to 20 intersections.

2.4.5 Coaxial Cable; FDM and TDM

This communication method employs a single coaxial cable for connecting all intersections with the central computer and uses combined FDM and TDM techniques to take advantage of the broadband capabilities of the coaxial cable system (5 MHz to 300 MHz). Typically, the total frequency band is split (FDM) into an upper and lower portion for signals transmitted to and from central, respectively, and then these two bands may be further subdivided into separate frequency channels for the transmission of data, for TV, or for other purposes. As with the wire pair TDM method, sequential two-state signals (binary serial data) are used to transmit the information between central and the intersections using a polling technique. The principal difference between coaxial cable and wire pair TDM is

*Other techniques used to produce the two binary values (modulation, or keying, techniques) are described in Section 3 and Appendix B. Equipment employing more than two signal states is widely used for high-speed data transmission, but is not usually applicable to traffic control because it does not offer advantages commensurate with its added cost. Such equipment typically employs standardized "protocols" for controlling operation of data links between computers.

that the data rate required is much higher for the coaxial cable system since all intersections in the system must be polled in sequence within the allotted time period (usually one second for a central-type system).

2.4.6 Fiber Optics; TDM

This communication method employs a single optical fiber cable to connect all intersections with the central computer and uses a polling TDM technique to transmit data in both directions (to and from central). As with the wire pair and coaxial cable TDM communication methods, the central computer polls (addresses) each intersection individually, and waits for a response before it polls the next. As with the coaxial cable method, a high data rate is required to poll all intersections of a large system within a short time period. An amplifier at each intersection regenerates the optical pulses which represent the serial binary data.

2.4.7 Air Path Optics; TDM

This communication method employs a pole-mounted bidirectional optical transceiver plus a microcomputer at each intersection. The bidirectional transceiver consists of two optical "heads" which face their upstream and downstream counterparts at adjacent controlled intersections. The microcomputer at each intersection performs the distributed processing functions. Operation of this type of system is identical to that for wire pair TDM except that each optical transceiver acts as a repeater for all signals traversing the network in both directions.

2.4.8 Wire Pairs; FDM/TDM

Transmitters and receivers which do not utilize the full voice band may be used to provide two or more simultaneous channels of TDM transmission at low data rates. Units which may be used for this type of operation are available from multiple commercial sources. Their characteristics range from two channels at a data rate of 600 bits per second to 23 channels at 75 bits per second (standard 120-Hz-spaced FDM).

This approach would be useful where the maximum required data rate is low (as in some distributed processing systems) and where savings in channel cost outweigh the cost of additional communication equipment. It would also be useful for overcoming signal loss due to line loading of a multipoint channel, since units having different frequencies appear as high impedances (light loads) to each other.

2.4.9 Mixed Media Communications

Under some circumstances, it may be desirable to use two or more different transmission media within the same traffic control system. For example, if an air path optical system must surmount a difficult line-of-sight problem in some areas, then either leased or owned wire pairs might prove to be a cost-effective substitute. Combined owned-wire and leased wire systems should also be considered to take advantage of any existing conduit and/or low leasing rates in different areas of particular traffic control communication networks.

2.5 CHARACTERISTICS OF INFORMATION TO BE TRANSMITTED

2.5.1 General

Communication requirements are directly affected by how frequently and with what accuracy the various items of information must be transmitted. For example, transmitting an accurate representation of every vehicle's presence time (when volume is high) requires several bits of information each second for each detector, while transmitting an accumulated value of several vehicle presence times may require only a few bits every minute. The information characteristics for central and for distributed-processing type architectures are discussed in the following paragraphs.

2.5.2 Centralized Type System

Each vehicle detector produces an output voltage waveform (vehicle pulse) representing vehicle presence time at a maximum rate of two vehicles per second. A signal representing one or more such presence pulses must be transmitted to the central computer with a timing accuracy (pulse width accuracy) that is a function of traffic control system design.* Typical allowable maximum error values are in the range of $\pm$ 0.15 second to $\pm$ 0.02 second, while the quantity of presence pulses (number of vehicles) should be transmitted without error. These vehicle presence times are used in the central computer for calculating vehicle occupancy, speed, number of stops, and total delay, while the number of detected vehicles (vehicle count) is used to compute volume (vehicles per hour).

The number of different controller monitoring signals to be transmitted is also a function of traffic control system design, and may vary from one signal (e.g., A-phase green) to as many as 10 signals representing various controller functions. These signals may be

*Factors influencing these requirements are discussed in Section 5, subsection 5.2, "Vehicle Detector Data Processing and Communication".

present for periods ranging from one second to several days, and may have repetition periods of 40 seconds or more. Permissible delays in transmitted data representing such signals is also a function of traffic control system design, and is typically one second. A delay limit of this amount, for example, provides a reasonably accurate indication of when a controller phase change occurs, and thus is suitable for malfunction detection.

The number of traffic signal controller commands may consist of as few as two (Hold-on-Line, Advance) to as many as 10 signals representing various controller functions. These commands may occur at rates as high as once per second, and must be transmitted to the controller within at least one second of the time they are generated by the central computer to avoid significant variations in relative timing among adjacent traffic signals.

2.5.3 Distributed Processing Type System

Because the computers located at the intersections process much of the data for the vehicle detectors and controllers in a distributed processing type of system, the amount of data that must be transmitted to and from each intersection in a typical system is considerably less than that required for a comparable-size central type system. The vehicle detector presence times and vehicle count are accumulated as digital data in the local intersection computer for periods of one minute or more, and may be used by the local computer for computing volume, occupancy, speed, stops, and delay for this period. These quantities may then be transmitted to the master or central computer. (The local computer may also compute smoothed (filtered) values of volume and occupancy and transmit this quantity once per minute, as discussed in Section 5, subsection 5.2.)

The local intersection computer also processes controller monitor data for a period of a minute or more, and then transmits the results of this processing to the master or central computer.

The local computer also provides real-time controller commands for changing the traffic signals. Timing of these commands is based on timing pattern information stored in the local computer memory. This information is updated when necessary by the master or central computer via the communication subsystem, which, in a typical system, must transmit the information to all local computers within two minutes of the time that the master determines that the new pattern is required in order to avoid unacceptable delays in starting the new pattern.

2.6 DATA REPRESENTATION OF INFORMATION TO BE TRANSMITTED

2.6.1 DC Switching and FDM Communications

The DC Switching (DCS) and FDM transmission techniques essentially replicate the originating signal, and therefore, the most severe timing accuracy requirements are determined by the signal having the smallest permissible timing error, namely, the vehicle detector presence pulse width. For example, in a system design calling for a 0.02-second maximum communication error, the difference in delay of relay turn-on and turn-off for DCS communications, or the difference in delay for "1" and "0" transition times in the narrow-band filters of an FDM system must be within a 0.02 second time limit. This value can easily be met in both cases by low-cost off-the-shelf equipment.

2.6.2 TDM Communications

2.6.2.1 General

As noted in paragraph 2.4.4 above, TDM communications consists of polling a number of interconnected points (intersections) using serial binary data, and waiting for a response from each. The central or master computer initiates the polling process by sending a serial data "message" containing an intersection address (3 bits for up to seven intersections, 4 bits for up to 15, etc.) plus a series of command bits which may contain traffic-signal timing information for the intersection controller, or an instruction to the intersection requesting a particular type of response. Additional bits may be included in the message for data synchronization, for error detection, or for other purposes, depending on system requirements.

The response message from the intersection may contain current controller timing data, signal state or controller malfunction information, vehicle detector information, error detection bits, etc.

Factors affecting transmission rates of TDM information for both directions of transmission are discussed in the following paragraphs.

2.6.2.2 Factors Affecting Communications Timing Requirements

Because the transmitted information using TDM is represented by serial binary data rather than a one-for-one replication of the originating signal, the factors affecting TDM communications timing requirements are more complex than those for the DCS and FDM techniques discussed in the previous paragraph. These factors include*:

a. The amount of information (number of bits) to be transmitted to and from each point (intersection), including the bits required for synchronization, addressing and error detection at each point.

b. The time available (in seconds) for completing the polling of all intersections in a multipoint group.

c. The speed capability (number of bits per second, or data rate) of the combined communications equipment and transmission medium.

d. The amount of time (turn-around time) required by the communication equipment to prepare for transmission after a message is received at each point (in seconds).

e. The number of points (intersections) in a multipoint group, not counting the central or master point.

f. The amount of spare time allocated for repeat transmission resulting from error detection, and growth capability.

Before discussing each of these factors, it is instructive to note the significance of their interrelationships through the use of examples.

2.6.2.3 Examples of Timing Factor Inter-relationships

If all factors except the number of intersections are assumed to be known, then the relationship among them (using their above-listed letter identification) can be expressed as:

$$e = c \times (b - f - e \times d)/a \qquad (2\text{-}1)$$

or

$$e = \frac{c \times (b - f)/a}{1 + (c \times d)/a} \; . \qquad (2\text{-}2)$$

*In succeeding paragraphs, the lower case letters (a, b, c, d, e, f) representing these factors are used in algebraic expressions relating the factors, and are also referenced in explanatory test material.

If the various factors are assumed to have the following values: a = 60 bits, b = 0.5 second, c = 1200 bits per second, d = 0.01 second for a 4-wire (2 pair) multipoint circuit, and f = 0.1 second (which are realistic values for a central type system), then:

$$e = \frac{1200 \times (0.5 - 0.1)/60}{1 + (1200 \times 0.01)/60} = 6.6 \quad (2\text{-}3)$$

That is, a maximum of six intersections can be interconnected on each multipoint circuit with these values, or, a typical 200-intersection system would require 34 multipoint circuits (user-owned 4-wire or leased 4-wire voiceband channels).

Note that by doubling the amount of time available for polling (to one second), the number of points can be increased to 15, while by halving the number of bits transmitted (to 30) the number of points can be increased to 11. If a higher bit rate can be used (together with lower turn-around time) as with coaxial or fiber optics cable, the number of points can be increased nearly proportionately to bit rate increase.

As a second example, assume the following values (which are realistic maximum values for distributed processing type systems) are used: a = 600 bits, b = 60 seconds, c = 1200 bits per second, d = 0.01 second, and f = 20 seconds. Then,

$$e = \frac{(1200 \times 40)/(600)}{1 + (1200 \times 0.01)/(600)} = 78 \quad (2\text{-}4)$$

That is, a maximum of 78 intersections could theoretically be interconnected on one multipoint circuit based on these timing considerations alone. However, other factors, primarily circuit loading and difficulty in locating faults usually limit this number to about 20 for wire pair communications.

As discussed in the following paragraph, the actual values of the factors for any given traffic control system are based on system design considerations, such as the complexity of controller equipment, average number of detectors per intersection, and whether or not distributed processing is used.

2.6.2.4 Amount of Transmitted Information

The amount of information to be transmitted to and from each intersection (item "a" in the list of timing factors) (paragraph 2.6.2.2) may include the following types of information in typical systems.

a. Central Type System

To intersection (once per second):	No. of Bits
Hold, Advance, Test, Flash, Yield, Skip	6
Standby Pattern (synchronized, offset 1, offset 2)	3
Communication synchronization	6
Address	4
Error check and synchronization	16
From intersection (once per second)*:	**No. of Bits**
Detector presence accumulation (2 @ 4 bits)	8
Detector vehicle count (2 @ 1 bit)	2
Signal states (4 @ 1 bit)	4
Flash, pre-empt	2
Communication synchronization	6
Address (repeat back)	4
Error check and synchronization	16
Total both ways:	77

b. Distributed Processing Type System

To intersection (once per minute):	No. of Bits
Controller mode selection (multiple combinations of phases, etc.)	8 to 48
Time of day update	24 to 64
New timing pattern	32 to 96
Format	16
Error check, address, and synchronization	24 to 120

*Factors affecting detector data transmission are discussed in Section 5, subsection 5.2.

From intersection (once per minute)*:	No. of Bits
Detector data (Volume, Occupancy, Speed, Stops, Delay)**	56
Repeat back of received message	32 to 150
Self-test results	16
Local pattern (cycle, offset, splits)	32 to 80
Phase state	2 to 8
Format	16
Error check, address, and synchronization	24 to 200

It should be noted that the central type system usually employs a fixed message length and message format that is determined by the longest combination of items. With the distributed processing type of system, however, the message length may vary with each transmission (in both directions) depending on the type of information being sent. The "Format" bits of the message define which of the remaining items in the list are contained in the particular message being transmitted, and also provides other types of information.

The bit sequence of the binary serial message to the intersection, for both the centralized and distributed types of system, usually consists of the following: a synchronizing bit (or several bits), intersection address bits (a unique binary number for each intersection), the "message content" defining bits ("Format" bits), the information bits representing the functions, error check bits, and finally one or more end-of-message bits (if desired). The bit sequence of the message from the intersection is similar, except that the address portion is not necessary, and is only included in some systems as a confirmation of intersection identity.

The most common message format for low to medium speed business machine communications (and therefore the one offered by the widest selection of commercial equipment) is the asynchronous 11-bit format consisting of a "start" bit, eight information bits, a parity bit and a "stop" bit. A complete message would typically consist of a string of such 11-bit

*Typical combinations of functions transmitted at any one time are listed in Appendix E.
**See Section 5, subsection 5.2.

"frames". Other formats which are unique to a particular manufacturer's communication equipment are also used. These usually include longer bit strings preceded by several synchronizing bits which allow the receiver to "lock-on" to the incoming message.

If the intersection equipment detects an error in the message it receives, the usual practice is to ignore the message contents and to omit the response message entirely, thus notifying the central or master computer that it should try again. If the central or master detects an error in the message from the intersection, it will ignore the contents and request another message during either the present or the following polling cycle.

2.6.2.5 Polling Time

The time available for polling (item "b" of timing factor list, paragraph 2.6.2.2) is determined by the function requiring the most rapid updating. For central type systems, the detector outputs should be sampled at least once each second if individual vehicle data is required, and the controller advance command should also be transmitted with a variation in delay of no more than once per second to avoid significant timing variations among adjacent controllers. For distributed processing type systems, the intersection controllers provide the real-time controller commands and compute detector surveillance quantities. Therefore, information needs to be transmitted no more often then necessary for the central or master computer to compute optimum area timing patterns and to change the intersection patterns as required. This period is usually in the order of one minute or more.

2.6.2.6 Communication Subsystem Speed

The data rate (item "c" of timing factors list, paragraph 2.6.2.2) is limited by the transmission medium, which in turn affects the speed of the equipment designed for use with that medium. For wire pairs, a limit of about 1800 bits per second is usually observed, principally because at speeds above this value (2,000 to 9,600 bps), some form of line conditioning may be required for equipment designed to operate with telephone company channels, and such equipment is usually much more expensive than the lower-speed equipment. However, if user-owned wire pairs are used, together with equipment designed to operate outside the telephone company band, then much higher rates can be considered, especially for short distances, as discussed in Appendix F.

With coaxial or fiber optics cable, the bit rate can be set high enough to handle any number of intersections on a single cable.

With air path optics, the data rate is limited to about 2000 bits per second (at the time of this writing).

2.6.2.7 Turn-around Time

The time required to start transmitting after the completion of a received message (item "d" of the timing factors list, paragraph 2.6.2.2) is a function of commercial wire pair modem designs. Shortening of this time usually results in some sacrifice of signal-to-noise margin, since the degree of low pass filtering is reduced.

2.7 INFORMATION FLOW DIAGRAMS

2.7.1 General

Information flow diagrams may be used to show how the basic traffic control information flow processes can be adapted to various communication techniques. For those personnel having sufficient technical background and experience in computerized traffic control processing, such diagrams can be useful in understanding and predicting the results to be obtained by using different communication approaches. Therefore, a set of information flow diagrams has been included in subsection 5.6.

SECTION 3

TRAFFIC CONTROL COMMUNICATION METHODS

This section contains the following material:

- A discussion of significant features of the communication methods which were examined.
- A brief discussion of multiplexing and error control.
- Descriptions of communication methods using the following transmission media:
  - Wire pairs (both user-owned and leased)
  - Coaxial cable
  - Air path optical spectrum
  - Fiber optics cable.

3.1 INTRODUCTION

This section summarizes the communication methods that were examined during the study and provides additional descriptions of those considered suitable for urban traffic control systems. The methods examined consist of those employing the following transmission media: wire pairs (user-owned and leased), coaxial cable, atmospheric optical spectrum (air path optics), optical fibers, UHF radio spectrum, power lines, and microwave baseband radio spectrum. Those considered suitable for traffic control include all except the last three of these.

The descriptions of the methods considered suitable for traffic control communications include a discussion of factors to be considered in applying the methods to particular situations.

In addition, multiplexing and error control, which are common to all methods, are discussed in this section.

3.1.1 Significant Features of Communication Methods

a. Wire Pair Transmission

Communication using twisted wire pairs is the most common method presently in use for traffic control systems, and is expected to remain popular, especially in those locations where facilities already exist or can be made available at low cost. Both the cable itself, and low-cost equipment (modems, etc.) suitable for wire transmission and reception are commercially available from a number of sources, since this type of equipment is widely used for transmission of computer data over telephone system voice-grade lines and for remote operation and monitoring of unmanned industrial control equipment.

The principal factors affecting the choice between user-owned and leased wire facilities are primarily the differences in cost and reliability of service. Cost of user-owned wire is affected by availability of existing conduit (or poles) and local construction costs. Leased line costs vary widely from area to area and are subject to sudden increases which are likely to be high in the future as regulatory agencies force rates in line with costs of leased line service (which the telephone companies have generally subsidized in the past). Leased line costs are also affected by the construction cost required to connect the intersection equipment to the nearest telephone line. Another factor that is important to most users is that user-owned costs are paid from a capital budget, while leased line costs are paid from both a capital budget (for interconnection to the telephone line) and an operating budget (for the leasing fee).

Reliability of service will generally be high for user-owned cable (if properly installed) unless construction activity in the area is widespread (with its consequent high incidence of inadvertent cable cutting). Leased lines may experience occasional outages resulting from telephone company maintenance activities, and maintenance of service will be dependent on the responsiveness of the local telephone company.

b. Coaxial Cable

Communication employing wide-band coaxial cable has been successfully used for traffic control communication, and development of low-cost electronic equipment for the cable TV industry is expected to keep system costs at a reasonable level. Other factors to be considered in evaluating this medium are its capability for expansion by simply adding cable to the initial network, and the possibilities for future incorporation of TV surveillance or leased cable TV. Installation cost factors are similar to those for twisted-pair cable, namely, terrain features, availability of existing conduit or poles, and local construction costs. Where cable TV service is provided within the traffic control system area, a portion of the cable frequency spectrum may be leased from the CATV franchise operator at cost-effective rates.

c. Air Path Optics

Communication employing air path optics together with local processing at each intersection has been included as an applicable communication method because it has the potential of reducing communication costs, is nearly immune to electrical interference, and has been proven in a traffic environment. This technique employs lost-cost, low-data-rate, pulsed laser diode transmitters and optically-sensitive semiconductor receivers to send messages along a narrow-beam line-of-sight path for distances up to one mile (1.6 km) in length. In a typical traffic control system, one pair of optical heads and a transmitter/receiver is located on a mast arm at each intersection, and acts both as a repeater and a terminal for signals to and from the control center (or master controller). This technique provides essentially interference-free operation under all weather conditions except severely reduced visibility.

d. Fiber Optics

Communication employing fiber optics has been included as an applicable method because recent advances in the state-of-the-art, and the availability of lost-cost fiber optics cable and associated equipment have made this technique competitive. In addition, fiber optics cable is essentially immune to electrical interference, is easy to handle and rugged, and, because of its wideband capabilities, can be readily expanded by adding more cable to the initial network. Its potential for transmission of TV surveillance signals is another factor that makes this method attractive.

Although fiber optics have been used for other communication purposes, certain requirements such as the need for numerous cable splices at field locations have not yet been demonstrated in connection with traffic control systems at this writing. The traffic system designer should assure himself that such installation issues as those may be appropriately resolved.

e. Radio

Communication using radio is potentially useful for computerized traffic control, and is being used in several localities for one-way transmission of control signals. However, the lack of off-the-shelf equipment employing techniques directly applicable to computerized traffic control have resulted in the decision to recommend a special study and demonstration of this method rather than to include it as one of the candidates for trade-off comparison. This communication method is discussed in Appendix K.

f. Power Lines

Communication using power lines as the communication medium was examined, but was found to be unsuitable for general use in traffic control primarily because of low data handling capability, difficulty in evaluating network characteristics (with resultant high design costs), and the potential conflict with information transmission needs of the power industry itself. This method is discussed in Appendix L.

g. Baseband Microwave Radio

Communication using baseband microwave radio was also examined and found to be unsuitable for inclusion in the trade-off at this time. This method employs pulses of short duration (under one nanosecond) to transmit energy over a wide band from a dipole antenna, and this energy is detected and amplified by a special tunnel-diode receiver. Although experimental results showed that acceptably long ranges could be obtained, and that projected equipment costs are low, it was felt that additional development work would be required before this method could be considered as a viable candidate.

3.1.2 Multiplexing Techniques

Multiplexing is a technique used to transmit signals from more than one source on a communication medium when the bandwidth of the medium is greater than the total bandwidth required by all the signals. Two types are commonly used for transmitting binary data: Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM). Frequency Division Multiplexing divides the available bandwidth of the medium into several narrow bands - one for each source - and all signals may be transmitted simultaneously. Time Division Multiplexing divides a specific time period into smaller periods - one period for each source - and the signals are transmitted as time-serial pulses organized into "messages" representing information to be conveyed. Communication methods using twisted pair wire media (both user-owned and leased), coaxial cable, and UHF/VHF radio employ either FDM or TDM, or both simultaneously; while communication methods using air path optics, fiber optics, and baseband radio employ TDM exclusively.

Frequency division multiplexing requires a separate transmitter and receiver for each signal source, and the receiver binary output is essentially a replica of the input to the transmitter. Time division multiplexing usually requires a polling technique to be used, in which a master transmitter sends messages to receivers at a number of intersections in sequence, and the intersections respond by sending messages back to the master receiver.

The two states of the binary data (using either FDM or TDM) may be represented by various forms of modulation, namely, amplitude change (carrier signal on/off), frequency shift (carrier signal higher/lower) phase shift (carrier phase $0^\circ/180^\circ$), or DC voltage (on/off). Of these modulation techniques, frequency shift (known as frequency shift keying or

FSK) is the most common for all except the optical methods, which normally use on/off keying of a laser or light-emitting diode.

Additional details on multiplexing are contained in Appendix B.

3.1.3 Error Control

Error detection and correction is employed with serial data transmission to counteract the effects of electrical noise or other sources of interference, such as equipment malfunction, that can cause changes in the transmitted bit pattern. Such errors can be detected by using additional bits in the data stream, and therefore error detection techniques require additional transmission time, as well as additional equipment (or software). Wire communications employing either unmultiplexed DC switching (DCS) or FDM does not normally require error detection because of lower noise susceptibility resulting from either the large signals employed (DCS) or the narrowband filtering (FDM).

Error correction can be accomplished by using error detection with either automatic request for repeat transmission (either explicit or implicit) or automatic correction at the receiver based on the received patterns of error correction code bits (forward error control). The repeat request approach has generally proven to be the more efficient and reliable of the two, particularly in a burst noise environment.

For traffic control applications, the frequency with which information is automatically updated may influence the choice of error correction technique to be used. For example, with a centralized type of architecture using a once-per-second TDM polling technique, a single infrequent undetected error in vehicle detector data represents only one second's worth of sampling time and, therefore, can be disregarded. Also, an undetected erroneous controller command will cause erroneous timing of the traffic control signal which will be automatically corrected within two controller cycles. Thus, a relatively modest amount of error correction could be considered for this type of system, since the consequences of undetected errors are not catastrophic.

A distributed processing system (hierarchical or network) having longer periods between updates (typically one minute for detector data and possibly hours for controller timing pattern data) requires more elaborate error correction techniques in order to avoid the more serious consequences of undetected errors. Fortunately, the added bandwidth required for such error correction is usually available with this type of system because of the relatively small amount of data exchanged among the processor units.

Therefore, in selecting an error control technique, the following systemwide goals for undetected errors in controller command data of once per week for a central system and once per year for a distributed processing system could be considered adequate, unless other system design factors indicate that different values should be selected. These values result in the following undetected error rates required of individual transmitter/receiver links to each intersection for a typical system having 200 intersections and operating continuously:

	Centralized architecture	Distributed architecture (hierarchical or network)
Typical data rate per intersection	50 bits/sec 3×10^7 bits/week	100 bits/min 5×10^7 bits/year
Data rate for 200 intersections	6×10^9 bits/week	10^{10} bits/year
Allowable undetected error rate per intersection link	$\frac{1}{6 \times 10^9} = 1.6 \times 10^{-10}$	10^{-10}

With communication systems using twisted pair wire, the noise environment can be assumed to be no worse than that established by a 1969 Bell System study of the switched network, and techniques for correcting errors in this environment are discussed in Appendix C. In designing a communication system using wire media, the designer is generally limited by the characteristics and error-correction features of off-the-shelf equipment, and thus may be faced with less than optimum choices. However, if a distributed processing system is used, he can make use of the microprocessor capability to augment hardware error detection features through modifications to the software.

With the coaxial cable medium, the noise environment is much less severe since this equipment is built to maintain high signal-to-noise ratios for TV reception and, therefore, relatively simple error correction techniques can be used. Again, the choice will usually be limited to those offered by communication system suppliers.

The optical techniques are essentially free of electrical noise interference except at the amplifier sites, and there the exposure can be well controlled. However, optical interference (with air path optics), imperfections in materials, or equipment malfunction can cause errors and, therefore, some form of error control is necessary.

Radio transmission is the most severely affected by electrical noise, as well as multipath fading, and therefore presents the most difficult challenge in design for error control. This subject is dealt with in Appendix K.

Additional material on error control is contained in Appendix C.

3.2 WIRE PAIR CABLE COMMUNICATION

This subsection describes communication methods that employ wire pair cable. The description includes a summary of cable characteristics, a description of applicable transmission techniques, and an evaluation of these transmission techniques.

3.2.1 Cable Characteristics

At the time of this writing, multi-conductor, twisted-pair, shielded cable is the most widely used communication medium for computerized traffic control. This type of cable is available from a number of manufacturers, and is built to conform to standard specifications issued by agencies such as the Rural Electrification Administration (REA) or the International Municipal Signal Association (IMSA). Such cables may be installed overhead or underground as required by local ordinances. Standard numbers of pairs per cable vary from 6 to 1200*, wire gauges from 26 AWG to 19 AWG, and reel lengths from 1,000 feet (305 m) to 10,000 feet (3050 m). The number of pairs and wire gauge to be used in designing a system are a function of the communication path length, number of intersections, system architecture (central, hierarchical, network) and type of data transmission used.

The principal characteristic of twisted wire pairs that influences owned-system design is signal loss (attenuation) with distance as a function of signal frequency. As shown in Table 3-1, the loss increases with frequency, and is greatest for the smallest diameter wire (26 AWG), reducing the signal power to nearly one half (3 db) in a mile at 1000 Hz. (This loss also increases with increasing temperature at about 0.4% per degree C.)

By inserting inductance in series with the line at regular intervals (loading coils) the transmission loss may be reduced for designs using only voiceband frequencies (defined as 300 to 3,000 Hz by Telephone Company practice) as shown in Table 3-1. This attenuation characteristic influences design decisions regarding selection of frequencies to be used, wire sizes, and transmission power levels.

A second cable characteristic that influences design is the line impedance, which is also a function of frequency and cable gauge. This impedance varies from about 200 ohms at

*Number of pairs per cable: 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, 1200.

TABLE 3-1. WIRE-PAIR CABLE LOSSES

Inductive loading coil	Wire size (AWG)	Loss (db per mile)[a] at indicated frequency			
		300 Hz	1000 Hz	2000 Hz	3000 Hz
None	19	0.70	1.3	1.7	2.1
	22	1.0	1.8	2.5	3.0
	24	1.3	2.3	3.2	3.9
	26	1.6	2.8	4.0	4.9
88 MH @ 6000 feet*	19	0.40	0.42	0.43	0.52
	22	0.70	0.80	0.80	0.88
	24	1.0	1.2	1.2	1.35
	26	1.4	1.8	1.9	2.0

[a]1 mile = 1.6 km

the high frequencies (for 19 AWG wire) to over 2000 ohms at 300 Hz (for 26 AWG wire). Transmitters and receivers that connect to the line should be designed to match this impedance to a reasonable degree in order to obtain efficient power transfer and to avoid signal reflections on the line. Most commercial equipment is designed to have a nominal impedance of 600 ohms at 1000 Hz, which is an acceptable compromise value.

3.2.2 Transmission Techniques and Equipment

A number of possible data transmission techniques are available to meet the needs of a computerized traffic control system. These include point-to-point direct current switching (DCS), frequency division multiplexing (FDM), and time division multiplexing (TDM). These are described in the following paragraphs.

3.2.2.1 Wire Communication Using Direct Current Switching (DCS)

Direct Current Switching utilizes relays to transmit two-state (on/off) signals as replicas of the originating signals (Figure 3-1). While relays can operate at a level up to 115 volts, affording excellent noise immunity, this technique has a very low multiplex capability (two wire pairs per controller, minimum, plus one wire pair for each detector).

Differences in turn-on and turn-off delay can be held to under 10 milliseconds, thereby providing sufficient timing accuracy. The maximum on-off switching rate available using relays is limited by the relay turn-on and turn-off time, and is therefore usually constrained to values less than 100 on-off cycles per second.

*1 ft = 0.3048 m

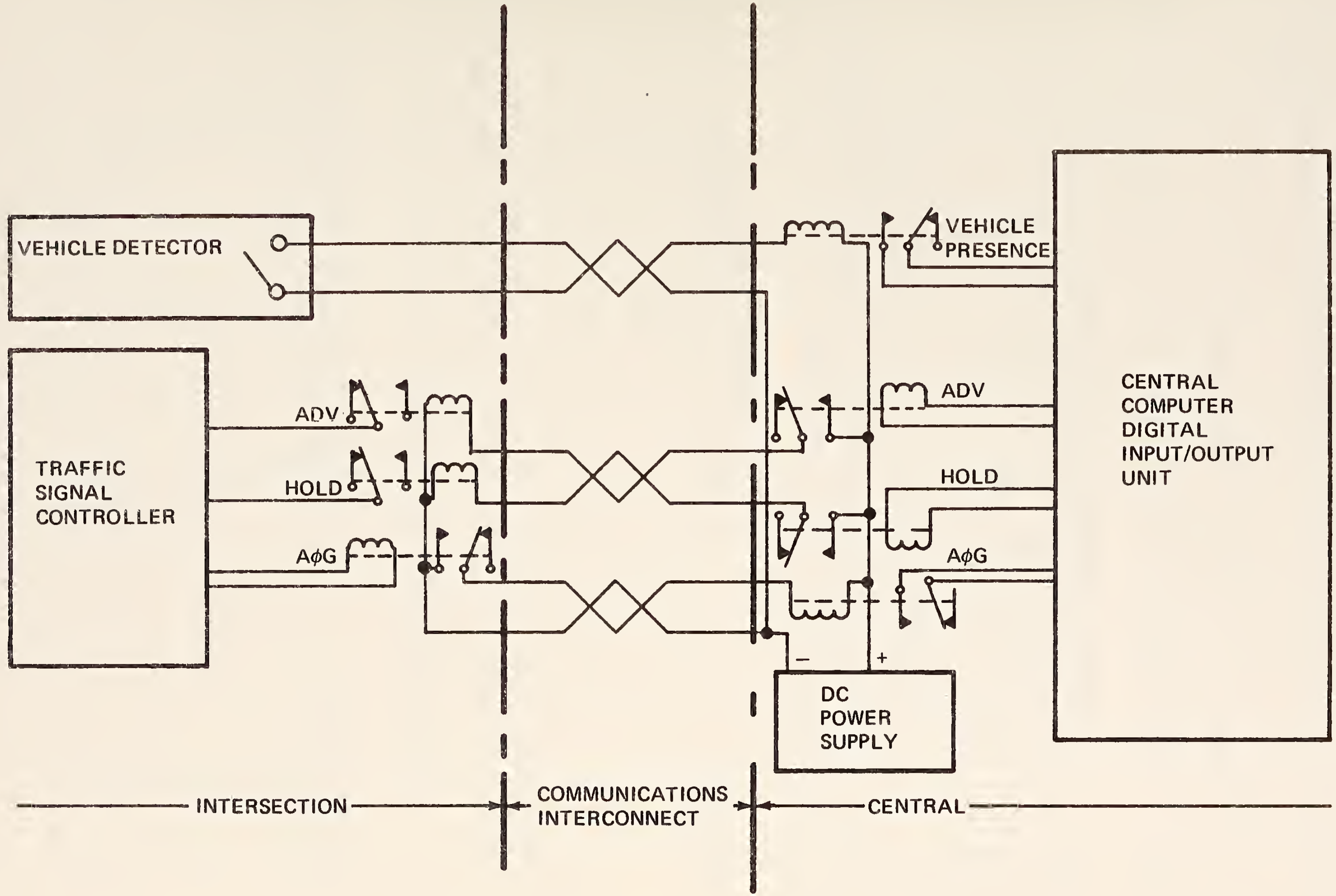


FIGURE 3-1. DC SWITCHING COMMUNICATIONS SYSTEM

The distance over which a relay system can communicate depends upon operating voltage, wire gauge, relay sensitivity and level of multiplexing. The following formula relates the maximum resistance of the transmission medium's wire to the above parameters for the case where a single cable pair is dedicated to each relay.

$$R_D = R_C (V_{NOM}/V_{PI} - 1),$$

where

R_D = Maximum resistance of transmission path
R_C = Resistance of relay coil
V_{NOM} = Nominal operating voltage of relay
V_{PI} = Pull-in voltage of relay

The values of R_C, V_{NOM} and V_{PI} are specified by the relay manufacturer.

The maximum distance is calculated by dividing R_D by R_{loop} where R_{loop} is the resistance per thousand feet for a pair of wires feeding a relay coil. The following values are typical for several common wire sizes:

Wire gauge	R_{loop} (ohms per thousand feet)[a]
19	16.2
22	32.2
24	51.4

[a]1000 ft = 305 m

The following table, obtained using the above formula, and using a relay series of which $V_{NOM}/V_{PI} = 1.33$, expresses the maximum transmission range as a function of operating voltage and wire size.

Operating voltage (volts DC)	Maximum distance (thousands of feet)[a] 19 AWG	22 AWG	24 AWG
12	3.8	1.9	1.2
24	14.4	7.2	4.5
48	20.5	10.3	6.5
72	119	60	38
115	305	154	96

[a]1000 ft = 305 m

If two pairs are used to carry three bits of data for the controller's signals, the maximum distance is halved.

Relays offer excellent reliability with some having an expected life in excess of ten million operations, and the cost of a relay communication system is typically less than $200 per channel.

Solid state devices can be used in place of electromechanical relays, and can provide much higher data rates. Such devices, however, do not have the inherent noise immunity of the electromechanical relays and might require filters to avoid transmission errors.

The DC switching technique is applicable where the cost of installing cable plus the cost of the dc switching equipment is less than the capital equivalent cost of leased lines plus multiplexing equipment. Such a situation may exist, for example, where a large number of detectors are located within a relatively short distance of each other, and must communicate with a control center over a long distance. With this geometry, point-to-point DC switching can be used to connect the detector outputs to a field data processing unit which produces vehicle data averaged over a fixed time period; the resulting processed data can then be sent to the control center using transmission techniques described below, such as TDM or FDM.

The tasks of system design, installation, checkout, and maintenance of a DC communication system are all relatively straightforward. However, system documentation must be done carefully because of the large number of wire connections required.

Another form of DC switching uses electronic circuitry rather than relays for modulating time division multiplexing equipment (rather than one of the forms of AC modulation) where direct wire connections are available. This technique is discussed below under the subject of time division multiplex transmission.

3.2.2.2 Wire Communication Using Frequency Division Multiplexing (FDM)

The frequency division multiplexing technique employs audio tones in the voiceband (300 to 3000 Hz) to provide transmission of up to 23 data sources and their corresponding receiving terminals located at any point on a single wire pair or leased voiceband channel. Binary information (two state) is represented either by presence or absence of a tone (amplitude modulation or AM), a pair of tones (frequency shift keying or FSK) or two phases of a tone (phase shift keying or PSK). A separate transmitter and receiver is required for each independent signal to be transferred, except that where two signals are mutually exclusive, a single transmitter/receiver pair employing three tones (3 FSK) may be used. A typical set of FDM transmitters and receivers for traffic control units on two wire pairs is shown in Figure 3-2.

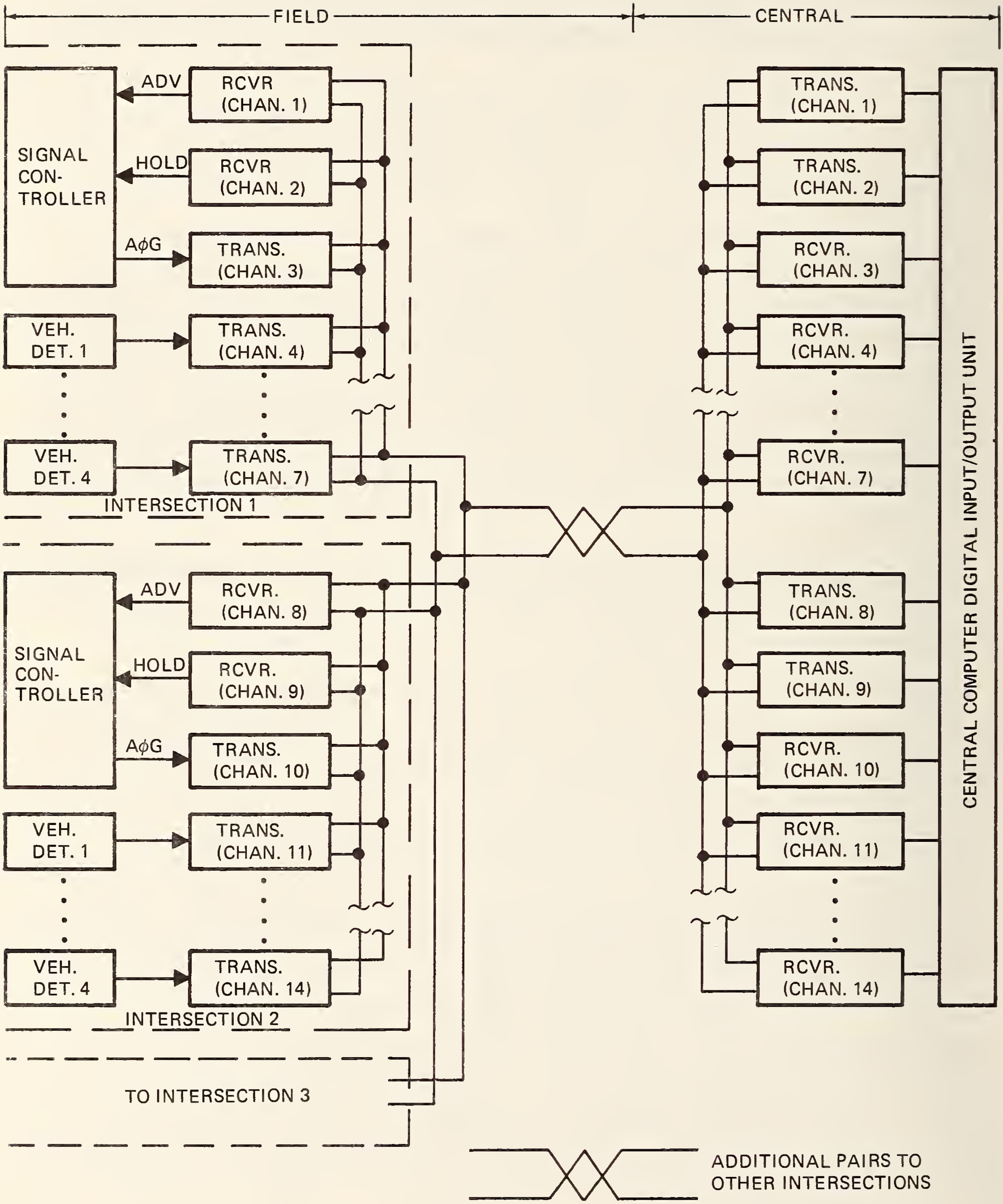


FIGURE 3-2. FDM COMMUNICATIONS

This technique is normally used where the traffic system field units (detectors, controllers, etc.) require minimal amounts of data and are scattered as single units or small groups of units (as is typical of many existing traffic control systems). Serial data transmission of FDM tones (that is, combined FDM and TDM) may be employed where data from several scattered devices provide serial data at rates low enough to be multiplexed on a single voiceband channel.

The cost of FDM communication equipment is usually less than $500 per tone channel, including all cabinets, power supplies and the central computer interface. Total system cost may be competitive with other cable methods only if a relatively small number of independent functions (two or three per intersection) are required, and if a central type of architecture is used.

Wire communication using FDM has been used in a number of computerized traffic control systems, and experience has shown that the technique is reliable and relatively error-free.

FDM application considerations including the task of designing an FDM network an allocation of wire pairs and tone frequencies to specific functions (controller command and monitor, vehicle detection, pre-empt monitor, etc.) at each intersection using a network map to estimate distance and to make maximum use of existing facilities such as conduit or poles. This allocation is done in such a way as to provide adequate signal margins at each receiver, and usually requires that lower frequencies be assigned to the more distant points to overcome the cable attenuation characteristics (Table 3-1). Line amplifiers (which boost all tone signals equally) may be required if attenuation is excessive on some lines. Also, to reduce the possibility of crosstalk between transmitters and receivers at the same location, separate wire pairs are usually assigned for each transmission direction (one pair outgoing, one pair incoming). If leased lines are used, the attenuation characteristics are usually established at a fixed value by the telephone company and therefore the frequency allocation task is simplified. However, the connection of each intersection to the telephone company lines must be designed in cooperation with the local telephone company.

Installation and checkout of FDM equipment is relatively easy, but does require careful documentation to provide correct wiring, matching of frequencies, and setting of transmitter signal levels and receiver sensitivity.

Maintenance of FDM equipment is also relatively straightforward, since each signal output appears as a DC level at a specific terminal, and equipment for measuring and adjusting transmitter and receiver performance is simple and relatively easy to operate. Also, the distinction between equipment faults and line faults is usually apparent, since a line fault will affect more than one FDM channel.

3.2.2.3 Wire Communication Using Time Division Multiplexing (TDM)

The polled time division multiplexing technique employs one or more central master transmitter/receiver units (modems) each connected to a number of scattered field transmitter/receivers typically 4 to 20 on a party line (one or two wire pairs or a leased voice-band channel) as shown in Figure 3-3. The master unit sends commands addressed to each field unit (typically at an intersection serving a signal controller with neighboring detectors) using serial binary data, and each field unit sends a reply before the next one is addressed. Each message from the master unit contains the necessary pulses (bits) for synchronization, intersection address, information (commands, etc.) and error detection. The receiver serial data at each end is temporarily stored in a shift register which interfaces with a buffer register connected to the device that is to use the data (central computer, local computer, controller or detector). Because the transmission from each point normally occurs at rates of once per second or slower, vehicle detector presence samples and vehicle counts or processed detector data are usually accumulated in counters, registers or microcomputer memory for transmission as binary numbers. The transmitter output signal representing the two binary states may be modulated using any of the AC modulation techniques (AM, FSK or PSK) or it may use DC switching (DCS) modulation using "limited distance" modems if a complete wire path exists. Typical data rates are 600 to 1800 bits per second.

This type of communication technique is widely used in traffic control systems having complex traffic signal controllers and/or distributed processing at the intersections (hierarchical or network architecture), because it is usually lower in cost than FDM under these circumstances, and the number of field units per transmission channel (wire pair) is also potentially greater.

The TDM field equipment for one intersection includes digital interface units as well as the transmitter/receiver unit (modem). Equipment at the control center (or master controller) includes computer interface and control logic which temporarily stores all messages leaving and entering the computer. At the beginning of each polling cycle,

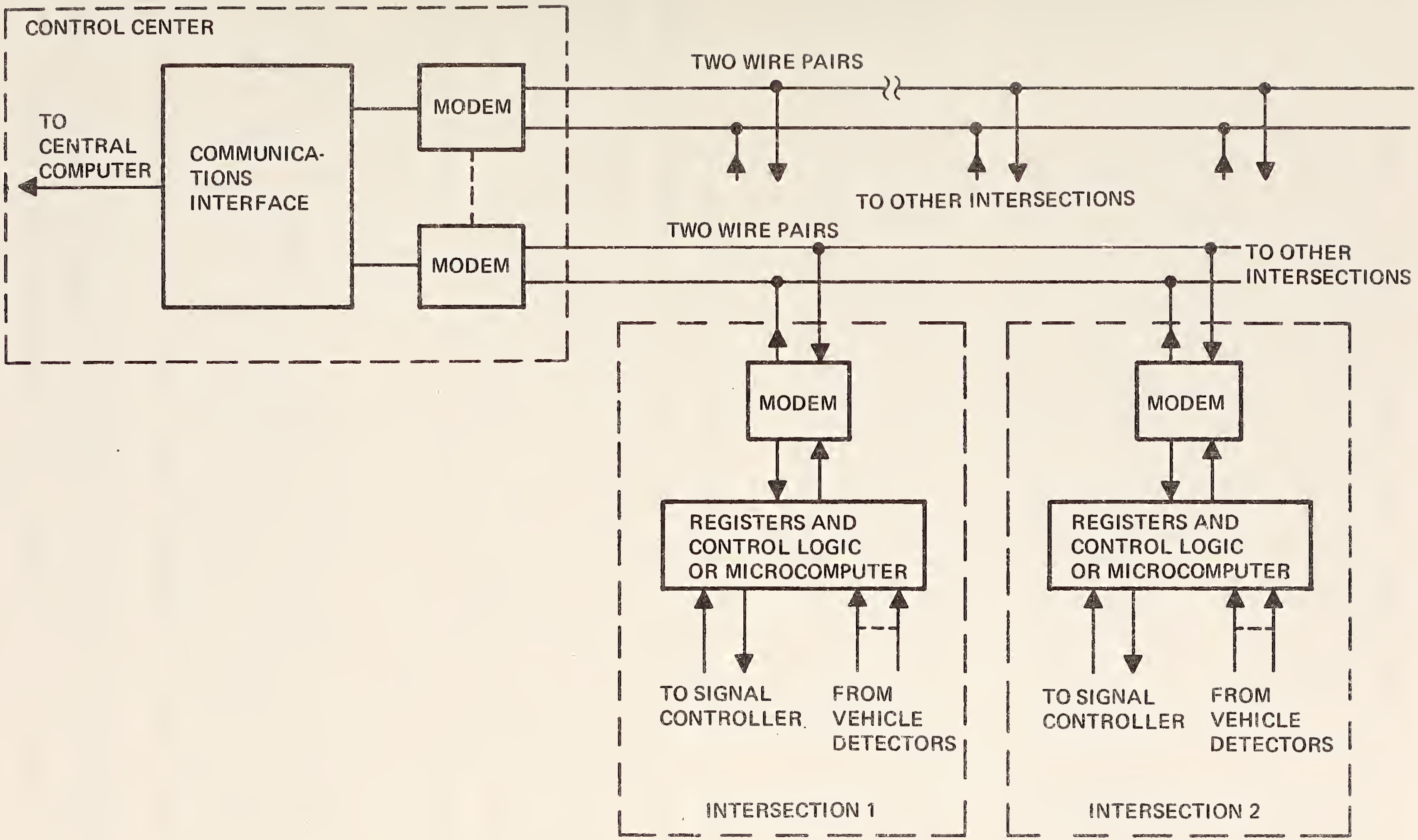


FIGURE 3-3. TDM COMMUNICATIONS

typically a one second period for the central architecture and one minute for the distributed processing architectures, this central communication unit shifts the data representing one message as a serial bit stream onto each multidrop line (party line) and the messages on all lines are thereby transmitted in the same time frame to an appropriately addressed intersection on each line. After this command message is transmitted, the central communication unit receives a serial-message response from the addressed field unit on each multidrop line, temporarily stores it, and enters it into the computer under computer program control. This process is repeated until all field units on all multidrop lines have been polled, and the polling cycle then starts again. It should be noted that the multidrop line typically consists of two pairs: one for outgoing messages, the other for incoming messages.

As an example of the data rate required, assume 20 drops (intersections) on each line, a command message length of 30 bits (including sync, address, information and error check), a response message length of 40 bits, and a modem turn-around delay of 5 milliseconds. With a once-per-second polling period, the data rate required would be (neglecting computer input/output transfer time):

$$\text{Data Rate} = 20 \times (30 + 40)/(1 - 20 \times .005) = 1555 \text{ bits per second.}$$

TDM application considerations include equipment costs for a TDM system which are typically about $700 for each field unit and $300 to $500 per multidrop line for the central unit (at the time of this writing). System costs are competitive with other wire pair cable techniques (FDM or DCS), and are usually lower if the average number of independent functions required at the intersections is greater than two or three.

The task of designing a TDM network requires an allocation of wire pairs to specific functions at each intersection, using a network map to estimate distances and to make maximum use of existing conduit or other facilities. This allocation is a function of the data rate and message efficiency of the TDM equipment selected and the type of system architecture (central, hierarchical, network) to be used. If leased lines are used, the network layout task is eliminated but connections to the telephone company lines must be designed, in cooperation with the local telephone company.

Installation and checkout of TDM equipment is somewhat more difficult than for FDM equipment, because the data is in serial form and messages from different sources are present only at periodic time intervals. Maintenance is also somewhat more difficult than for the other wire pair cable techniques because a malfunctioning unit could produce interfering pulses and thus complicate fault isolation procedures. However, test sets to facilitate installation and maintenance of TDM equipment are available from the communication equipment manufacturers and have proved to be satisfactory as diagnostic tools in existing systems.

3.2.3 Leased Line Considerations

Private line voiceband communication media leased from the local telephone company have been successfully used in many traffic control systems. This medium provides either single point or multipoint (multidrop) channels having a bandwidth of 300 to 3000 Hz and having characteristics which are rigorously defined by each local (intra-state) telephone company.* Most of the local channel specifications conform to the characteristics of the Bell Telephone System Interstate Tariff FCC No. 260, which defines the voiceband private line as a Type 3002 channel. The significant features of this channel which are of importance to the design of a communication system are the maximum allowed transmitter power levels (0 dbm**), the signal level to be expected at the receiver (-16 dbm) and the limitation on number of points (drops) on a multipoint line (20 drops recommended for the Type 3002 channel).

A wide variety of equipment has been developed for use on this voiceband channel and is available from a number of manufacturers at reasonable prices. The transmission techniques described in paragraphs 3.2.2.1 through 3.2.2.3 may be used with leased lines, except that direct current switching (DCS) techniques are not permitted in many localities, especially if more than one telephone company central office is included in the network.

In conducting a trade-off study to determine the feasibility of using leased lines as the transmission medium, close cooperation with the local telephone company's data

*Dataphone Digital Service (DDS) is expected to be a candidate transmission medium within a few years from the time of this writing. This service, which is leased from the Telephone Company, is intended primarily for intercity communications at medium-to-high data rates (2,400 to 56,000 bits per second), but intra-city service is also planned. This service is expected to offer high reliability of service and high data accuracy, but will require leasing of telephone company interface units as part of the service.

**The term "0 dbm" is defined as one milliwatt of power in a 600 ohm resistance, or 0.78 volts across 600 ohms.

communication representative is required. The representative should be asked to furnish information on the following subjects:

- Capability of the local telephone company to furnish service to the intersections being controlled, and capability for expansion.
- Estimated period of time until service can be provided.
- Local exceptions, if any, to the Type 3002 channel specifications, and verification that local practice includes the significant features of this specification.
- Limitations, if any, on the number of multipoint drops on a line.
- Availability of electrical continuity between all points to be interconnected so that DC transmission techniques can be considered.
- Location of nearest access point to the telephone company cable from each curb-side cabinet, and the division of work (between the telephone company and the user) in connecting to this point.
- Rules regarding the construction of the termination at the traffic control cabinet at the intersection. (A separate access door or separate cabinet for telephone company termination equipment mounted on or in the traffic control cabinet is usually required.)
- Leasing rates for 4-wire service, and method of measuring the distances specified in the local tariff.
- Special charges for gaining access to the telephone company cable (e.g. penetrating walls of manhole).
- Special charges for connecting to the terminals in the field cabinets and at the traffic control center.
- Maintenance policies, including method for determining charges if fault is determined to be in the user's equipment after telephone company maintenance has been called for and provided.
- Pending rate increase requests, if any, and an estimate of expected increases in leasing rates or in the method of computing distances.*

*See Section 5, subsection 5.5, "Effects of Leasing Cost Increases".

Once the above information has been obtained, a preliminary system design can be made to obtain cost estimates for trade-off purposes. The design procedure for the various transmission techniques (DCS, FDM, TDM) is similar to that for the owned-cable case, except that the number and location of lines is computed in accordance with the telephone company rules. In addition, the distances to the nearest telephone line (manhole or pole) from each curbside cabinet must be determined, since the cost of installing cable to this point is usually the largest cost factor in a communication system installation.

Equipment installation and checkout tasks for the various transmission techniques using leased lines is similar to those described for the user-owned wire pair communication methods.

Maintenance for a leased-line system is also similar, except that any faults caused by telephone company equipment or media must be identified, and the telephone company maintenance department must be requested to make repairs.

3.3 COAXIAL CABLE COMMUNICATIONS

3.3.1 Description

A traffic control communication system employing coaxial cable as the transmission medium consists of coaxial cable and repeater amplifiers arranged as a tree network connecting a control-center communication unit with transceivers at each intersection as described in Appendix H. The cable and amplifiers have a wide radio-frequency bandwidth (5 MHz to 300 MHz) which can handle the traffic control communications requirement of any city, and can also provide up to 30 television channels at the same time, if required. The cable normally used has low signal attenuation losses while the repeater amplifiers have low noise levels and excellent signal linearity over a wide range of output levels. The repeater amplifiers are placed along the cable network at points where the signal has been attenuated to the minimum permissible level. Using the appropriate filters and amplifiers at the repeater amplifier positions, the cable can carry signals in both directions simultaneously by dividing the total bandwidth into two parts, one for signals toward the intersections, and one for signals from the intersections (a form of frequency division multiplexing).

This type of communication system employs a time division multiplexed (TDM) polling technique in which the control center communications unit sends serial data commands addressed to each intersection in sequence and receives an immediate serial data response message from the addressed unit before interrogating the next. The communication unit at the control center includes a group of transmitters and receivers which connect to the first repeater amplifier of the main "trunk" of the tree-shaped coaxial network, and the branches of the network establish a path to each intersection. Each intersection traffic controller cabinet is equipped with a combination radio-frequency transmitter and receiver (transceiver) which is connected via a small 'drop' coaxial cable to a directional coupler on the network.

The central communications transmitters and receivers are typically connected to the central traffic control computer through a communication control (front-end) computer which provides temporary data storage and message formatting for transmission as well as message decoding and temporary data storage on reception. For transmission, the front-end computer forwards information to the appropriate transmitter which modulates the r-f carrier (using frequency shift keying) thus sending the message signal through the network. Conversely, on reception, the front-end computer receives demodulated signals from the communications receivers, encodes the signal address and data, and forwards the information to the traffic-control computer at the appropriate time.

At the intersection, the radio frequency transceiver is connected to the network by a radio frequency coupler. When the intersection receiver obtains a signal of the proper frequency, it decodes the signal, and if the proper address is present, it accepts the data. This transceiver then transmits information to the central site immediately after interrogation. Various polling rates, message formats, and carrier frequency distributions are used by the various equipment suppliers, since the equipment they offer consists of modified versions of units they manufacture for the cable television (CATV) industry, and each one has his own preferred technique.

3.3.2 Application Considerations

The equipment and installation costs of coaxial cable networks are similar to those of twisted wire pair networks for pole-mounted, direct burial and underground construction. Additional costs are required for the procurement and installation of the line (repeater) amplifiers plus their power sources and cabinets. Coaxial cable cost is similar to twisted pair costs for the smaller diameter (0.412-inch (1 cm)) coaxial cable, but additional cost must be allocated for the procurement and installation of large diameter (0.50-inch (1.3 cm) or 0.75-inch (1.9 cm)) coaxial cable because the cable rigidity requires careful site preparation, particularly for conduit installations. Some cost advantage over twisted pair networks results from the fact that twisted pairs require extensive design and installation effort to identify, splice, or connect each wire at every intersection. Coaxial cable networks require that only a single coaxial cable and a trunk-line tap be installed at each intersection, thus eliminating much of the design, documentation and installation cost. Cost of transceivers at the intersection is generally comparable to that of twisted pair TDM units, but the front-end computer cost and the cost of programming it is usually higher than that of typical twisted pair central communication units.

If an existing or planned cable TV installation encompasses an appreciable part of the traffic control network, a portion of the cable spectrum may be leased from the CATV operator, thus substituting a monthly leasing cost for cable installation cost.

Other factors to be considered in conducting a trade-off to determine feasibility of the coaxial cable method include:

- Cost of maintenance, which may be somewhat higher than other methods because of higher skill levels required.
- The possibility of future expansion, either within the network or into contiguous areas, which can be done by simply adding equipment and a coaxial cable of length sufficient to reach the existing network.
- The possibility that if TV surveillance is to be considered in the future, coaxial cable provides the necessary bandwidth for TV transmission at no significant additional cost.
- The large inherent electrical interference rejection capability of coaxial cable systems.
- The nearly complete immunity from current surges caused by lightning or power line faults due to the large current-carrying capability of the cable's outer conductor.

Regulatory aspects of coaxial cable communications are limited to control of any interference such a system could cause to other services. The interference radiation requirements of the cable system should be observed as specified by the FCC rules given in the document "Federal Communications Commission Rules and Regulations - Volume II, Part 76, Cable Television Service".

Additional material on coaxial cable communications is contained in Appendix H.

3.4 AIR PATH OPTICS COMMUNICATION

3.4.1 Introduction

Energy in the optical spectrum (usually visible or near infra-red) may be used for transmission of data through the atmosphere. This type of transmission has become practical in recent years through development of low-cost injection laser diodes for transmission, and light-sensitive diodes for reception.

By using a laser in the transmitter of an optical data link, much greater range, and/or signal to noise ratio at the receiver, can be achieved than by using non-coherent light sources of comparable input power for several reasons:

- Many types of lasers can produce relatively high peak power with low average input power; this is particularly true of pulsed injection (diode) lasers. For example, ten to fifty watts peak power can be produced in narrow pulses, using only milliwatts of average input power.
- Due to the laser's coherence, very narrow beamwidths can be produced using simple optics (lens or mirrors), as discussed in Appendix I.
- The laser's coherence also results in a very narrow optical spectrum, that is, highly monochromatic light, so that the data link receiver can use an optical filter matched to the laser's wavelength. Due to the narrow spectral width (usually under 50 to 100 Angstroms) the receiver filter passband therefore rejects most of the background light due to sunshine or artificial sources. This greatly enhances the system's receiver signal-to-noise ratio.

A pulsed laser diode in the transmitter typically produces 10 watts or more, which is collimated into a narrow beam (typically one to five milliradians) using a single simple lens. This beam is sufficient to produce usable signals with good signal-to-noise margins in a receiver at distances of over five miles (8 km) in clear weather, and over half a mile (0.8 km) in heavy rain, when ordinary visibility is about one-quarter of a mile (0.4 km).

The data rate of such a system is limited by the power dissipation of the transmitter. Using low-cost laser diodes available at the time of this writing, data rates of 5,000 to 10,000 bits per second can be obtained with pulse widths of 40 to 80 nanoseconds. Systems have actually been implemented with a rate of 1,800 bits per second.

3.4.2 Traffic Control Application

Equipment for traffic control communications consists of pole-mounted optical transceivers (single or multiple heads)* at each intersection facing their upstream and downstream counterparts at adjacent controlled intersections, plus a microcomputer at each intersection for processing the data (Figure 3-4). Each bidirectional transceiver acts as a repeater for data being transmitted in both directions and also communicates with the microcomputer in the controller cabinet via a short cable.

This type of system uses a polling TDM technique for communications, with a "master" unit (which may be either at a control center or at an intersection) connected via the optical link to a number of "local" units. The master unit sends traffic signal timing patterns and other information to the local units and requests various forms of information in return, such as vehicle detector data, confirmation of current pattern, and failure status. The optical transceiver at the master location obtains information from its computer as a series of pulses representing the local address, command information, and error check bits, and transmits this information to the transceiver at the adjacent intersection. This unit, in turn, immediately forwards it (via the oppositely-directed optical head on the same pole) to the next intersection, and also sends the data to its microcomputer in the controller cabinet. Each microcomputer checks the incoming address, and when it matches the microcomputer's wired-in address, the entire message is read into the microcomputer. The command information is processed and all information requested by the master is immediately transmitted to the master via the same optical path, using the oppositely-directed optical heads. Each intersection is polled in this way at a rate of once per minute in a typical hierarchical or network type of system.

3.4.3 Transceiver Electronics Unit

The transceiver electronics unit is typically located in one of the optical heads. The transceiver electronics unit contains transmitter and receiver sections, gain control and blanking circuits, digital logic circuits and power supplies (Figure 3-5). The source for each transmitted beam is an injection laser diode typically having a peak power output of 10 watts at a pulse repetition rate of 2,000 pulses per second. An avalanche photodiode serves as the receiver for optical energy.

*Single heads at ends of network branches; double heads along single-road links; and three or four heads at intersections within a grid type of roadway network.

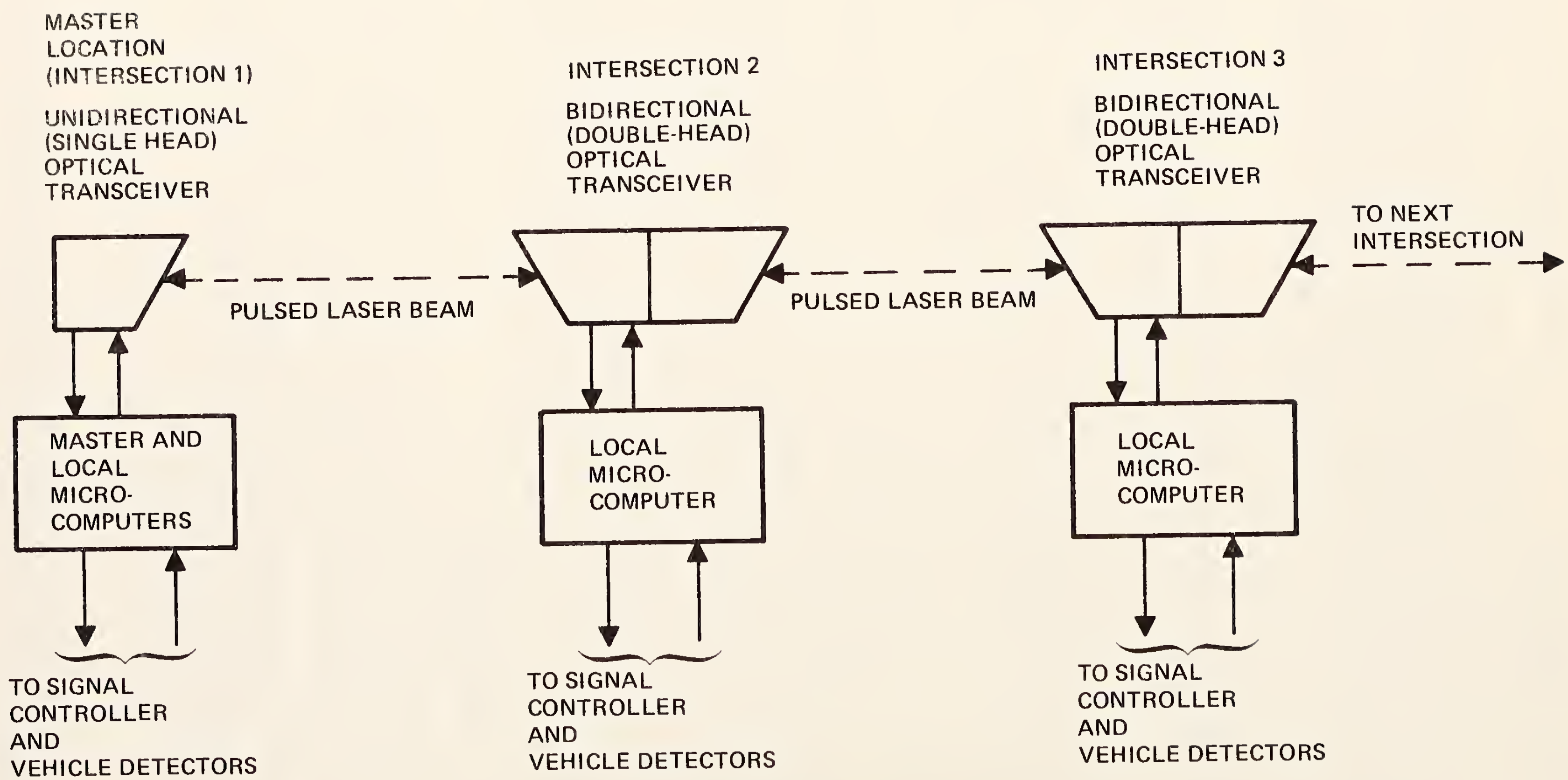


FIGURE 3-4. AIR PATH OPTICAL COMMUNICATION SYSTEM

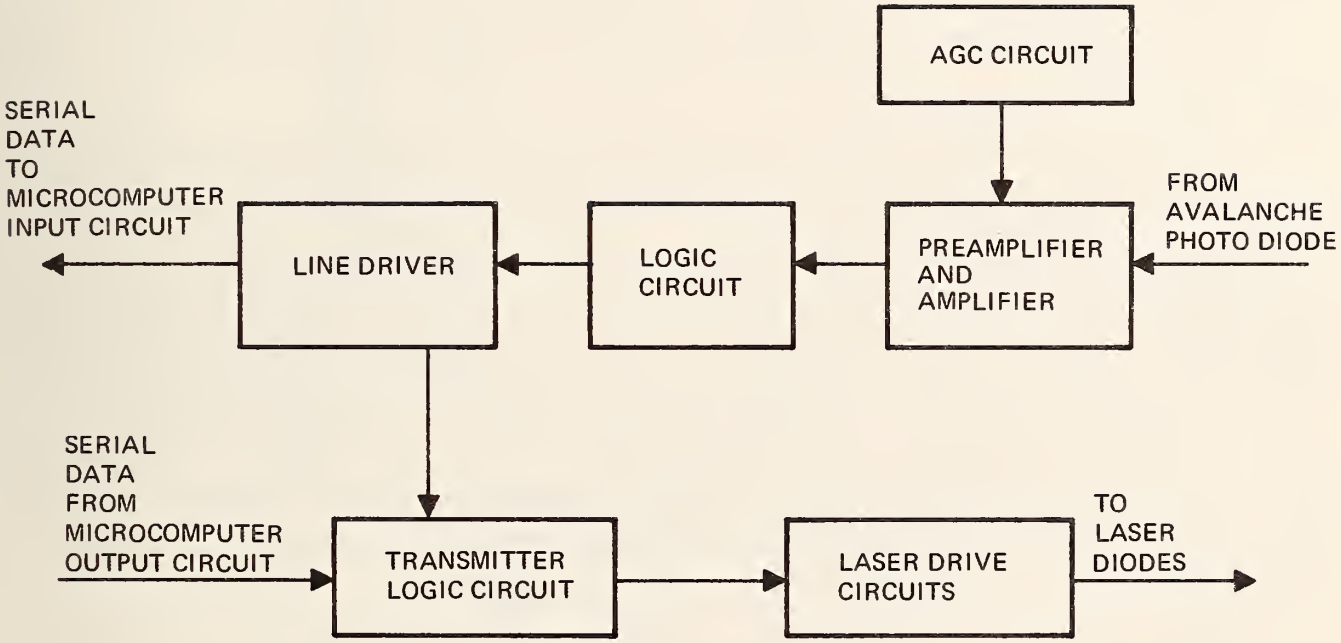


FIGURE 3-5. TRANSCEIVER UNIT

When operating as a combined repeater and terminal at a controlled intersection, the pulsed laser energy from an adjacent transmitter is sensed by the avalanche diode and the resulting electrical output is amplified and sent to the laser driver circuits for re-transmission to the next intersection.

The amplified pulses are also further amplified for transmission down the pole to the microcomputer in the intersection cabinet. Whenever the data entering the microcomputer contains the local address, the microcomputer recognizes this address and immediately feeds a response message to the laser drive circuit via the transmitter logic. As a result, a serial-pulse message from a master unit is passed from intersection to intersection until it reaches the addressed local unit, causing the local unit to send back a serial-pulse response.

Figure 3-6 shows typical equipment interconnections in block diagram form.

3.4.4 Application Considerations

In conducting a trade-off study to determine if an air path optical system is feasible, the intersections to be controlled must be physically checked to establish the mounting locations required for obtaining line-of-sight paths to all intersections. The costs of installing additional optical repeater mounting poles, if any, are then estimated, and the total cost of equipment and installation is estimated by multiplying the number of controlled intersections and the number of intermediate repeater points (which do not require a microcomputer) by their respective average costs. Two wire pairs (leased or owned) may be used for links which do not have unobstructed line-of-sight paths, since the data rates used with this system may be made compatible with voiceband transmission media and equipment.*

Installation and checkout of this type of communication system includes performing the following tasks:

- Mounting the optical heads, and optically aligning them with each other and checking their operating margin as described in Appendix I.
- Installing the microcomputer and connecting it to the optical head as well as to the controller and to vehicle detectors, if any.

*For those cases where the master computer is not at the control center, automatic dialing equipment connected to the telephone company switched network can be used to provide display, print-out, and storage of history data to the control center, and up-dated traffic signal timing pattern values to the master computer.

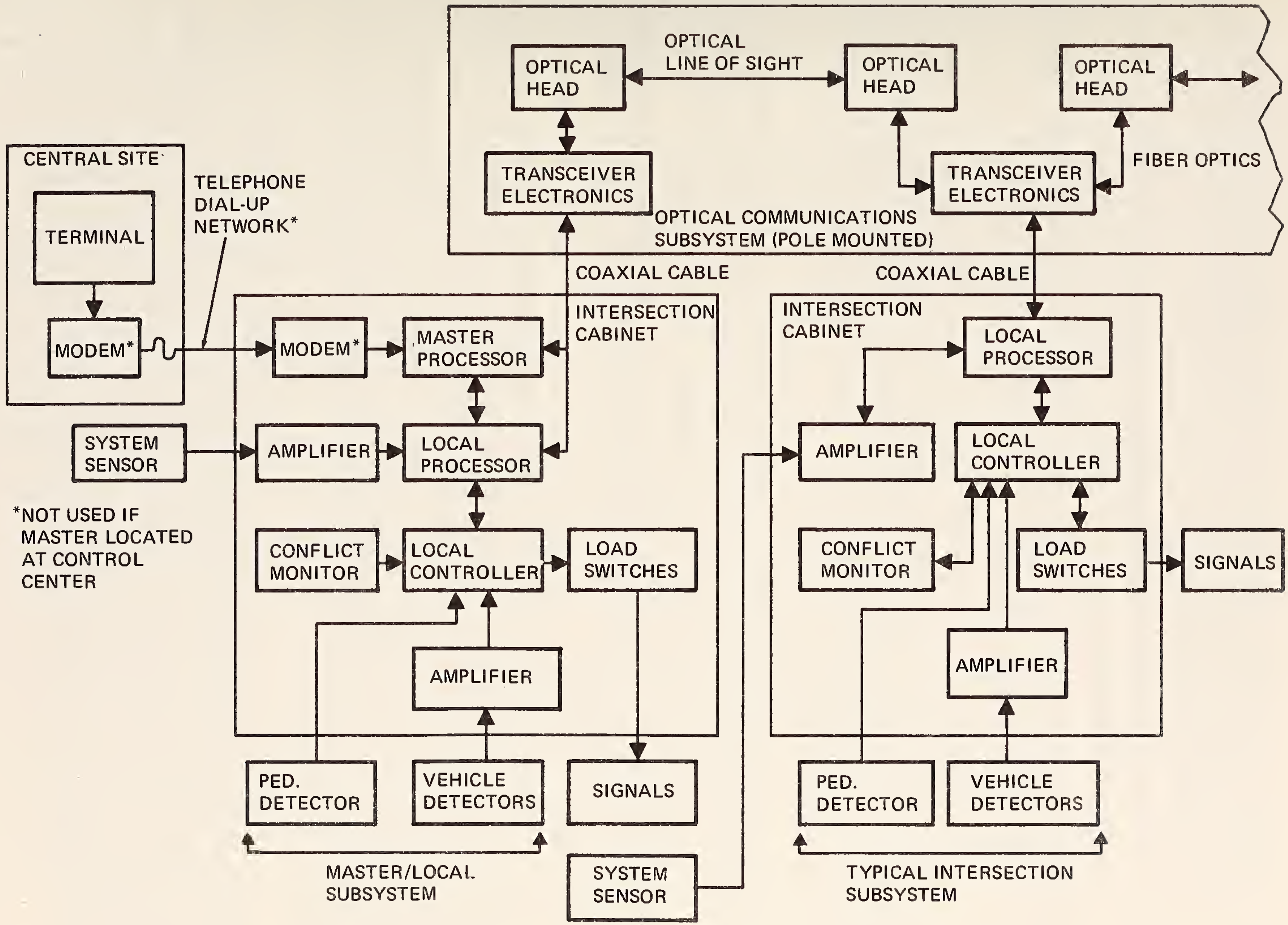


FIGURE 3-6. SYSTEM BLOCK DIAGRAM

- Inserting a test program into each microcomputer which checks all functions of the communication system (including message formats and error detection software) and records the number of errors.
- Operating the system for a period of time (several weeks if possible) to obtain a measure of its performance.

Appendix I contains additional material on the air path optics communication technique.

3.5 FIBER-OPTICS COMMUNICATIONS

A fiber optics data link is functionally the same as a data link using wires or coaxial cable as the communication medium, except that the transmitter module converts electronic signals into optical signals. The fiber optics transmission medium is an optical waveguide, which in the case of a single fiber data channel, is quite analogous to a coaxial cable, or more accurately, a cylindrical waveguide.

The glass fibers are coated with a cladding of glass or plastic having a different refractive index from the glass in the fibers. When these elements are properly designed, light rays entering one of these clad fibers will be reflected off of the fiber walls so that they propagate along the inside of the fiber without escaping until they reach the end. Continuous fibers can be made as long as several miles and interconnected by specially designed connectors where necessary.

By employing high purity fused quartz, it is possible to transmit modulated optical signals through glass fibers over distances of up to 10 kilometers (6.2 miles) without the need of re-amplification in repeaters. Transmission factors as high as 50 percent (3 db loss) per kilometer (0.62 mile) can be obtained in commercially-available fiber optics cables at the time of this writing. At large information data rates, low-loss fiber optics cables have been considerably more economical than typical coaxial cable in terms of line amplifier requirements.

Serial binary (on/off) modulation is the simplest technique for transmitting data over fiber optics data links and thus is the method most commonly employed. The very large data handling ability of fiber optics data links (which can be greater than several hundred megabits per channel) permits conversion of a large number of parallel inputs into a single serial data channel by multiplexing. A similar type of circuit is then used at the receiver and to convert the serial data back to parallel form at standard logic levels.

Conversion between electronic signals and optical signals at either end of the fiber optics transmission cable are performed by relatively simple electronics. The typical light-emitting diode (LED) used at the transmitting end is normally a low-level device (1 milliwatt average power output) that can be readily modulated (switched on and off to represent binary data) by a low voltage driver. Similarly, on the receiving end of the fiber optics data link, simple and reliable solid state devices are used to convert the modulated optical signal back to an electronic signal. Here the end of the optical fiber emits light that is detected by a small silicon photo-voltaic detector. Low-noise transistor amplifiers are then used to amplify the detected optical signal to a level where it can be used as desired.

At the transmitter (Figure 3-7), the electronic data signal, usually in TTL form from a computer or logic circuits, is amplified and fed to a low impedance driver (of 10 to 50 ohms output impedance) which modulates the light-emitting diode (or in some special cases, a CW injection laser diode). With appropriate connectors, the LED or laser is coupled to the end of the fiber optics bundle. This can be done by simply locating the end of the fibers in close proximity to the emitting LED chip, or by use of some form of focusing lenses to concentrate a high percentage of the LED output into the fiber bundle or single fiber.

At the receiver module (Figure 3-8), the light is coupled into the receiver detector through close-spaced fibers as is done with the transmitter. A silicon PN diode, or avalanche photo-diode, are the most commonly used detectors. The detected signal is then amplified by a low noise pre-amplifier, further amplified in one or more stages of video amplifier, and finally coupled to the data output terminal via a high speed comparator/regenerator. This final stage removes any degradation in signal waveform due to receiver bandwidth limits, or non-linear effects. It also sets a suitable threshold limit so that noise will not appear in the output; an output occurs only when a signal exceeds a certain threshold determined by the required allowable bit error rate. Some receiver modules also employ some form of automatic gain control to compensate for LED aging, various cable lengths, interconnect loss variations, etc.

Fiber optics cables are connected to transmitter and receiver modules with connectors of various types. To date, the most common connectors are ones which are similar to standard coaxial cable connectors. The outer connector shell and couplings are essentially the same as their coaxial counterparts. Only the inner parts that mate the tips of fiber optics bundles together are different. The one most applicable for traffic applications is identified as an SMA connector. It is small and provides a precise mating of opto-electronic devices to the fiber optics cable.

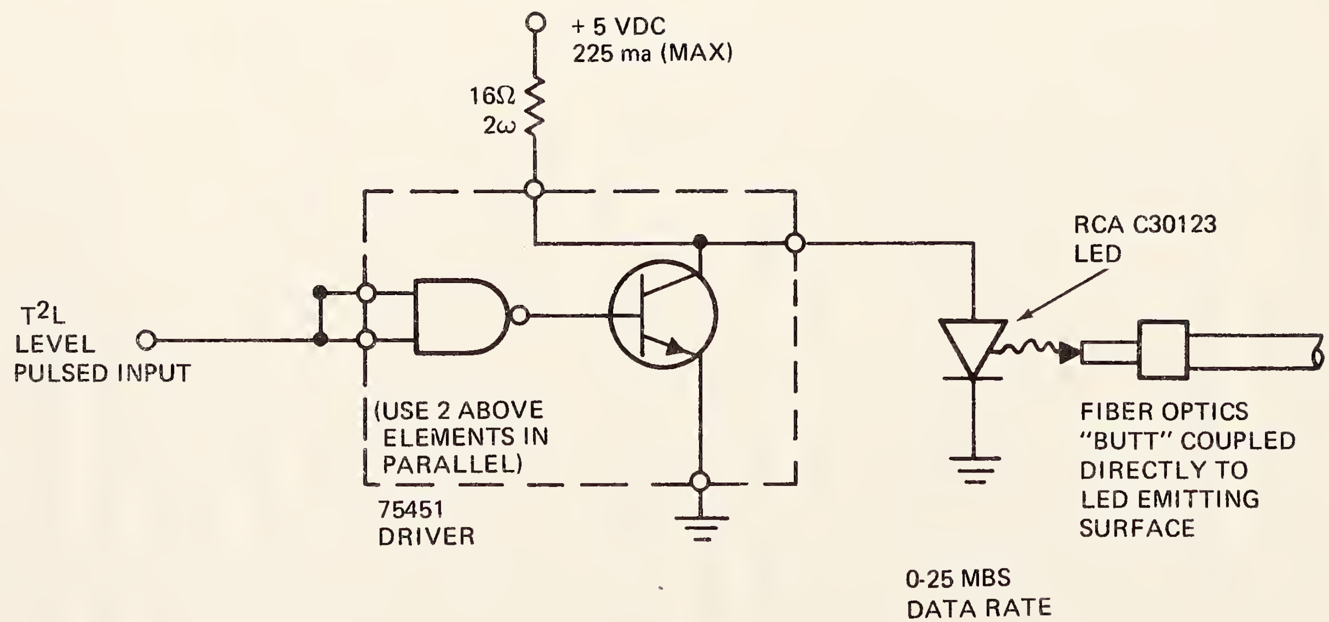


FIGURE 3-7. FIBER OPTICS TRANSMITTER

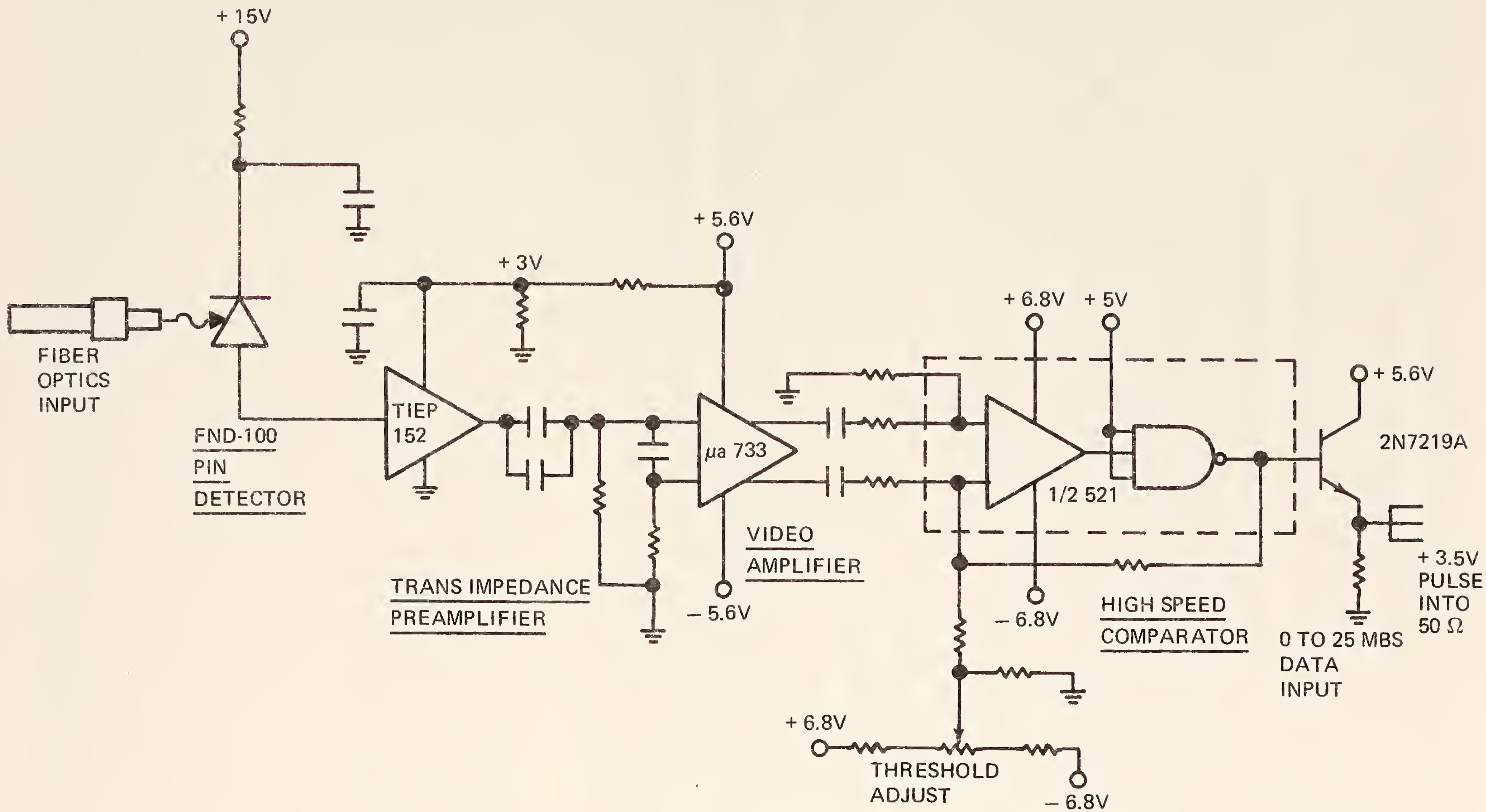


FIGURE 3-8. FIBER OPTICS RECIEVER

Unlike electrical cables, junctions with fiber optics need not make intimate contact. Radial alignment at cable junctions is usually required to be within one to five mils, depending on fiber optics fiber, or bundle, diameter, and this tolerance is readily achieved through the use of standard matched connectors, or couplings.

The cost of fiber optics system installation is essentially the same as for wire pair cables and coaxial cable. High data rate fiber optics cables, however, are smaller and lighter, and therefore are somewhat easier to handle and occupy less space in a conduit.

Cable costs runs from 30 cents per foot (98 cents per meter) for 20 db/km single 10 mil fiber in a jacket to over one dollar per foot (3 dollars per meter) for 5 db/km single fiber strengthened cables. Hence, although the typical low loss cable cost is higher than small diameter coaxial cable, the lowest cost fiber cable is about the same. Since conduit installation cost is the dominant cost factor, the overall cost difference between a fiber optics and coaxial cable installation may be insignificant.

The cost* of transmitter and receiver modules for commercial traffic applications with data rate requirements under 10 megabits per second is estimated to be in the range of $100 to $200 per transmitter/receiver set for production-line equipment.

Maintenance costs should be similar to those for other forms of cable communications.

Additional material on fiber optics communications is given in Appendix J.

*Since no known fiber optics communication installation for traffic control have been employed at this writing, the cost estimates are projections base on manufacturer's equipment for other applications.

SECTION 4

TRADE-OFF ANALYSIS

This section contains the following material:

- A discussion of factors affecting communication cost.
- A brief description of the three traffic control systems and six communication methods used as examples in the trade-off analysis.
- A list of communication cost parameters for each of the three traffic control systems used as examples.
- Descriptions of cost computation procedures and examples of numerical computations for each of the eleven communication subsystems considered.
- A description of the procedure used for determining system utility measures and utility/cost figures, using the eleven communication subsystems as examples.

4.1 INTRODUCTION

This section describes procedures for computing costs and utility measures for the communication techniques discussed in Section 3. These procedures are illustrated using examples of three traffic control systems based on the New Orleans, Bellevue, and SR-5 (Seattle) systems. The parameters of these systems have been modified to provide suitable values for the cost computation procedures and to show how such parameters affect costs of various communications configurations.

It should be emphasized that the cost totals are highly sensitive to the particular parameter values chosen for these examples, and therefore should not be used to compare the various communication methods. That is, a separate trade-off (including consideration of various processing architectures) should be made for any city being considered for computerized traffic control.

4.2 FACTORS AFFECTING COMMUNICATIONS COST

4.2.1 General

For any city in which a traffic control system is to be installed, the potential cost of various types of communication methods is affected by a number of factors. These factors can be divided into two groups; namely, locality-specific and function-specific.

The locality-specific factors are those physical features and local ordinances that are unique to the city, and should be examined carefully because their large impact on cost can markedly influence the choice of communication method to be used.

The function-specific factors are essentially the features of the traffic control system (such as, for example, a requirement for instantaneous real-time display of controller or detector status) which can influence communication costs. The number of functions and the data rate with which they must be transmitted are the principal function-specific factors which may influence cost because they directly affect the bandwidth required.

Additional factors which contribute to communications costs include the fraction of the engineering and programming costs attributable to communications. These have been assumed to be the same for each type of system examined in the section.

4.2.2 Locality-Specific Factors

The locality-specific factors which have an impact on communications include the following:

- Number and location of field cabinets to be served and location of the control center, all of which affect the length of the transmission path and number of communication units.
- Number and complexity of traffic controllers and number of vehicle detectors.
- Amount, type, quality and location of existing available cabling, conduit or poles.
- Number of useable existing traffic controllers.
- Tariffs and policies of the local telephone company.
- Location of telephone line terminations relative to field cabinets. (This distance usually requires conduit installation for interconnection if leased lines are used.)
- Rules regarding use of different types of conduit (metal, plastic), overhead cabling, jacking under pavement, pullboxes, antenna structures, or curbside cabinets.
- Restrictions on work procedures and traffic maintenance.
- Nature of the terrain (e.g., asphalt, reinforced concrete, curbing, rock, soil) to be trenched and backfilled.
- Location of other utility equipment that may interfere with installation.
- Skill levels of traffic department personnel.

- Local labor rates for street work and maintenance activities.
- Climatic conditions that affect installation or equipment costs (e.g., temperature extremes, lightning, ice storms).
- Local radio or optical transmission propagation characteristics (e.g., trees, buildings).
- Expected vandalism threat.
- Existence of freeways within or near the control area (e.g., need for ramp control, vehicle classification and/or variable message sign control).
- Proximity of unusual electrical noise sources (e.g., electric railway, high-voltage lines, radio or TV transmitters).
- Desired degree of system expansion.

4.2.3 Function-Specific Factors

The traffic control functions which have an impact on communications costs include the following:

- Quantity of vehicle surveillance data and controller monitor data transmitted from the roadside cabinets to a central or master computer.
- Quantity of controller command data transmitted from the central or master computer to the roadside cabinet.
- Quantity of data required for special functions.

The transmission rates required by these functions, the choice of communication method, and the system processing architecture are all related in the following way. The architecture determines how close in real time the received data corresponds to the occurrence of events at the other end of the communication link, with the central-type architecture being capable of providing the greatest degree of time concurrence and the distributed processing architectures (hierarchical and network) normally transmitting data that has been processed for one minute or more, or data that is to be used at some future time. Thus, if individual vehicle presence is required at the control center accurately in time, or if traffic signals must change instantly in response to central or master computer outputs, then a central type architecture will probably be selected and the communication method selected will have to be capable of transmitting data at relatively high rates of speed. Since the bandwidth required of the transmission medium is directly related to the data rate to be transmitted, the choice of transmission medium will be influenced accordingly. For example, with leased channels, a separate voiceband channel is required for every 3000 Hz of bandwidth that is required within the system; however, broadband media (coaxial cable and fiber optics) are not directly affected by typical increases in bandwidth requirements.

If real-time transmission of data is not required, then one of the distributed processing architectures (hierarchical on network) may be chosen, and the data rates (and, therefore, the bandwidths required of the medium) may be reduced accordingly, as discussed in Section 2. Consequently, the communication method selected for this type of architecture will be influenced more by the locality-specific factors than by the function-specific factors.

4.3 DESCRIPTION OF COMMUNICATION SYSTEMS

4.3.1 Centralized Type Architecture

4.3.1.1 General

The centralized type system used for comparing various types of communication techniques consists of an idealized 200-intersection grid network as shown in Figure 4-1. The system contains 182 pretimed controllers, 18 actuated controllers and 260 vehicle detectors (the locations of which are shown in Figure 4-1). Each intersection cabinet contains a communications unit in addition to its controller and up to 5 detectors. The control center contains communication units with their computer interfaces, in addition to the computer and its peripherals.

Six different communication techniques were compared using the centralized type architecture, namely, user-owned wire and leased lines with both FDM and TDM equipment, plus a coaxial cable system and a fiber optics cable system each using TDM equipment.

4.3.1.2 User-Owned Wire TDM System

The communication equipment used for this example employs a polling TDM technique with a three-word message format consisting of two data words and one checksum word. Each word consists of one start, one stop and one parity bit with the data words containing 8 data bits and the checksum word containing 8 checksum bits for error detection. Each intersection requires one command message from central, one monitor message from the intersection and one surveillance word for each two vehicle detector electronic units located in the intersection cabinet. The intersection communications equipment includes hardware to receive, transmit, decode and encode messages, and to accumulate detector data. The communication equipment at central consists of equipment to interface with the central

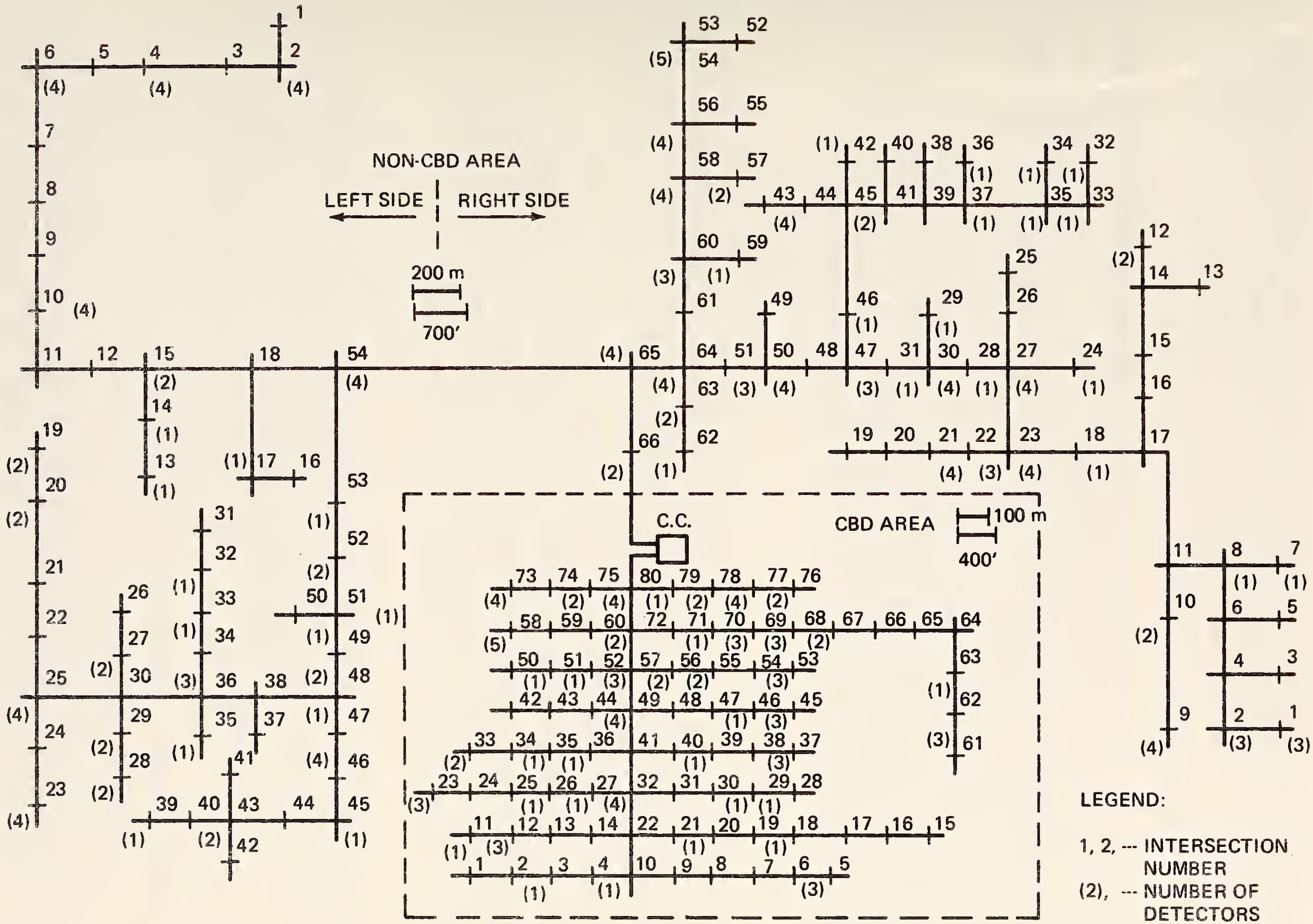


FIGURE 4-1. CENTRALIZED SYSTEM INTERSECTION GEOMETRY

computer and modems to receive and transmit the messages to the intersections over two pairs of wires. The hardware operates at 1,200 bps with capacity of 25 messages for each two wire pair. Each intersection is interrogated once per second.

4.3.1.3 User-Owned Wire FDM System

In this example, one FDM communications channel (transmitter and receiver) is required for each vehicle detector and three for each controller (AϕG, HOLD or YIELD, and ADVANCE or FORCE OFF). Each cable pair is limited to a maximum of 18 FDM channels.

4.3.1.4 Leased-Line TDM System

The communications system utilized in this example contains the same hardware complement with the same multiplex capability and data rates as does the user-owned TDM example. In this system, however, the communication medium consists of type 3002 voiceband private line channels leased from the local telephone company.

4.3.1.5 Leased-Line FDM System

The communications system utilized in this example contains the same equipment complement and multiplexing capability as does the owned-wire FDM example except the medium consists of type 3002 voiceband private lines leased from the local telephone company.

4.3.1.6 Coaxial Cable System

The communications equipment utilized in this example employs coaxial cable as the transmission medium. A TDM polling technique is utilized, in which the control center communications unit sends serial data commands to each intersection, one at a time, and receives an immediate response message from the addressed unit before interrogating the next unit.

The communication hardware at central consists of a communications computer (front-end computer) plus transmitters and receivers which connect to the first repeater amplifier of the main "trunk" of the coaxial network. Branches of this main trunk establish a path to each intersection which contains a transceiver to receive and transmit the messages. Repeater amplifiers are used along the cable to prevent the signal level from falling below a permissible level.

4.3.1.7 Fiber Optics Cable System

The fiber optics data link used in this example is functionally equivalent to the user-owned wire pair TDM system except that the transmitter module converts electronic signals into optical signals by use of LED's, and at the receiving end, a solid state device converts the optical signal back to an electrical signal compatible with the receiving electronics. The fiber optics transmission medium is an optical waveguide which is analogous to the coaxial cable.

4.3.2 Hierarchical-Type Architecture

4.3.2.1 General

The hierarchical-type system used for this example consists of a 19-intersection grid network (Figure 4-2) with microcomputers and modems at each intersection and a communication unit at the control center that interfaces with the central computer. The system contains 19 actuated controllers and a requirement to accommodate up to 110 detectors located as shown in Figure 4-2. Three different communication techniques were compared using the hierarchical-type architecture, namely, user-owned and leased-wire TDM systems, and an air path optics system.

4.3.2.2 User-Owned Wire TDM System

The communication equipment used for this example employs a polling TDM technique with a message format consisting of a 32-bit word (one start bit, one stop bit, 25 data bits, and five BCH error check bits) for transmission in both directions. Each intersection requires at least one command word (from central) and one monitor word (to central), and additional monitor words are used to handle up to three vehicle detectors each, using a one-per second polling period. The equipment operates at a data rate of 1,200 bits per second, transmitting a maximum of 28 words per second, and handling up to 8 intersections on each set of two wire pairs.

4.3.2.3 Leased-Line TDM System

The equipment used for this example is the same as for the user-owned wire case (paragraph 4.3.2.2 above) using a communication medium consisting of type 3002 voiceband private line channels leased from the local telephone company.

4.3.2.4 Air Path Optics System

The equipment used for the air path optics example consists of a microcomputer and one or more optical heads at each intersection as shown by the arrows in Figure 4-2. Additional pairs of repeater heads are used, as necessary, to bypass obstacles. The master unit at the control center interrogates one intersection at a time, using a polled TDM technique and receives a reply from the addressed intersection at a polling rate of once per minute.

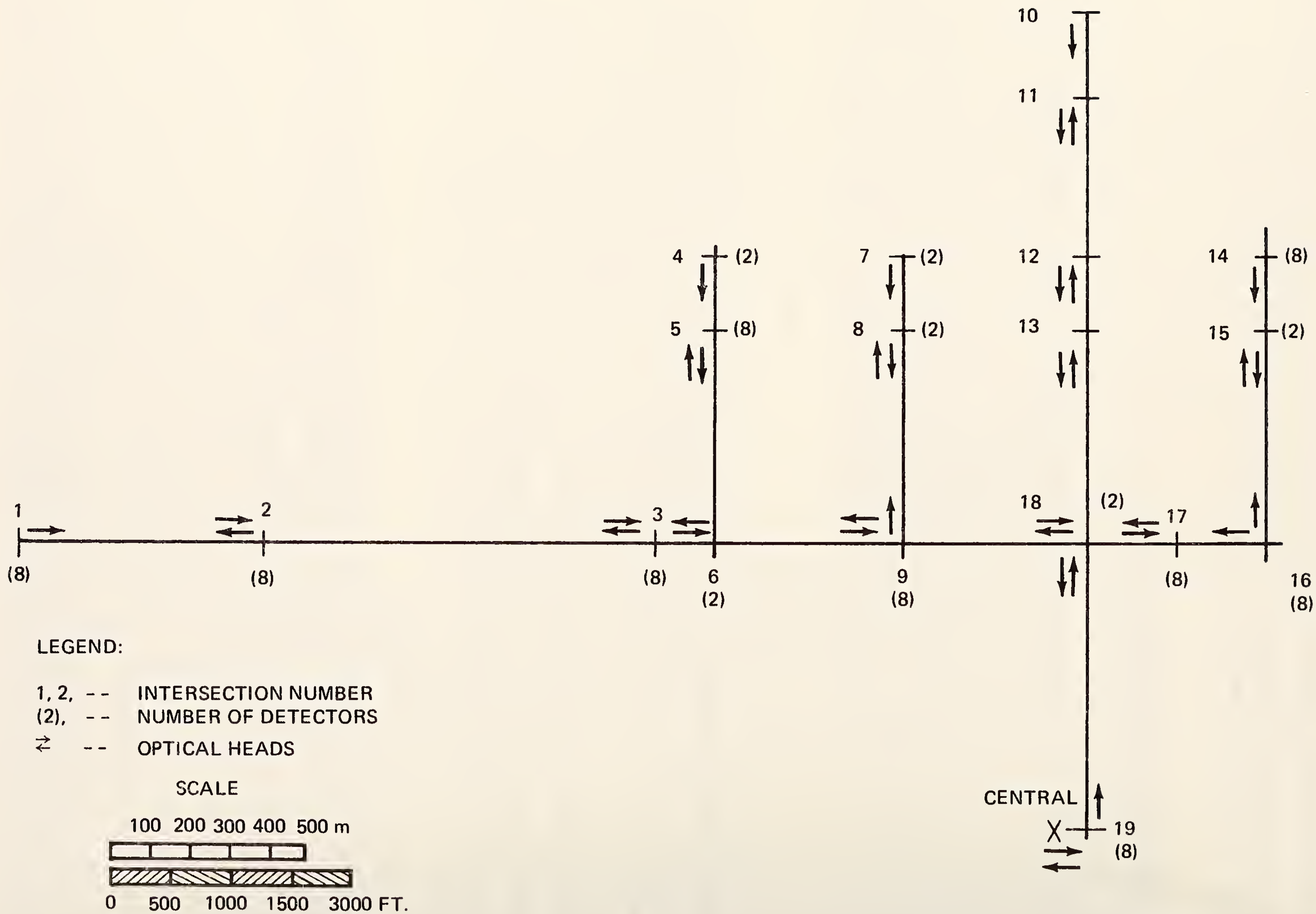


FIGURE 4-2. HIERARCHICAL SYSTEM INTERSECTION GEOMETRY

4.3.3 Network-Type Architecture

4.3.3.1 General

The network system used for this example consists of 25 intersections located on separate arterials (Figure 4-3). Each arterial group includes one "master" microcomputer (located at one of the intersections) and "local" microcomputers at each intersection, including the master intersection.

The communications techniques were compared using the network architecture, namely, a leased-line TDM system and an air path optics system.

4.3.3.2 Leased-Line TDM System

This system utilizes two dedicated pairs between each local microcomputer and its associated master, and also utilized two dedicated pairs between each master and a control center computer for pattern updating and display purposes. Pairs of modems on these lines transmit and receive data between the locals and the master on each arterial, and between the master and the control center computer.

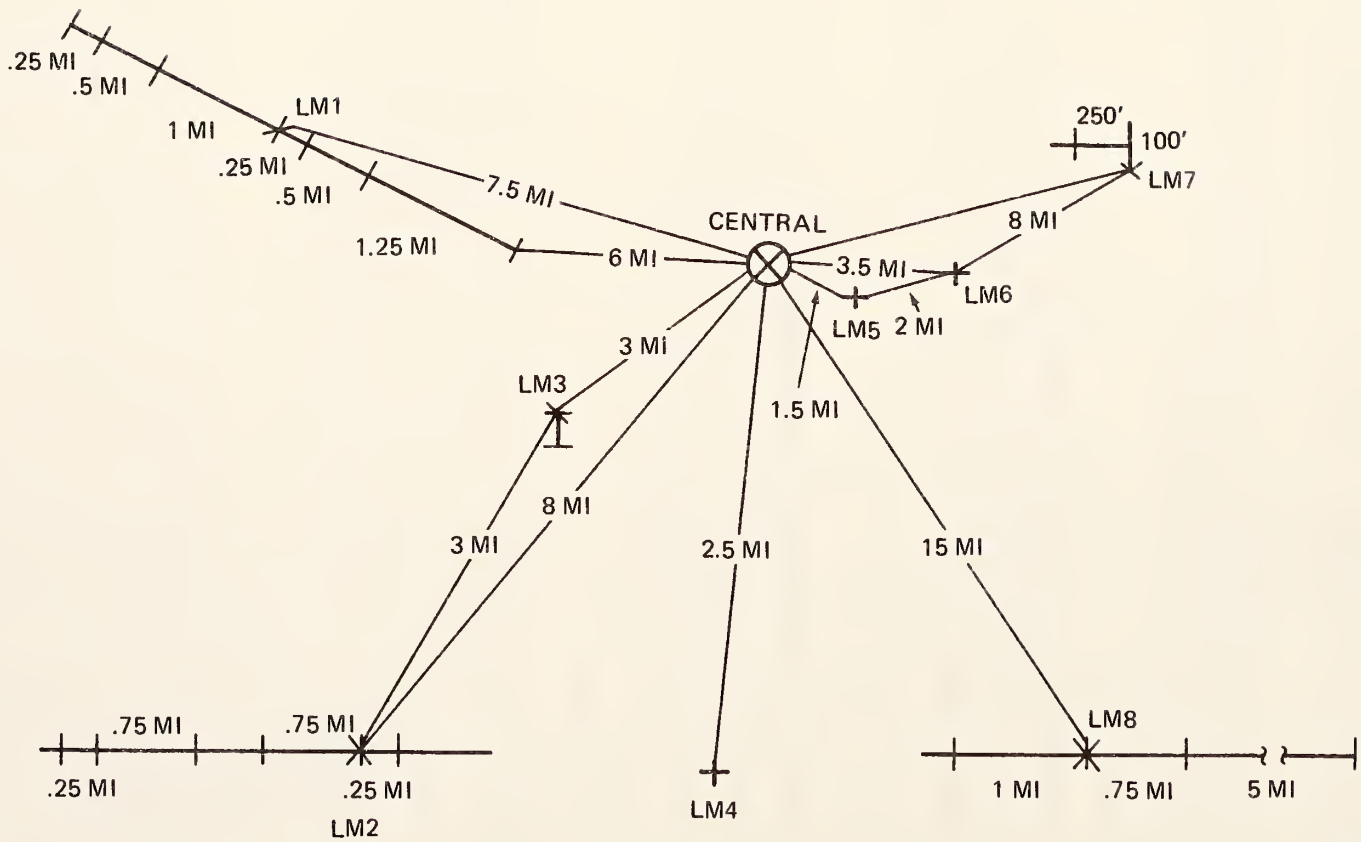
The master microcomputers provide timing pattern data to the local microcomputers and also receive surveillance and controller monitor data from the local microcomputers. The control center computer receives display and surveillance data, and transmits timing pattern modification to the master microcomputers as necessary.

4.3.3.3 Air Path Optics System

The equipment used for the air path optics example consists of a microcomputer and one or more optical heads at each intersection, as well as repeater pairs to connect the master units to distant locals and to the control center. Each master communicates with its associated locals as in the hierarchical system; and, in addition, the central computer uses an identical polled TDM technique to communicate with each master.

4.4 DEFINITION OF REQUIREMENTS

The first step of the cost computation procedure is to determine the traffic control system parameters that affect communication system costs (as discussed in subsection 4.2 above. Table 4-1 shows the parameter values which are used for the example system computations, and lists the type of communications system that are affected by the parameter values. Typical unit costs for these parameters are defined, as applicable, in the following subsections, where computations for examples of each communication technique are presented.



NOTE: 1 MI = 1.6 km

+ LOCAL CONTROLLER
* LOCAL CONTROLLER & LOCAL MASTER

FIGURE 4-3. NETWORK SYSTEM INTERSECTION GEOMETRY

TABLE 4-1. TRAFFIC CONTROL SYSTEM PARAMETERS

Parameter	Parameter quantities			Comm system affected
	Centralized	Hierarachical	Network	
1. Number of pretimed controllers	182			All
2. Number of actuated controllers	18	19	25	All
3. Number of vehicle detectors	260	146		All
4. Length of communication path (K feet)	116	23	300	All
5. Cable installation features (K feet)				Wire, Coax, Fiber Optic
Trench/Conduit - hard surface	20 (6.1)	10 (3)	40 (12.2)	
Jack conduit under pavement	10 (3)	3 (.9)	15 (4.6)	
Trench/Conduit - soft surface	7 (2.1)	1 (.3)	90 (27.4)	
Direct burial of cable	3 (.9)	1 (.3)	60 (18.3)	
Install in available conduit	10 (3)	5 (1.5)	20 (6.1)	
Install on poles (aerial cable)	60 (18)	3 (.9)	75 (22.2)	
Useable cable already installed	6 (1.8)	0	0	
6. Number of pullboxes	200	20	25	Wire, Coax, Fiber Optic
7. Number of intersections having aerial cable	90	2	6	Wire, Coax, Fiber Optic
8. Number of additional poles needed for optical heads	---	3	2	Air Path Optics
9. Number of additional optical repeaters needed	---	2	4	Air Path Optics

TABLE 4-1. TRAFFIC CONTROL SYSTEM PARAMETERS (Cont.)

Parameter	Parameter quantities			Comm system affected
	Centralized	Hierarachical	Network	
10. Leased channel data:				Leased-Line
Method of computing cost[a]	(1)	(2)	(3)	
Average distance to nearest Telco line (drop) from intersection cabinet (feet)	100	100	100	
Note: 1000 feet = 305 meters				

[a]Methods of computing cost for multipoint service:

(1) Mileage from Telco central offices to each intersection, and mileage between Telco central offices

(2) Mileage between points (intersections or control center)

(3) Fixed rate per point, and mileage between Telco central offices

The next step of the procedure is to establish the data rates required for the various types of systems, since data rates affect the cost of most communication methods. These rates are based on traffic system requirements, and Table 4-2 lists values which are used for the example system cost computation. (The method of computing data rate values from system requirements is presented in Section 2 and Section 5.8.)

The succeeding steps depend on the type of communication system being examined and examples are given in the following eleven subsections (4.5.1 through 4.5.11).

TABLE 4-2. DATA RATES

Message	Maximum data rates[a]	
	Centralized (bits/sec)	Hierarchial and network (bits/min)
Command message to local controller	8	120
Monitor message from local controller	6	160
Vehicle detector	7	40

[a]Does not include address, sync or error check bits.

The results of the cost comparison for the examples within each of the three basic processing architectures are shown in Table 4-3. As noted previously, these values are sensitive to the system parameter values chosen, and therefore should not be used for comparing the different methods. However, they do provide an indication of the relative costs of various elements for typical systems.

TABLE 4-3. COST SUMMARY

Architecture and communication method	Cable or leasing cost (K$)	Cable installation (K$)	Equipment (K$)	Maintenance (K$)	Total (K$)
Centralized					
User-owned wire, TDM	11	795	146	71	1,023
User-owned wire, FDM	10	795	403	44	1,252
Leased-line, TDM (0%)[a]	214	481	146	63	904
Leased-line, TDM (10%)[a]	428	481	146	63	1,118
Leased-line, FDM (0%)[a]	158	481	403	44	1,086
Leased-line, FDM (10%)[a]	316	481	403	44	1,244
Coaxial cable	55	830	190	170	1,225
Fiber optics cable	47	830	145	84	1,086
Hierarchical					
User-owned wire, TDM	2.3	242	30.5	14.8	289.6
Leased-line, TDM (0%)[a]	16.8	48	30.5	14.8	110.1
Leased-line, TDM (10%)[a]	33.6	48	30.5	14.8	126.9
Air path optic (min. est.)*		43	8.4	21	72.4
Air path optic (max. est.)*		108	14.5	41	163.5
Network					
Leased-line, TDM (0%)[a]	82	57.6	60	34.2	233.8
Leased-line, TDM (10%)[a]	164	57.6	60	34.2	315.8
Air path optics (min. est.)*		130	25	55	210
Air path optics (max. est.)*		337	42	116	495

[a]Leased-line escalation rate.

*The basis for the range of costs is described in paragraph 4.5.9.

4.5 EXAMPLES OF COST COMPUTATIONS

4.5.1 Central Type, User-Owned Wire, TDM Cost

This subsection describes the procedures for computing the cost of a centralized type of traffic control system employing user-owned wire pair cable and a time division multiplexing (TDM) transmission method. The procedure includes cost computations for cable, cable installation, equipment, and maintenance. The procedure is described in paragraphs a. (1) through a. (4) below and the corresponding example computations are given in paragraphs b. (1) through b. (4).

a. Description of Procedures

(1) Cable

The cable cost is computed using a layout of the cable network and a tabulation of cabling requirements at the intersections. Unit costs for cable sizes used in the numerical example are approximate prices paid for 19 AWG, REA type PE-22 cable purchased in 1977. In practice, these prices will vary over a wide range, principally as a function of wholesale copper prices.

(2) Cable Installation

The cable installation cost is computed using typical unit costs of both underground and overhead installations and multiplying by the example quantities listed in Table 4-1. These costs include the cost of the basic tasks listed, as well as all auxiliary tasks such as diversion of traffic and restoring of original surfaces. Pullbox cost includes furnishing and installing the box in a paved surface.

(3) Equipment

The equipment cost covers the cost of communication and interface equipment at all intersections and at the control center. The intersection equipment cost includes hardware capable of responding to an addressed message from the control center containing controller commands, as well as accumulating detector data, formatting the detector and intersection data into a checksum format and transmitting it to central at 1,200 bps. The central TDM communications cost is on a per channel basis, with an average of eight intersections per channel and includes modems, interface circuits, buffers, communication racks, surge protection and power supplies.

The costs used for the example computation are typical values that include the cost of installing and checking out the equipment at the intersection and at the traffic control center.

(4) Maintenance

Maintenance costs used for the example computation are based on typical failure rates, the degree of difficulty in isolating failures and replacing modules, typical replacement cost of modules, and the pro-rated cost of locating and repairing defective cable sections. In practice, such costs will vary as a function of actual equipment reliability and ease of replacement or repair, local labor rates, and maintenance personnel skill levels.

b. Example of Computation

(1) Cable

To determine the cable cost, either one of two methods may be used, depending on the degree of accuracy required. For initial trade-off purposes, an assumed cable cost of $100 per thousand feet usually provides sufficient accuracy since the cost of cable usually is a small percentage of the communication systems cost. However, if greater accuracy is desired or the cable cost is greater than 20% of the overall system cost, the method described in Section 5.6 may be used. In this example, the cost of cable is approximately one percent of the communication system cost.

For the simple method, the following steps are performed:

(a) The cable network is layed out on a scaled map as shown in the example system (Figure 4-1).

(b) This network is used to determine the total path length.

(c) The cable costs are then estimated by multiplying the path length 110,000 feet (33,500 m) by $100 per thousand feet (305 m), giving $11,000.*

(2) Cable Installation

The cable installation cost is obtained from the unit costs shown in Table 4-4 multiplied by the lengths for the centralized system repeated from Table 4-1. The resulting total is added to the pullbox cost ($500 each for this example).

Total cable installation cost is $795K.

*This value results in an error of less than 0.1% in total communications cost when compared with the more precise method given in Section 5.6.

TABLE 4-4. CABLE INSTALLATION COSTS

Installation type	Unit cost[a] ($/ft)	Length[a] (K feet)	Cost (K$)
Trench/Conduit hard surface	15	20	300
Jack under pavement	20	10	200
Trench/Conduit soft surface	8	7	56
Direct burial	3	3	9
Install in available conduit	1	10	10
Install on poles	2	60	120
Useable cable	0	6	0
Total			$695K
Pullboxes: 200 @ $500 =			$100K
Total			$795K

[a]1000 ft = 305 m

(3) Equipment Cost

The intersection equipment cost is obtained from Table 4-5, which shows the relationship between the number of detectors, message lengths and equipment costs per intersection, as well as the number of intersections associated with each of the listed number of detectors (obtained from Figure 4-1).

The traffic control center equipment cost is based on the cost per channel ($250 for this example) multiplied by the number of channels, which is equal to one-half the number of data pairs since there are two pairs per channel.

Total equipment cost is $146K.

(4) Maintenance

Maintenance cost for the TDM communication system is based on an assumed MTBF of 2.7×10^4 hours for equipment per intersection*; and 2.3×10^4 hours for cable per 2 pair line* for an average of 10 intersections; or 2.3×10^5 hours per intersection.

The combined MTBF is $[2.7 \times 23/(2.7 + 23)] \times 10^4 = 2.4 \times 10^4$ hours.

*See Appendix D.

TABLE 4-5. COST OF TDM EQUIPMENT AT INTERSECTIONS

No. of detectors	Message length	Equipment unit cost ($)	No. of intersections	Cost (K$)
0	2	650	81	49
1, 2	3	700	75	49
3, 4	4	750	42	29
5, 6	5	800	2	2
			Total =	$139K
Central TDM equipment cost: $250 x 28 = $7.0K				7K
				$146K

Assuming two hours average time to replace a module, an average labor cost of $15 per hour (including overhead), and a module repair cost of $100 (through exchange of modules by the module supplier), the cost of each failure is $15 x 2 + $100, or $130.

Assuming an operating time of 8,700 hours per year (24 hours per day and 7 days per week), maintenance cost per intersection per year is $\$130 \times 8{,}700/2.4 \times 10^4 = \$47$.

The cost for 200 intersections is 47 x 200 = $9,400.

Present worth based on a 15 year life and 10 percent interest is 7.6 x 9,400 = $71,000.

The total cost of the TDM system is the sum of the costs computed above, namely:

Cable	$ 11,000
Cable Installation	$795,000
Equipment	$146,000
Maintenance	$ 71,000
Total	$1,023,000

4.5.2 Central Type, Owned-Wire, FDM Costs

The procedure for computing the cost of a centralized type of communication system employing user-owned cable and frequency division multiplexing (FDM) is similar to that described above for time division multiplexing.

The procedure is described in paragraphs a. (1) through a. (4) below and the corresponding example computations are given in paragraphs b. (1) through b. (4).

a. <u>Description of Procedure</u>

(1) Cable

The cable cost procedure is the same as for the TDM approach, paragraph 4.5.1.

(2) Cable Installation

The cable installation procedure is the same as for the TDM approach, paragraph 4.5.1.

(3) Equipment

The FDM unit cost values include the cost of receiver and transmitter, communication chassis, and surge protection equipment required at both the control center and at the intersection, as well as the cost of central communication cabinets, and the costs of power supplies pro-rated on a per-channel basis.

(4) Maintenance

The maintenance cost procedure is the same as for the TDM approach, paragraph 4.5.1.

b. <u>Example of Computation</u>

(1) Cable

As with the TDM system (paragraph 4.5.1 above), cable costs may be computed using either one of two methods. The more precise method is described in Section 5.6, while the simpler method is described in the TDM example, giving the same cable cost, namely $11,000.*

(2) Cable Installation

The cable installation costs are computed in the same manner as for the TDM system and, for this example, the results are the same, namely, $795K.

*This value results in an overall error in the communications system's cost computation of less than 0.08% when compared with the value obtained using the procedure of Section 5.6 for this example.

(3) Equipment

The intersection equipment cost is based on an average cost of $500 per FDM channel times the total number of channels. This cost is $500 x 806 = $403,000.

(4) Maintenance

Maintenance cost for the FDM communication system is based on the following MTBF values* (in hours):

Field transmitters	2.8×10^5
Field receiver	4.0×10^5
Central transmitter	3.8×10^5
Central receiver	4.9×10^5
Cable (per intersection)	2.3×10^5

The MTBF of the incoming data channel is:

$$2.8 \times 4.9 \times 10^4/(4.0 + 4.9) = 1.8 \times 10^5$$

and the MTBF of the outgoing data channel is:

$$4.0 \times 3.8 \times 10^4/(4.0 + 3.8) = 1.9 \times 10^5$$

Since the average intersection has one incoming and three outgoing data channels, the combined equipment MTBF is:

$$1.8 \times (1.9/3) \times 10^4/(1.8 + 1.9/3) = 4.7 \times 10^4$$

The combined equipment and cable MTBF is:

$$4.7 \times 2.3 \times 10^4/(4.7 + 2.3) = 3.9 \times 10^4$$

Assuming the same operating time and average repair costs as the TDM system (8,700 hours and $130 respectively), the average yearly maintenance cost is:

$$130 \times 8{,}700/3.9 \times 10^4 = \$29$$

The cost for 200 intersections is:

$29 x 200 = $5,800 per year

Present worth based on a 15 year life and 10 percent interest is:

7.6 x 5,800 = $44,000

*See Appendix D.

The total cost of the FDM system is the sum of the costs computed above, namely:

Cable		$ 10,000
Cable installation		$795,000
Equipment		$403,000
Maintenance		$ 44,000
	Total	$1,252,000

4.5.3 Central Type, Leased-Line TDM Cost

a. Description of Procedure

The procedure for computing the cost of a communication system employing leased-lines and time division multiplexing includes computing the leasing costs (including one-time charges), the cost of connecting to the nearest telephone company line, the equipment cost and maintenance cost. The intersection layout for this example (Figure 4-4) is the same as for the owned-cable cases, and includes the locations of six Telephone Company central offices (Telco A, B, C, D, E and Main) which serve separate sections of the city.

The leasing cost for this example is based on radial distance measurements from each intersection to the local Telephone Company Central Office (C.O.) that serves the intersection, plus the distance measurements from each local C.O. to the main C.O., plus the distance from the main C.O. to the traffic control center. A leasing rate of $1.50 per pair per month for each quarter mile (402 m) of radial distance is assumed and is typical of rates charged in 1977.* Three pairs are connected to each intersection; two for two-way data transmission and one "order wire" pair to be used for voice communication during maintenance operations.

The cost of the connection to a telephone line consists of conduit material and labor to trench from the roadside cabinet to the nearest telephone company terminal board or splice point (either at a manhole or telephone pole), and usually involves the breaking and restoration of the sidewalk, curb, and street. The costs presented include the telephone company charge for penetrating each manhole for the connection from the intersection cabinet and the cost of connecting each drop (pair or dual pair).*

*In practice, such charges and the manner of computing them are likely to vary widely with location and with time.

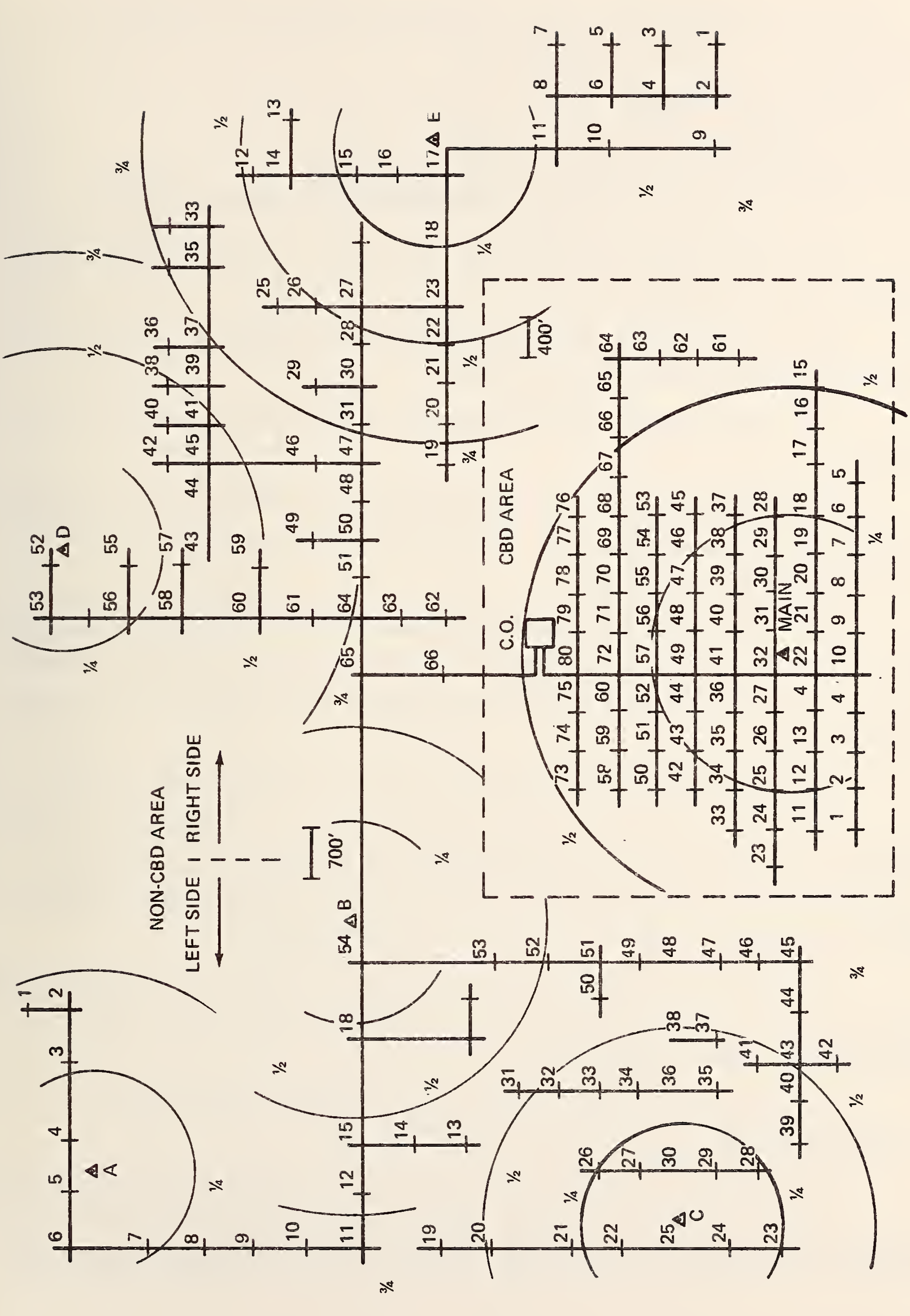


FIGURE 4-4. TELEPHONE COMPANY CENTRAL OFFICE COVERAGES

Equipment and maintenance cost computation procedures are the same as for the user-owned wire TDM system, paragraph 4.5.1.

b. Example of Computation

(1) Leasing Cost

To determine the leasing cost, the following steps are performed:

(a) Concentric circles differing by one-quarter mile* in radius are drawn about each C.O. as shown in Figure 4-4.

(b) For each C.O., the number of intersections assigned to the C.O. that fall within each quarter-mile* radius is counted.

(c) These counts are multiplied by their respective quarter-mile* distances (segments).

(d) The number of quarter-mile* segments for each local C.O. are summed and the total is entered into column A of Table 4-6. (Example for Telco A: 4 x 1 + 5 x 2 + 2 x 3 = 20 quarter-mile* segments.)

(e) The number of quarter-mile* segments between each local C.O. and the main C.O. and between the main C.O. and the control center are measured and entered into column A. (In practice, such C.O. interconnection patterns will vary from location to location.)

(f) The number of data messages required to service all intersections assigned to each C.O. is computed and entered into column B. This quantity is based on the number of detectors at the intersections as shown in subsection P. (For example, of the eleven intersections served by Telco A, four of them have four detectors each and seven have none, giving a total of 4 x 4 + 7 x 2 = 30 data messages.)

(g) The data message entries for step (e) are repeated for each of the local Telco-to-Main rows in the table and the sum of the data message entries is entered into the Telco-Main-to-Control Center row.

(h) Three pairs (2 data, 1 voice) are entered into column C for each "Intersection-to-Telco" row.

(i) The number of data pairs required to carry these messages between the control center and each C.O. is computed, and this number plus one are entered into the appropriate row of column C. These values are based on the 25 message limit per dual

*1 mi = 1.6093 km

TABLE 4-6. LEASED-LINE CABLE DATA

Segment	TDM system				FDM system		
	A. Quarter-mile segments	B. Total data messages	C. Total pairs	D. Pair quarter miles	E. FDM channels	F. Total pairs	G. Pair quarter miles
Int. to Telco A	20	30	3	60	-	2	40
Int. to Telco B	62	64	3	186	-	2	124
Int. to Telco C	56	71	3	168	-	2	112
Int. to Telco D	52	59	3	156	-	2	104
Int. to Telco E	87	101	3	261	-	22	174
Int. to Telco Main	137	215	3	411	-	2	274
Telco A to Telco Main	8	30	5	40	49	4	32
Telco B to Telco Main	5	64	7	35	91	7	35
Telco C to Telco Main	6	71	7	42	114	8	48
Telco D to Telco Main	7	59	7	49	104	7	49
Telco E to Telco Main	6	101	11	66	148	10	60
Telco Main to Control Center	2	540	45	90	827	50	100
			Total	1564			1152

pair derived in paragraph 5.4.2. (For example, the 64 messages for Telco B to Telco Main require three dual pairs - 25, 25, 14 messages respectively - plus one order wire pair or 7 pairs total.)

(j) The number of pairs is multiplied by the number of quarter-mile segments and entered into Column D.

(k) The number of pair quarter miles is summed, and is seen to be 1,564 in this example.

(l) The leasing cost is computed by multiplying the number of pair quarter miles by the leasing rate, or 1,564 x $1.50 = $2,346 per month.

(m) The present worth, based on a 15 year life and 10 percent interest rate is: 7.6 x 2,346 x 12 = $214,000. Assuming a 10 percent increase in yearly leasing rate, this value is doubled to $428,000. *

---

*The method of computing the cost resulting from increases in leasing rates with time is shown in Section 5.5.

(2) Interconnection Cost

The cost of connecting the intersection equipment to the leased line consists of a one-time connection charge of $15 per half duplex (order wire) and $22.50 per full duplex pair (data lines) plus the cost of installing cable to the nearest Telco line (drop), and adding an auxiliary Telco enclosure to the traffic controller cabinet. Where underground Telco cabling is used, installation of conduit and penetration of the Telco manhole wall is required, while for overhead Telco cabling, installation of conduit to the nearest pole is assumed. The cost of underground cabling is assumed to be $20 per foot ($66/meter) and the cost of manhole penetration is assumed to be $200. Ninety of the 200 intersections are assumed to be served by overhead cable. The average distance to both poles and manholes is assumed to be 100 feet (30.5 m).

The interconnection cost is, therefore, the sum of the following:

(a) Half duplex connection charge for 200 intersections plus one at control center: 201 x $15 = $3,015

(b) Full duplex connection charge for 200 intersections plus 44 at control center: 244 x $22.50 = $5,490

(c) Auxiliary enclosures: 200 x $250 = $50,000

(d) Interconnect cable installation: $20 x 100 x 200 = $400,000

(e) Manhole penetration: $200 x 110 = $22,000

Total interconnection cost $481,000.

(3) Equipment Cost

Equipment used for the leased-line method is the same as for the user-owned cable method. Therefore, the cost is the same (paragraph 4.5.1): $146,000.

(4) Maintenance

Maintenance cost for the leased-line method is the same as for user-owned cable (paragraph 4.5.1) except for the cost of maintaining the cable. Thus, the MTBF to be used in the computation is 2.7×10^4 instead of 2.4×10^4, giving a total present worth equivalent cost of 2.4/2.7 x $71,000 = $63,000.

The total cost of the leased TDM system is the sum of the costs computed above, namely:

	No leasing escalation	10% leasing escalation
Leased-line	$214,000	$428,000
Interconnect	$481,000	
Equipment	$146,000	
Maintenance	$ 63,000	
Total	$904,000	$1,118,000

4.5.4 Central Type, Leased-Line, FDM Cost

a. Description of Procedure

The procedure for computing cost of a communication system using leased-lines and frequency division multiplexing is similar to that for TDM systems (paragraph 4.5.3). For this example, the same methods of measurement and unit costs used for the TDM computation are assumed, and the number of intersections within each quarter mile annulus about each C.O. is determined in the same way as for the TDM case.

b. Example of Computation

(1) Leasing Cost

To determine the leasing cost, the following steps are performed:

(a) From Figure 4-4, the number of FDM channels required for each C.O. is determined by multiplying the number of intersections served by 3 (hold, advance, green monitor) and adding one channel for each vehicle detector. (For example, Telco A serves eleven intersections and sixteen vehicle detectors, thus requiring 11 x 3 + 16 = 49 FDM channels.)

(b) This number is entered into column E of Table 4-6 for each C.O. trunk line (to Telco Main and to the Control Center).

(c) Two pairs are entered into column F for each "Intersection to Telco(X)" row (one for FDM data channel, one for "order wire" voice channel).

(d) To determine the number of pairs required for the "Telco to Main" and "Main to Control Center" the number of FDM channels for each C.O. (column E) is divided by 18 (the maximum number of FDM channels permitted for this example) and the nearest integer value containing this result is the number of pairs required for data. One additional pair is added for the voice channel, and the total is entered into column F. (For example, the 49 FDM channels at Telco A require 49/18 = 3 + 1 = 4 wire pairs).

(e) The number of pair quarter miles (column G) is obtained by multiplying the entries in column A by the entries in column F.

(f) The monthly leasing cost is obtained by multiplying the total number of pair quarter miles by the rate: $1.50 x 1,152 = $1,728.

(g) The present worth, based on a 15-year life and 10 percent interest rate is: 7.6 x 1,728 x 12 = $158,000. Assuming a 10 percent increase in yearly leasing rates, this value is doubled to $316,000.

(2) Interconnection Cost

The interconnection cost is the same as for the TDM system (paragraph E), namely $481,000.

(3) Equipment and Maintenance Costs

The equipment and maintenance costs for the FDM leased system are the same as for the FDM user-owned system, namely $403,000 and $44,000.

The total cost of the leased FDM system is the sum of the costs computed above, namely:

	No leasing escalation	10% leasing escalation
Leased-line	$158,000	$316,000
Interconnect	$481,000	
Equipment	$403,000	
Maintenance	$ 44,000	
Total	$1,086,000	$1,244,000

4.5.5 Central Type, Coaxial Cable Cost

a. Description of Procedure

(1) Cable and Line Amplifiers

The cable and line amplifier cost is computed using a layout of the cable network to determine cable length and number of cable components required, as well as the number of amplifiers required to overcome the cable attenuation. Cable lengths are assumed to be the same as those for the user-owned wire pair cable systems (paragraph) 4.5.1). Amplifier cost includes the cost of installation and checkout.

(2) Cable Installation

Cable installation costs are assumed to be the same as for wire pair cable (paragraph 4.4) with the exception that conduit installation is substituted for the 3,000 feet* of direct burial listed in Table 4-1. The cost of pulling the coaxial cable through conduit and installing is assumed to be somewhat greater than the cost of pulling wire pair cable, but this is assumed to be offset by the lower cost of splicing.

(3) Central and Intersection Equipment

The equipment cost includes the purchase cost of the equipment as well as cost of installation and checkout. Central equipment cost includes the front end computer (communications control computer) and transceivers as well as all interface equipment necessary to connect the front end computer with the traffic control computer. The intersection equipment includes the transceivers and all necessary interface equipment.

(4) Maintenance

Maintenance costs are based on typical failure rates and typical costs of correcting failures in both equipment and cable.

b. Example of Computation

(1) Cable and Line Amplifiers

(a) The cable network is layed out on a scaled map as shown in the example network of Figure 4-1, and the total length is computed. For this example, the length is 120 x 700 + 80 x 400 = 116,000 feet*.

(b) The length is multiplied by the cost per foot* of 0.75-inch* diameter cable (assumed to be $0.32 per foot* for this example), giving $0.32 x 116,000 = $37,100.

---

*1 in = 2.54 cm
1 ft = 0.3048 m

(c) The number of line amplifiers, amplifier power supplies, and cable components are determined as described in Appendix H. For this example, the quantities and unit prices (including installation and checkout) are as follows:

Line amplifiers	17 @ $700	=	$11,900
Amplifier power supplies	6 @ $200	=	1,200
Directional couplers	226 @ $15	=	3,400
Splices	120 @ $3	=	400
Intersection drop cable	200 @ $6	=	1,200
			$18,100

Total cable and line amplifiers: 37,100 + 18,000 = $55,200

(2) Cable Installation

Cable installation cost is assumed to be the same as for user-owned wire pair cable plus the difference in cost for pulling 3,000 feet** in conduit instead of direct burial or: $795,000 + (8 - 3) x 7,000 = $810,000.

(3) Equipment Cost

Central:	Front end computer and interface	$56,000
Intersections:	200 transceivers @ 670	134,000
	Total	$190,000

(4) Maintenance Cost

Maintenance cost for the coaxial cable system is based on an estimated intersection transceiver MTBF of 1×10^4* which includes the equipment and cable link to the next intersection. (The contribution of central transceiver and line amplifier failures is ignored because the MTBF values are higher and the equipment quantities are much smaller.)

Assuming the same values of operating time and repair costs as for the user-owned cable TDM equipment, the yearly maintenance cost for 200 intersections is: $130 x 8,700 x 200/1 x 10^4 = $22,600.

Present worth for 15 year life and 10 percent interest is 7.6 x 22,600 = $170.000.

*See Appendix D.

**1 ft = 0.3048 m

The total cost of the coaxial cable communication system is the sum of the costs computed above, namely:

Cable and amplifiers		\$ 55,000
Cable installation		\$810,000
Equipment		\$190,000
Maintenance		\$170,000
	Total	\$1,225,000

4.5.6 <u>Central Type, Fiber Optics Cable Cost</u>

a. <u>Description of Procedure</u>

The procedure for computing the cost of a fiber optics communication system is similar to that for the coaxial cable type except that, at the time of this writing, the cost estimates are based on costs of early production runs rather than the products and user experience associated with the more mature coaxial cable industry.

b. <u>Example of Computation</u>

(1) Cable and Connectors

The fiber optics cable cost is based on the total cable length obtained from the example network layout (Figure 4-1) or 116,000 feet*. This length is multiplied by the unit cost of heavy duty, medium loss, single fiber cable (\$0.38 per foot* for this example). Total cost is: 116,000 x 0.38 = \$44,000.

The number of cable connectors is a function of the intersection geometry, varying from two to four per intersection for zero to two branches respectively. In this example, the number of connectors is 440, and the cost is \$6.00 each or a total cost of \$2,640.

(2) Cable Installation

Cable installation cost is assumed to be identical to that of the coaxial cable system, or \$810,000.

(3) Equipment Cost

The cost of intersection transceivers is based on a 1977 prototype cost of \$650 each plus \$50 for installation and check-out or a total cost of 200 x 700 = \$140,000.

*1 ft = 0.3048 m

Central communication cost includes the cost of a central transceiver and a front-end computer, together with its interface, plus installation and checkout of $5,000 for this example.

Total equipment cost is then 140,000 + 5,000 = $145,000.

(4) Maintenance Cost

Maintenance cost for the fiber optics communication system is based on an estimated MTBF of 2.0×10^4 per intersection* which includes the equipment and the cable link to the next intersection.

Assuming the same values of operating time and repair costs as for the wire systems, the yearly maintenance cost for 200 intersections is: $200 \times 130 \times 870/2.0 \times 10^4$ = $11,000.

Present worth for 15 year life at 10 percent interest is 7.6 x 11,000 = $84,000.

The total estimated cost for the fiber optics communication system is the sum of the costs computed above, namely:

Cable and connectors	$ 47,000
Cable installation	$810,000
Equipment	$145,000
Maintenance	$ 84,000
Total	$1,086,000

4.5.7 Hierarchical Type, User-Owned Wire TDM Cost

This subsection describes the procedure for computing the cost of a hierarchical type of traffic control system employing user-owned wire-pair cable and a time division multiplexing (TDM) communication method.

The procedure for computing costs for this system is essentially the same as that described for the central type of architecture (subsection 4.5.1) and is outlined in paragraph a. below. An example of the computations is given in paragraph b. below.

a. Description of Procedure

The costs of cable, cable installation, equipment and maintenance are computed in the same way as for the central system. That is, a layout of the cable network (Figure

*See Appendix D.

4-2) is used to tabulate the cable sizes and lengths required, and typical unit costs are used to compute total cable cost.

Cable installation cost is based on the example quantities listed under cable installation features in Table 4-1.

Equipment cost covers the cost of microcomputers and communications units in the roadside cabinets as well as the control center communication equipment. The costs for the example computation are based on typical values that include the cost of installing and checking out the equipment.

Maintenance costs are based on typical failure rates and the cost of locating and replacing failed equipment and maintaining a stock of spares.

b. Example of Computation

(1) Cable

To determine the cable cost the simplified method of assuming a cable cost of $100 per thousand feet** is used. If greater accuracy is required, the method outlined in Appendix F should be used.

The approximate cost of 23,000 feet** of cable (Table 4-1) is then: $100 x 23 = $2,300.*

(2) Cable Installation

The cable installation cost is obtained using the unit costs given in Table 4-4 multiplied by the lengths for the hierarchical system given in Table 4-1, and the result is added to the pullbox cost (20 @ $500 for this example). This computation results in a total installation cost of $242,000.

(3) Equipment

Cost of the intersection microprocessor and modems is assumed to be $1,100 and $400 respectively including installation and checkout, or $28,500 for 19 intersections.

The control center communications and computer interface is assumed to cost $500 per channel (dual wire pair) or $2,000 for 4 channels.

Total equipment cost is 28,500 + 2,000 = $30,500.

*This value results in an overall error in the communications system cost computation of less than 0.2% when compared with the value obtained using the procedure of Section 5.6 for this example.

**1 ft = 0.3048 m

(4) Maintenance Cost

Maintenance cost for the hierarchical system is based on estimated failure rates for the TDM equipment and cable computed for the central type user-owned system (MTBF = 2.4×10^4) and the microcomputer failure rate given in Appendix D (MTBF = 2×10^4). The composite failure rate for this equipment is $2.4 \times 2 \times 10^4/(2.4 + 2) = 1.1 \times 10^4$ hours. Assuming the same operating time and repair costs as for the central type user-owned system (8,700 hours and $130 per failure), the yearly maintenance cost for 19 intersections is: $130 \times 8,700 \times 19/1.1 \times 10^4 = \$1,950$.

Present worth (15 years at 10 percent) = 7.6 x 1,950 = $14,800.

The total cost of the TDM system is the sum of the costs computed above, namely:

Cable	$ 2,300
Cable installation	$242,000
Equipment	$ 30,500
Maintenance	$ 14,800
Total	$289,600

4.5.8 Hierarchical Type, Leased-Line TDM Cost

a. Description of Procedure

The communication system costs using leased-lines includes the cost of leasing, connecting to the nearest Telco line, equipment and maintenance.

The leasing cost for this example is based on a fixed cost per drop (i.e., roadside cabinet or control center for a traffic control system). The assumed charges are $8 per month per drop, and $60 one time installation charge.

An "order wire" is not included in this system because the area is small and therefore a handi-talkie type of radio communication could easily be used for maintenance communications.

The cost of connecting to the nearest Telco line, and the cost of equipment and maintenance are computed in a manner similar to that for the central type system using leased-lines.

b. Example of Computation

(1) Leasing cost

- 19 intersection drops @ $8/month = $ 1,824/year
- 4 control center drops (from paragraph a. above) @ $8/month = 384/year

Total: $ 2,208/year

Present worth (15 years, 10 percent no escalation): 7.6 x 2208 = $16,800.

At 10 percent leasing escalation: 2 x 16,800 = $33,600.*

(2) Interconnection Cost

Installation cost: 23 drops @ $60	$ 1,400
Auxiliary enclosures: 19 @ $250	$ 4,800
Cable installation: 100 feet** @ $20/foot** = $2,000/intersection	
19 intersections @ $2,000	$38,000
Manhole penetration: 10 @ $200	$ 3,800
Total interconnect cost	$48,000

(3) Equipment Cost

Same as for user-owned wire system $30,500

(4) Maintenance Cost

Same as for user-owned wire system $14,800

Total cost is:

	No leasing escalation	10% leasing escalation
Leasing	16,800	33,600
Interconnect	48,000	
Equipment	30,500	
Maintenance	14,800	
Total	$110,100	$126,900

*See Section 5.5.

**1 ft = 0.3048 m

4.5.9 Hierarchical Type, Air Path Optics Cost

a. Description of Procedure

The procedure for computing the cost of a communication system using air path optics includes computing the cost of equipment, installation, and maintenance.

The equipment cost is computed by first determining the number of units required using a scaled map and a maximum line of sight distance (4,000 feet* in this example). Additional repeaters are included, as necessary, to bypass obstructions. The quantities of units so determined are then multiplied by the unit costs to obtain the total equipment cost.

Installation costs are a function of the number and type of useable support structures available for mounting the optical heads and mast arms. For this example, it is assumed that three intersections require additional poles in order to bypass line of sight obstructions or to overcome structural deficiencies in existing poles.

Maintenance costs are based on typical failure rates and the cost of replacing and repairing equipment.

b. Example of Computation

(1) Equipment

The equipment cost for each intersection includes the cost of the optical heads plus the fraction of the microcomputer cost that is required for communications. For this example, a range of estimated values, based on prototype costs, has been selected, namely \$2,000 to \$5,000 per intersection (or control center) and \$1,500 to 4,000 per repeater (without microcomputer).

The range of costs for the 19 intersections, control center, and two additional repeaters is then:

Minimum value: 20 x 2,000 + 2 x 1,500 = \$43,000

Maximum value: 20 x 5,000 + 2 x 4,000 = \$108,000.

(2) Installation

Installation cost per intersection includes the cost of mounting a mast arm on an existing pole, mounting an optical head on the mast arm, connecting the optical head to the microcomputer, providing AC power to the optical head, and aligning the head with the adjacent heads. For those locations requiring an additional support pole, a foundation

*1 ft = 0.3048 m

must be laid and the pole installed. The range of costs estimated for this example is \$300 to \$500 where an existing pole is used, and \$800 to \$1,500 where an additional pole must be installed.

The cost for 19 intersections, the control center communications and three additional poles is:

Minimum value: $20 \times 0.3 + 3 \times 0.8 =$ \$8,400

Maximum value: $20 \times 0.5 + 3 \times 1.5 =$ \$14,500.

(3) Maintenance

Maintenance cost is based on the estimated failure rates given in Appendix D for the pair of optical heads (MTBF = 1.1×10^4) and the microcomputer (MTBF = 2×10^4). The composite MTBF for each intersection is $1.1 \times 2 \times 10^4/(1.1 + 2) = 7 \times 10^3$ hours.

Assuming a range of \$100 to \$200 module repair cost and continuous operation, the range of yearly maintenance costs for the 19 intersections, control center communications, and repeaters is:

Minimum: $20 \times 8{,}700 \times 100/7 \times 10^3 + 2 \times 8{,}700 \times 100/1.1 \times 10^4 =$ \$2,700

Maximum: $2 \times 2{,}700 =$ \$5,400.

Present worth (15 years @ 10 percent) is:

Minimum: $7.6 \times 2{,}700 =$ \$21,000

Maximum: $7.6 \times 5{,}400 =$ \$41,000.

(4) Total Cost

The total range of costs is the sum of the costs computed above, namely:

	Minimum	Maximum
Equipment	\$43,000	\$108,000
Installation	8,400	14,500
Maintenance	21,000	41,000
Total	\$72,400	\$163,500

4.5.10 Network Type, Leased-Line TDM Cost

This subsection describes the procedure for computing the cost of a network type of traffic control system employing leased-lines and a time division multiplexing (TDM) communication method.

a. Description of Procedure

The communication system costs include the costs of leasing, connection to the nearest Telco line, equipment and maintenance.

The leasing costs for this example are based on the airline mileage between points measured in quarter-mile** segments. A unit cost of $3.00 per quarter-mile** per month for each four-wire channel is assumed.

The cost of interconnecting to the nearest Telco line, and the costs of equipment and maintenance are computed in a manner similar to that for the central type leased line system.

b. Example of Computation

(1) Leasing Cost

The network layout is used to measure the airline distances between each local and its associated master and between the masters and the control center. These distances are shown in Figure 4-3 to the nearest larger quarter-mile** interval. Total distance is 300 quarter-mile** intervals.

The leasing cost is:

$3.00 x 300 x 12 = $10,800 per year.

Present worth for 15 year life @ 10 percent and no escalation is:

7.6 x 10,800 = $82,000.

At 10 percent leasing rate escalation the present worth is: 2 x 82,000 = $164,000.*

(2) Interconnection cost

The Telco connection charge is assumed to be $22.50 per point. There are a total of 60 points (two for each local to master connection and two for each master to control center connection). Therefore, Telco connection cost is 60 x $22.50 = $1,350.

• Telco connection cost	$1,350
• Auxiliary enclosure: 25 @ $250	$6,250
• Cable installation: 100 ft.** @ $20/ft.** = $2,000 per intersection; 25 x 2000	$50,000
Total interconnection cost	$57,600

*See Section 5.5.
**1 mi = 1.6093 km
1 ft = 0.3048 m

(3) Equipment Cost

Assuming microcomputer cost = \$1,200 and modem cost = \$400, each local to master and each master-to-central channel costs 1,200 + 2 x 400 = \$2,000.

For 30 channels, equipment cost is 30 x 2 = \$60,000.

(4) Maintenance Cost

Maintenance cost is based on the same failure rates, operating time and module repair costs as for the hierarchical type user owned wire TDM system (MTBF = 1.1×10^4 hours, operating time = 8,700 hours per year, and repair cost = \$130 per failure. The yearly maintenance cost for 30 microcomputer/modem units (22 local, 8 master) is: $30 \times 8,700 \times 130/1.1 \times 10^4$ = \$3,100 and the cost for the 30 additional modems at the master and control center locations is: $30 \times 8,700 \times 130/2.4 \times 10^4$ = \$1,400. Total yearly maintenance cost is 3,100 + 1,400 = 4,500. Present worth (15 years @ 10 percent is 7.6 x 4,500 = \$34,200.

Total cost for the leased-line communication system for the network type traffic control architecture is the sum of the costs computed above, namely:

	No leasing escalation	10% leasing escalation
Leasing	\$82,000	\$164,000
Interconnection	57,600	
Equipment	60,000	
Maintenance	34,200	
Total	\$233,800	\$315,800

4.5.11 Network Type, Air Path Optics Cost

a. Description of Procedure

The procedure for computing the cost of a communication system for a network type of architecture using air path optics is similar to that used for the hierarchical type architecture (paragraph 4.5.8). This procedure includes computation of costs for equipment, installation and maintenance.

b. Example of Computation

(1) Equipment

The number of optical head installations is determined from the scaled map (Figure 4-3) and the number of additional repeaters listed in Table 4-1. Using a maximum optical head spacing of 4,000 feet* for this example, the total number of optical heads is 78 (25 intersection installations and 53 repeaters).

Using the same unit costs as for the hierarchical example (paragraph 4.5.8) the range of equipment costs are:

Minimum value: 25 x 2,000 + 53 x 1,500 = $130,000

Maximum value: 25 x 5,000 + 53 x 4,000 = $337,000.

(2) Installation

Installation costs per intersection are the same as for the hierarchical system, namely $300 to $500 for existing poles and $800 to $1,500 for added poles.

The range of installation costs for the 78 locations and 2 additional poles is:

Minimum value: 78 x 0.3 + 2 x 0.8 = $25,000

Maximum value: 78 x 0.5 + 2 x 1.5 = $42,000.

(3) Maintenance

Maintenance cost is based on the same failure rate, repair cost and operating time values that are used in the hierarchical system computation.

The range of yearly costs for the 25 intersection units and 70 repeaters is:

Minimum value: $25 \times 8{,}700 \times 100/7 \times 10^3 + 53 \times 8{,}700 \times 100/1.1 \times 10^4 = \$7{,}300$

Maximum value: 7,300 x 2 = $14,600.

Present worth (15 years @ 10 percent) is:

Minimum: 7.6 x 7,300 = $55,000

Maximum: 7.6 x 14,600 = $116,000.

*1 ft = 0.3048 m

The total range of costs is the sum of the costs computed above, namely:

	Minimum	Maximum
Equipment	$130,000	$337,000
Installation	25,000	42,000
Maintenance	55,000	116,000
Total	$210,000	$495,000

4.6 UTILITY COST ANALYSIS

4.6.1 Overall System Utility/Cost Analysis

In the design of a complete traffic control system, a communication subsystem utility/cost analysis comprises only a small part of the overall system analysis. In particular, the selection of the type of processing architecture, and consideration of various system factors would normally be addressed in advance of communications subsystem analysis, and, in fact, would probably result in the elimination of certain types of communication subsystems before any detailed communications trade-off is made.

These overall system considerations are discussed in the following paragraphs to provide some perspective on the task of integrating the communications subsystem into the traffic control system design.

4.6.2 Constraints on Communications Choices

Particular constraints may be imposed by the environment which may eliminate certain candidates from consideration. Examples of such constraints are:

- The requirement to preserve certain existing equipment.
- The requirement to have maintenance performed in certain ways, or to eliminate certain maintenance or operational manpower requirements because of local personnel budget limitations or related problems.

In certain cases, the choice of system architecture may be imposed by a constraint. For example, the traffic engineer may require a computer system which provides for sophisticated displays and has background capability (thus eliminating the network type of system). On the other hand, the traffic engineer may have little central office space and operating personnel available (and little prospect for obtaining more), thus essentially constraining him to a network system.

Systems which are not compatible with such constraints must be eliminated prior to utility/cost considerations.

In addition, each traffic engineer often has certain unique objectives which he is trying to accomplish which may influence the design of the traffic control system. Examples of these may be:

- To combine the traffic control function with a data acquisition system which may be used for long-range transportation planning functions.

- To coordinate the traffic control system with other systems such as freeway or corridor control systems.

In most cases, objectives such as these are treated in the system utility analysis. Objectives which are very strongly desired, to the extent that they are "non-negotiable", are treated as constraints.

The inclusion of supplementary modes of operation is dependent on system architecture and local needs, and to the extent that these modes are important in the traffic engineer's communications choices, they may be treated as constraints.

4.6.3 Trade-off Considerations

Once the various constraints have been used to bound the system choices, a set of candidate communication subsystems may be selected. These candidates may then be compared using a two-step utility/cost analysis procedure. The first step of this procedure is to determine the relative merits of the various candidates with respect to their ability to perform all functions required by the traffic control system. The second step is to compare the candidate with respect to utility measures associated with the communication subsystem itself.

The first step of this procedure was performed for the communication system defined in subsection 4.3 as part of this study. The "Utility Requirements" used in this procedure were essentially the same as those contained in Reference 1*, and are listed below:

- Number of control areas.

- Control area interface.

- Control area modification.

*Reference 1. Stout, T. L., et al: "An approach for Selecting Traffic Control Systems" (NCHRP Project 3-18(3), JHK & Associates, March 1977.

- Number of timing plans.
- Signal retiming.
- Local intersection control.
- Critical intersection control
- Plan selection mode.
- Hardware monitoring
- System expansion.
- Growth to second generation UTCS.
- Coordination with other systems.
- Preferential service.
- Technology advance.
- Traffic surveillance.
- Data processing.

These requirements were used to form a utility model by assigning weights to them in accordance with criteria similar to those given in Reference 1. Then, for each candidate traffic control system being considered, a set of "Scale Values" was assigned and multiplied by the utility requirement weights to obtain an overall system utility number.

This analysis showed that all candidates considered were able to meet the system requirements with nearly equal capability. In general, most candidate communication subsystems employing proven techniques will meet the functional requirements of traffic control systems more or less equally well.

The second step of the procedure - comparison of candidates' ability to satisfy communication subsystem utility measures - was also performed as part of this study, and is described in the following paragraphs.

4.6.4 Utility/Cost Comparison Method

4.6.4.1 General

This subsection discusses the utility/cost method of comparing alternate communications systems. The preparation of the utility model is discussed, and a typical problem is treated using the model. The problem involves selection among the six candidate communication systems discussed in Section 4.3. The selection is made for demonstration purposes only, and is not meant to imply any preference for one system over another in any given application.

This utility cost method employs a utility model in which the desirable attributes of the communication system (e.g., reliability, maintainability) are given numerical weights in proportion to their estimated contribution to the ultimate objective of the communication systems. The weights are used to compute a "utility", which is divided by the system cost, yielding a numerical index which is characteristic of the system.

The utility/cost approach was selected after examining three widely used methods of system comparison. These were:

- Benefit/Cost.
- Effectiveness/Cost.
- Utility/Cost.

The benefit/cost method is one of the most common evaluation techniques, and ideally represents the most meaningful measure of comparison. This is because both benefits and costs are expressed in the same units and a more or less quantitative way can be found to obtain the dollar value of some benefits. One shortcoming however, is that it is very difficult to assign a dollar value to many of the benefits a system can provide. Thus the benefit calculation is not complete, in the sense that system attributes to which dollar benefits can easily be attached are included, but those which do not have such tangible benefits (such as reliability or ease of installation), are not included. In this sense the benefit/cost method is deficient in its ability to make valid comparisons.

The effectiveness/cost method is another method of evaluation. It has the same drawbacks as the benefit/cost method, in that effectiveness is generally expressed in terms of attributes which are easy to assign numerical values to, such as delay or travel time, while other important, but hard to quantify attributes are neglected.

The utility/cost method is an alternate approach which allows a means for assessing all of the benefits of a candidate system, regardless of whether or not they are dollar-quantifiable. This method is more subjective than the others and relies heavily on sound judgment. It nevertheless represents a comprehensive examination of the problem, and affords the opportunity for the inclusion of many important factors which are often ignored. This, then, has been the method selected for application to this study.

4.6.4.2 System Utility Model

The utility/cost approach begins with the selection of a utility model. The model includes a number of system attributes, or "utility measures". The utility measures describe the properties which the system should have in order to fulfill its objective which, in this case, is to transmit data to and from the field.

The utility measures are then ranked and weighted. The list of utility measures and their corresponding weights constitutes the utility model and is shown in Table 4-7. It should be noted that the weights selected for this table are representative of a typical system, and would be manually adjusted by the user to suit his particular situation.

TABLE 4-7. SYSTEM WEIGHTS

Utility measure	Central	Hierarchical	Network
1. Reliability	28	28	28
2. Maintainability	23	23	23
3. Installation ease	16	15	14
4. Invulnerability to damage	9	10	10
5. Procurement ease	9	9	9
6. System expansion ease	6	8	10
7. Monitoring capability	9	7	6
	100	100	100

Note that a separate column of weights has been provided in Table 4-7 for each of the system architectures (central, hierarchical and network). The weights are identical for all architectures in the case of utility measures 1, 2, 4, and 5. They vary slightly from architecture to architecture in the case of utility measures 3, 6, and 7. For example, in the case of utility measure 7 (monitoring ability), the network architecture is not designed with system monitoring as a strong requirement. As a matter of fact, the network type of system might not even have a central location where monitoring could be accomplished. Thus, monitoring capability does not have the same importance in the case of networks as it does in the case of a central architecture.

Each of the utility measures shown in Table 4-7 is discussed below. The measures and their relative weights were chosen after careful consideration of all factors which contribute to the attainment of the communications system objective.

Utility Measure 1: Reliability

This attribute is a function of engineering design. It describes the designed-in ability of the communications system to maintain its functional integrity, i.e., to resist disruption of the communication link and to transmit the required data with a low error rate.

Utility Measure 2: Maintainability

A system which possesses characteristics which lend themselves to simple maintenance procedures receives a higher score for this utility measure than one which requires specially trained personnel or frequent preventive maintenance.

Utility Measure 3: Ease of Installation

This utility measure places a high value on characteristics which permit simple installation procedures within reasonable physical confines. Compactness and economy of special installation equipment requirements are typical highly valued characteristics.

Utility Measure 4: Damage Invulnerability

This utility measure depends on the system's ability to withstand malfunction due to causes other than those related to design; e.g., vandalism, hostile physical environment or rough handling.

Utility Measure 5: Ease of Procurement

This utility measure places a premium on the use of system equipment which is available from multiple sources within reasonable schedule. Correspondingly, systems using equipment manufactured by a single source receive lower ratings.

Utility Measure 6: Ease of Expansion

This utility measure provides the ability to distinguish between systems which allow expansion with a minimum of disruption and modification, and those which do require modification of equipment or software procedures when expansion takes place.

Utility Measure 7: Monitoring Capability

This utility measure describes the characteristics of communication systems which lend themselves to ease of monitoring. Some, for example, include digital timing systems which allow periodically performed equipment functions to be easily checked.

4.6.4.3 Compliance Factors for the Utility Model

To arrive at a system utility, a "compliance factor" ranging in value from zero to ten is estimated for each utility measure, on the basis of the known characteristics of the system. The sum of the products of utility measure weights and compliance factors is the system utility. The model has been constructed so that values for the system utility can range from 0 to 1,000.

A value of zero compliance indicates that the system has no capability in the desired area. A compliance factor value of ten is assigned if the subject system is "perfect" in the desired area.

In assigning compliance values, candidate system configurations are fixed at the outset, and it is not permissible to add utility to a given systems capability in some area by providing additional equipment refinements, even if the costs are modified correspondingly.

4.6.4.4 Candidate System Utility/Cost Analysis

Six candidate communication systems were described in Sections 4.3.1, 4.3.2, and 4.3.3. These were related to architecture in the following way:

Architecture	Candidate communication system
Central	FDM leased-lines or owned-lines
	TDM leased-lines or owned-lines
	Fiber optics cable
	Coaxial cable
Hierarchical	TDM leased-lines or owned-lines
	Air path optics
Network	TDM leased-lines
	Air path optics

Each of the candidate systems was subjected to a utility/cost analysis as described in Sections 4.6.2 and 4.6.3 above. Compliance values for each of the utility measures are shown in Table 4-8, and the system utilities (product of utility measure weight and compliance factor) and utility/cost ratio for each system are shown in Table 4-9.

System costs in this analysis are expressed in terms of present worth cost of ownership, i.e., the sum of initial capital costs and the present worth of yearly maintenance and operation costs over the system lifetime. The costs used in the analysis are those shown in Table 4-3.

As noted earlier, these examples are intended for illustrative purposes only. Because the costs and utility values are highly sensitive to the particular assumptions made for these examples, the results should not be used as an indication of relative merit for the communication methods examined.

TABLE 4-8. COMPLIANCE FACTORS FOR CANDIDATE SYSTEMS

Utility measure	Central						Hierarchical			Network	
	FDM		TDM		Fiber opt	Coax	TDM		Air opt	TDM	Air opt
	Leased	Owned	Leased	Owned			Leased	Owned			
1. Reliability	5	8	4	8	8	8	5	8	7	5	7
2. Maintainability	8	6	7	5	7	8	8	6	7	8	7
3. Installation ease	8	7	7	6	7	9	7	6	8	7	8
4. Invulnerability to damage	8	8	8	8	7	7	8	8	7	8	7
5. Procurement ease	9	9	8	8	6	7	8	8	4	8	4
6. System expansion ease	7	5	6	5	8	8	6	5	8	6	8
7. Monitoring capability	5	5	9	9	9	9	9	9	9	9	9

TABLE 4-9. CANDIDATE SYSTEM UTILITIES

Utility measure	Central						Hierarchical			Network	
	FDM		TDM		Fiber opt	Coax	TDM		Air opt	TDM	Air opt
	Leased	Owned	Leased	Owned			Leased	Owned			
1. Reliability	140	224	112	224	252	224	140	224	196	140	196
2. Maintainability	184	138	161	115	184	184	184	138	161	184	161
3. Installation ease	128	112	112	96	144	112	35	30	40	105	120
4. Invulnerability to damage	72		72		63	63	72		63	72	63
5. Procurement ease	81		72		54	63	72		36	72	36
6. System expansion ease	42	30	36	30	48	48	46	40	64	48	64
7. Monitoring capability	45		81		81	81	72		72	72	72
Total	692	702	646	690	826	775	623	648	632	693	712
Costs ($K)	1086	1252	904	1023	1106	1245	110	290	72	234	210
U/C ratio	.64	.56	.71	.67	.75	.62	5.7	22	8.8	3.0	3.4

SECTION 5

SUPPLEMENTARY REFERENCE MATERIAL

This section contains the following detailed supplementary material which is referred to in Sections 2, 3 and 4:

- Vehicle detector data processing and communication (subsection 5.2).
- Function block diagrams depicting successive operations on basic traffic control functions (subsection 5.3).
- Computation of number of drops allowable in a multipoint circuit for various communication methods (subsection 5.4).
- Effects of annual increases in leased channel rates (subsection 5.5).
- Computation of cable cost for situations where such cost is proportionately high (subsection 5.6).
- Information Flow Diagrams (subsection 5.7).
- Discussion of Distributed Processing (subsection 5.8).

5.1 INTRODUCTION

This section provides a convenient location for material pertaining to Sections 2, 3 and 4 which is too detailed for convenient inclusion in those sections. This material is summarized in the following paragraphs.

Subsection 5.2, "Vehicle Detector Data Processing and Communication", analyzes vehicle detector data sampling and smoothing, and discusses the effects of these processes on traffic control and communications. The general features of traffic control systems are discussed as well as the effects of various detector data processing methods.

Subsection 5.3, "Function Block Diagrams", shows the type of information that is transferred between various system elements in three representative traffic control systems. The diagrams depict successive operations on basic traffic control functions as the signals representing these functions traverse the communication paths and processing elements within each system.

Subsection 5.4, "Multipoint Network Computations", provides examples of how to compute the number of points on a multipoint communication circuit as a function of multiplexing method and amount of information to be transmitted.

Subsection 5.5, "Effects of Leasing Cost Increases", shows how various annual increases in leased channel rates affect present-worth cost estimates. Computation examples are provided, as well as the derivation of the formula used.

Subsection 5.6, "Cable Cost Computation", provides three examples of cable cost computations. This computation procedure would be used in situations where cable cost is a high proportion of total cost, as, for example, in systems using unmultiplexed direct current switching as the communication method.

Subsection 5.7, "Information Flow Diagrams", shows the information flow processes leading to the selection of the controller timing patterns for typical systems having centralized and distributed processing types of architecture.

Subsection 5.8, "Distributed Processing", discusses distributed processing forms of computerized traffic control, with emphasis on those characteristics which affect communications.

5.2 VEHICLE DETECTOR DATA PROCESSING AND COMMUNICATION

5.2.1 Introduction

This subsection analyzes vehicle detector data sampling and filtering (smoothing) and discusses the effects on traffic control and communications. The general features of traffic control surveillance systems are described first to provide background and perspective, and then the effects of various detector data processing methods are discussed. The results of this analysis may be used as an aid in selecting an overall communication approach.

5.2.2 Traffic Control Surveillance System Features

Vehicle detectors are used throughout the area covered by the traffic control system to provide information on traffic activity, and the outputs of these "system" detectors are used by the traffic control computer to provide traffic responsive control.

The vehicle sensors (loops or other devices) for these system detectors are normally placed 200 to 300 feet** upstream of selected intersections in one lane (or more) of the roadway.* The sensor or detector output is thus a measure of traffic conditions on the road in one direction. Its output vehicle count is often multipled in the computer by a factor (based

*Detectors associated with actuated controllers are not normally included as part of the traffic control surveillance system, and their outputs are therefore not usually connected to the traffic control computer.

**1 ft = 0.3048 m

on traffic history) to estimate the actual traffic count on all lanes. Also, the length of time that each vehicle remains over the sensing loop (presence time) is assumed to be representative of the presence times of vehicles on the uninstrumented lanes (after adjustment based on historical data). Where accurate counts and presence times are required, as at the intersection of two main arterials (critical intersection), all lanes on all approaches may be instrumented with detector loops. Pairs of loops spaced about 15 feet (4.5 m) apart may also be used where accurate speed and/or vehicle length measurements are required (e.g., on freeways).

The digital computer receiving the vehicle detector output or its transmitted replica (either at the intersection or at another location) measures the presence time by continually sampling (AND-gating) the detector output at regular intervals of time, typically 8 to 32 times per second. This sampling operation also determines the vehicle count by noting when the string of sample pulses from the AND-gate either starts (start-of-vehicle signal) or ends (end-of-vehicle signal).

The string of sample pulses represents various vehicle presence times with varying degrees of accuracy, since the measured value must be in increments of the sampling interval (e.g., 1/8-second to 1/32-second). Therefore, it is necessary to determine the effects of this error on the overall traffic control pattern selection process in order to determine an optimum sampling rate; that is, a rate which is high enough for the required accuracy, but not so high as to unnecessarily burden the communication system. This pattern selection process employs vehicle occupancy (which is directly related to presence time) and volume as the input variables.

5.2.3 Factors Affecting Surveillance Data Accuracy Requirements

The number of bits required for transmitting surveillance data is affected by system design decisions as well as by errors inherent in the vehicle detection process. The system design decisions include:

- The degree of detectorization, which has a bearing on the uncertainty of vehicle counts and presence times in uninstrumented lanes as well as the loss of information due to turning movements and parking for uninstrumented blocks.
- The value of the smoothing constants chosen for occupancy and volume, which reduce errors as their value is decreased ("time-constant" increased).

The inherent inaccuracies of the vehicle detection process (other than detector sampling error) include:

- Variability of total traffic count and presence time for all lanes in relation to measured-lane traffic.
- Variability of vehicle lengths in relation to the value selected as "average" length.
- Amount by which vehicle is off-center over loop, which can cause short presence time.
- Stray pickup from adjacent lanes.
- Characteristic of vehicle (width, shape, clearance, materials) which affect the amount of change in loop inductance.
- Difference between rise-time and fall-time of detector output.
- Variations due to temperature or moisture.
- Variations due to differences in loop installation geometry, etc.
- Detector electronics unit-to-unit variations.

The error in both volume count and vehicle presence time resulting from the above sources* can be large and not easily estimated for a particular city. Therefore, the total error allowable for the sampling and smoothing process is normally designated on the basis of system experience, and a standard deviation value of one percent full scale with zero mean value has generally been accepted as adequate for both volume and occupancy. The error budget for the other surveillance quantities (speed, delay, and number of stops) may be larger, since these quantities are not used as part of the traffic control process, but only for display and historical data recording purposes.

*These errors may be characterized as bias or random errors, where a bias error is considered to be one that remains constant or varies slowly relative to the time over which it is averaged. Some bias errors can theoretically be compensated for in the processing algorithms, but such compensation has not generally proven to be practical.

5.2.4 Errors Resulting from Sampling and Smoothing

The way in which errors in presence time (or occupancy) affect communications* depends on several factors. These are:

- The length of the period between surveillance messages (polling period).
- The period over which the data is averaged before being filtered (averaging period).
- The constant selected for the data smoothing (filtering) algorithm.
- The location at which the data smoothing occurs (at intersection or at central computer).

Once these factors are known, then the number of bits per second (per detector) that must be transmitted can be computed. As shown in Appendix A, the effects of the first three of these factors on the number of bits that must be transmitted can be expressed by the following equation:

(Equation A-25): $$J = \frac{T_1}{(2^n - 1)} \sqrt{\frac{Kq'}{6T_2(2 - K)}}$$

where

J = Standard deviation of occupancy error.**

T_1 = Surveillance message transmission period (polling period) in seconds. This is also the period during which $2^n - 1$ samples are taken.

T_2 = Surveillance data averaging period (before filtering) in seconds.

n = Number of bits in occupancy message (binary number representing up to $2^n - 1$ samples).

K = Filter (smoothing) constant.

q' = Volume in vehicles per second.

Using values of T_1 = one second, T_2 = 60 seconds, $K = 0.5$ (worst case), and $q' = 2000$ vehicles per hour (worst case) in this equation, the standard deviation of occupancy error

*Such errors are not significant for FDM and DCS communication techniques, since sampling and smoothing occur after data transmission; therefore only TDM methods are analyzed.

**Vehicle occupancy rather than vehicle presence is used in the remainder of this analysis in order to be consistent with the terminology in Appendix A. These two terms are equivalent except for a constant factor.

is less than one percent for a 3-bit occupancy message. This indicates that a sampling rate of 7 times per second is satisfactory for the assumed values of T_1 and T_2. (In practice, a sampling rate of 7.5 samples per second derived from the 60 Hz power line would be used.)

To show how other values of polling period affect the number of bits that must be transmitted per unit time, the technique of Appendix A is used to obtain the number of bits transmitted for occupancy (or presence), n, plus volume count, n', to achieve the same accuracy as for the above example. The following equations (A-28), (A-29) and (A-30) are used to obtain values of T_1 corresponding to integral values of n; to obtain values of n' corresponding to these computed values of T_1; and, to determine the data rate, R.

(Equation A-28): $S = \frac{T_2}{T_1}(2^n - 1)$

(Equation A-29): $T_1 q_M \leq 2^{n'} - 1$

(Equation A-30): $R = (n + n') \times T_2/T_1$

where:

S = Number of detector samples taken during the T_2 period.

q_M = Maximum lane volume allowable (taken as one vehicle per second in the following examples).

Table 5-1 shows the data rates required for several values of T_1 to achieve a standard deviation of random occupancy error of less than one percent as in the previous example. The value of T_1(max) is obtained by first determining the value of S for the original case ($T_1 = 1$, $T_2 = 60$, and n = 3) and then substituting integral values of n in the first equation. That is, $S = 60/1 \times (2^3 - 1) = 420$, $T_1 = 60/420(2^n - 1)$. The values for T_1 are the next lower integral value that is divisible into T_2. The value of n' is obtained for each value of T_1 in the second equation by using $q_M = 1$ and determining the nearest value of n' that is greater than $T_1 q_M$.

TABLE 5-1. DATA RATE AS A FUNCTION OF POLLING PERIOD, T_1

Number of occupancy bits, n	Polling period T_1 (sec)		Number of volume bits, n'	n + n'	Data rate	
	Max.	Usable			(Bits per T_2 period per detector)	(Bits per second per detector)
3	1	1	1	4	240	4
4	2.2	2	2	6	180	3
5	4.4	4	2	7	105	1.75
6	9	6	3	9	90	1.5
7	18	15	4	11	44	0.73
8	37	30	5	13	26	0.43
9	74	60	6	15	15	0.25

This table shows that as the polling period is increased, the required communication data rate drops rapidly until at a polling period of 60 seconds, which is typical for distributed processing systems, a data rate of one-quarter of a bit per second per detector for both presence (occupancy) and volume is sufficient. Even at the 2-second and 4-second polling rates, the required data rates are reduced considerably; and as indicated in Appendix A, such polling rates should be considered for central type systems if a communication cost savings results, since the cost of the additional bits of integrated circuit accumulator and shift register hardware at the communications interface is insignificant.

The effects of other changes in variables can be deduced from the Appendix A equations. For example, equation (A-25) indicates that if the averaging time, T_2, is increased, the error decreases as the square root of T_2, and if the value of the smoothing constant, K, is increased, the error increases somewhat less than the square root of K.

If the value of n is reduced below 3, giving a detector sampling rate of $2^2 - 1$ or 3 samples per second (for $T_1 = 1$ second), then a problem arises in that the gap between closely spaced vehicles may be missed by the sampling pulse. With loop detectors, in particular, the vehicle lengths are effectively increased by the loop's finite along-street dimension (usually six feet - 1.8 m) so that, for example, vehicles spaced 10 feet** apart and traveling 20 miles per hour (32 km/hour) will produce a time gap of 0.14 seconds.* Such a gap

*Headways producing time gaps of this amount (or less) have been observed to occur in a significant fraction of vehicular traffic especially at high volumes (e.g., 13 percent at 1,400 vehicles per hour in one study).

**1 ft = 0.3048 m

would always be sampled at a 7.5 sample-per-second rate (0.133 seconds per sample), while it would be missed by many sample pulses at a 3 sample-per-second rate (0.33 seconds per sample). Therefore, 7.5 samples per second is considered to be a minimum practical loop detector sampling rate. This rate is also sufficient to avoid missing short, high-speed vehicles, namely, 10-foot (3 m) vehicles at 80 feet per second (24 m/sec).

In traffic control systems using distributed processing architecture, additional detector data processing beyond computation of volume and occupancy is often performed at the intersection, and the results transmitted to the central or master computer. This processing normally includes computation of average speed, number of vehicle stops, and total vehicle delay time during the polling period (typically one minute). The number of bits required for transmitting these quantities can be determined by establishing a required resolution (such as one percent of full scale) or a maximum value of the quantity and then assigning a sufficient number of bits to provide the degree of resolution required (e.g., for one percent resolution, a 7-bit binary number representing $2^7 - 1 = 127$ quanta would suffice).

For the <u>average speed</u> of vehicles measured during the computation period (say one minute), a total of 7 bits would be required for transmission, assuming a maximum speed of 63 mph (100 km/hr) and a required resolution of 0.5 mph (0.8 km/hr).

For a one-minute accumulation of <u>stops</u>, the maximum value would be 60 vehicles, assuming a maximum of 3,600 vehicles per hour, and therefore, a 6-bit binary number could be transmitted to represent this quantity (i.e., $2^6 - 1 = 63$).

For a one-minute accumulation of total vehicle <u>delay time</u>, the number of bits required for transmission is determined as follows:

- The resolution for the least significant bit is assumed to be one second (which has been found empirically to be a satisfactory value).
- The maximum number of vehicles stopped for one minute between the system detector and the intersection is assumed to be 15 (i.e., maximum distance = 15 vehicles x 20 feet (6 m) per vehicle = 300 feet (90 m).

For these conditions, the number of vehicle seconds is 15 x 60 = 900, which requires a 10-bit binary number for its representation (i.e., $2^{10} - 1 = 1,023$).

The surveillance data for such a distributed processing system would therefore consist of at least the following bits transmitted once per minute:

Occupancy	9	From last row in Table 5-1
Volume	6	
Speed	7	
Stops	6	
Delay	10	
Total data bits	38	

If occupancy and volume are filtered in the intersection computer before being transmitted, then the number of bits required for these quantities can be established by resolution requirements (e.g., one percent of full scale). Thus, 7 bits for each quantity would provide the necessary resolution. System design policy might dictate that the unfiltered values of these quantities be transmitted as well as the filtered values in order that the "raw" values be available to the central computer as historical data for computation of new patterns or for other purposes. In this case, the total number of data bits transmitted would be 38 + 14 = 52.

5.3 FUNCTION BLOCK DIAGRAMS

This subsection depicts data communications for three representative existing traffic control systems in terms of block diagrams showing successive functional operations within each major hardware or software element. Three diagrams are included for each system, showing surveillance, controller monitoring, and controller command functions. The text that follows briefly describes the information being transferred, and outlines the operation being performed by the hardware or software element.

5.3.1 New Orleans System

The New Orleans system consists of over 200 intersections and almost 300 detectors. It utilizes FDM communications, with a combination of leased channels and city-owned cable as the communication medium.

5.3.1.1 Surveillance Function

Figure 5-1 is a block diagram of the surveillance function. In this system, the presence of a vehicle is transmitted to central in real time. The passage of a vehicle over the loop changes the inductance of the loop and the detector amplifier detects this change and closes a relay which feeds the communication transmitter. The relay remains closed as long as

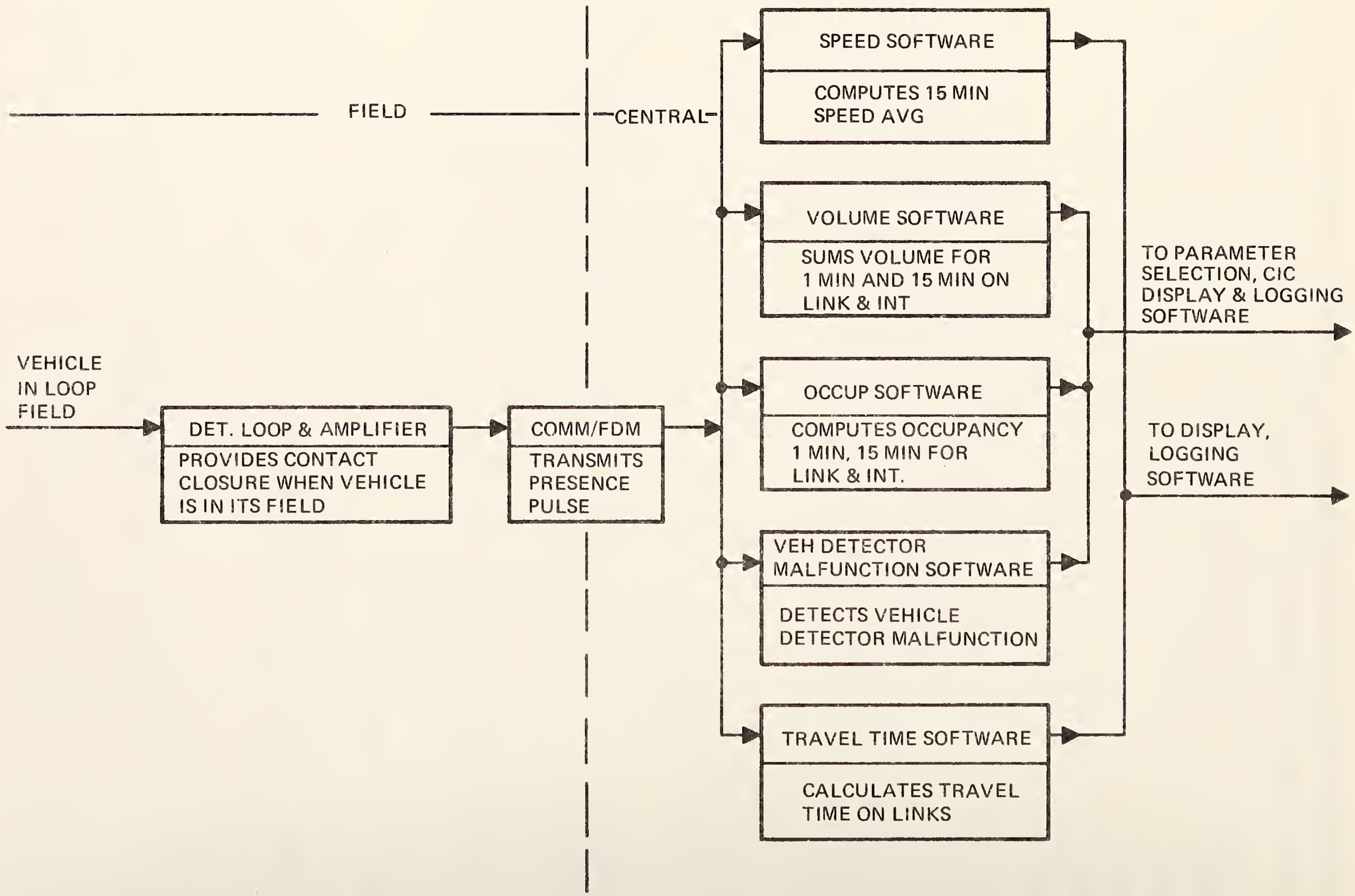


FIGURE 5-1. NEW ORLEANS SURVEILLANCE BLOCK DIAGRAM

the vehicle is in the effective field of the loop. (The transmitter input is a high impedance CMOS device operating from 24 VDC and drawing almost no current.) When the relay closes, the transmitter is keyed, shifting its frequency 60 Hz from its no-vehicle frequency, and remains in this state until the relay opens. The frequency shift is detected by the receiver and results in the turning on of its output transistor. This reproduced presence pulse at central, sampled by computing software 32 times per second, is processed by the software to calculate a 15-minute speed average, volume counts for the link and intersection, occupancy averages for the link and intersection, and travel time.

Other software examines the received data for a lack or excess of counts. If either of these conditions exist, a detector failure is reported.

The volume and occupancy data is used by software to select the optimum traffic pattern and to control the display and logging of the traffic parameters. Speed, detector failures, and travel time is also available for display and logging. Detector failures also effect pattern selection; an excessive number of failures causing the pattern selection function to revert to the time-of-day mode.

5.3.1.2 Controller Monitor Function

Figure 5-2 is a block diagram of the controller monitoring function. Each controller's A-phase green is transmitted to central in real time. The adapter unit transforms the 115 VAC from the load switch to a level compatible with the communications equipment. Software at central compares the received controller's state (A-phase green or not) with the expected state. When a conflict is detected, a failure alarm is activated and the conflict is logged. Additional software is utilized to control the display of the controller's status.

5.3.1.3 Controller Command Function

Figure 5-3 is a block diagram of the controller command function. Command data consisting of hold and advance signals is transmitted in real time from central to each controller. The computer's command software utilizes the volume and occupancy data to select an appropriate traffic pattern whose pattern-change time constant is determined by a variable loaded into the program by the system operator. Critical intersection splits are changed on a cycle-by-cycle basis.

Advance and hold signals are generated in accordance with the selected pattern. The communication interface keys the communications transmitter in response to commands from the computer. Advance and hold signals occurring at a maximum rate of once per second are transmitted over dedicated channels to the appropriate intersections where the

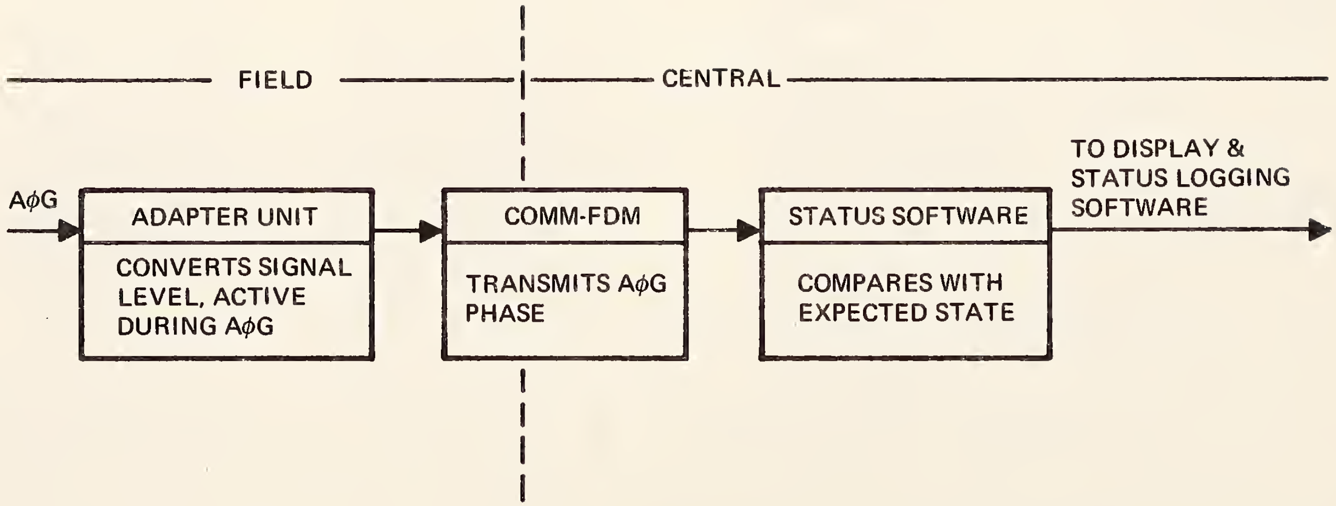


FIGURE 5-2. NEW ORLEANS CONTROLLER MONITORING BLOCK DIAGRAM

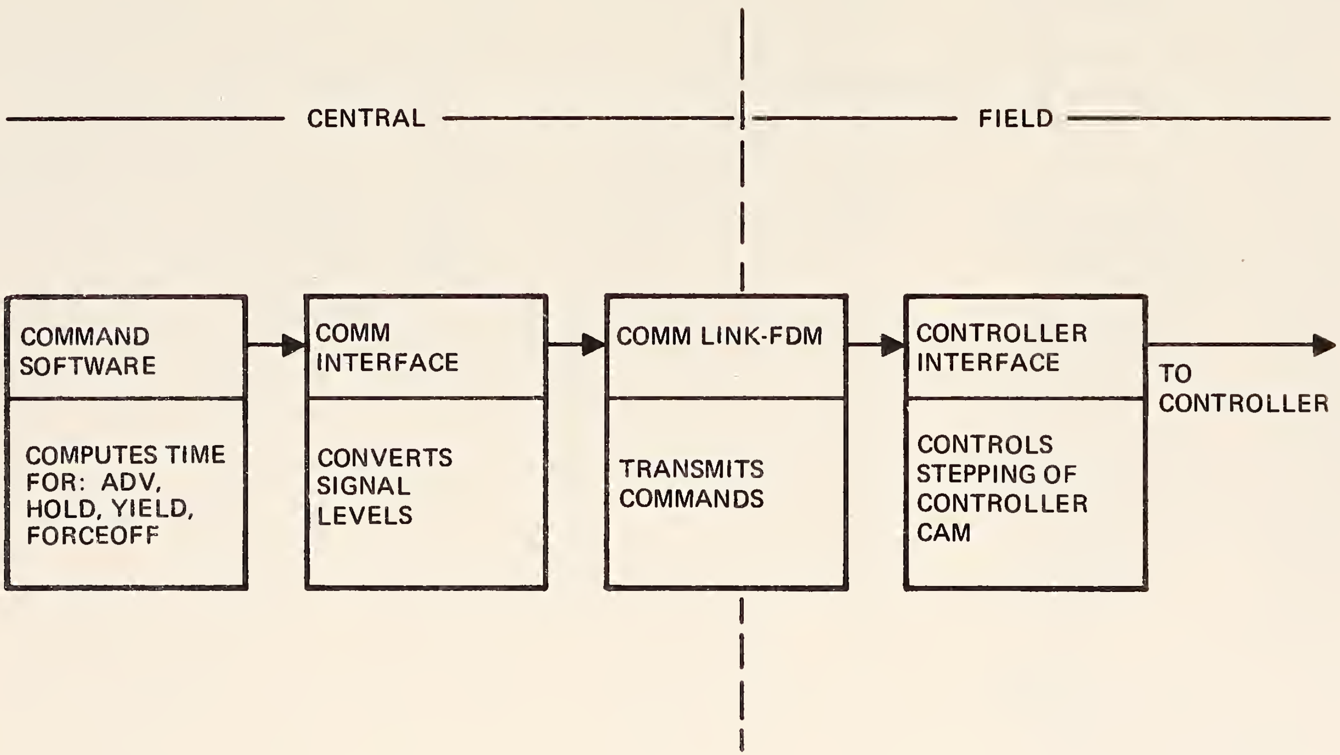


FIGURE 5-3. NEW ORLEANS CONTROLLER COMMAND BLOCK DIAGRAM

receiver demodulates the carrier and interfaces with the controller adapter. Two types of controller adapters are utilized. The "Type A" adapter utilized with pretimed controllers, converts the receiver advance and hold commands to camshaft motor drive signals. The "Type B" adapter, used with actuated controllers, converts the hold and advance signals to the yield and force-off signals required by the controller. Both adapters contain the interface hardware required to key the A-phase green transmitter during the A-phase green period (Figure 5-2).

5.3.2 Bellevue System

The nineteen intersections utilizing the microprocessor type controller and communications modem comprise a hierarchical type system. Each controller utilizes an early generation microprocessor.

5.3.2.1 Surveillance Function

Figure 5-4 is a block diagram of the surveillance function. The detector provides a contact closure as long as a vehicle is in the loop's field. This contact closure initializes and activates an accumulator in the detector monitoring software. The accumulator remains active for the duration of the contact closure, and its contents are transferred to a detector status buffer every second. The contents of the buffer's detector status word is formatted along with other data into a message that is transmitted to central at a rate of once per second. When the vehicle leaves the loop field, the current value of the accumulator is transferred to the detector status buffer and this value, plus any full-second accumulations, represents the period of the vehicle presence. If four or more arrivals have occurred during any one second period, a detector failure is deemed to have occurred and an alarm message is loaded into the status buffer.

The computer interface at central converts the communication output into a format compatible with the computer and generates computer interrupts. Software routines in the central computer check the message for validity and utilize the detector status data to calculate one-minute occupancy average, one-minute volume total, average speed, link stops and delays, and to monitor for detector failure messages. The occupancy and volume values are utilized by the pattern selection software and by the status and display software. The average speed, link stops, delays, and failures are also utilized by the status and display software.

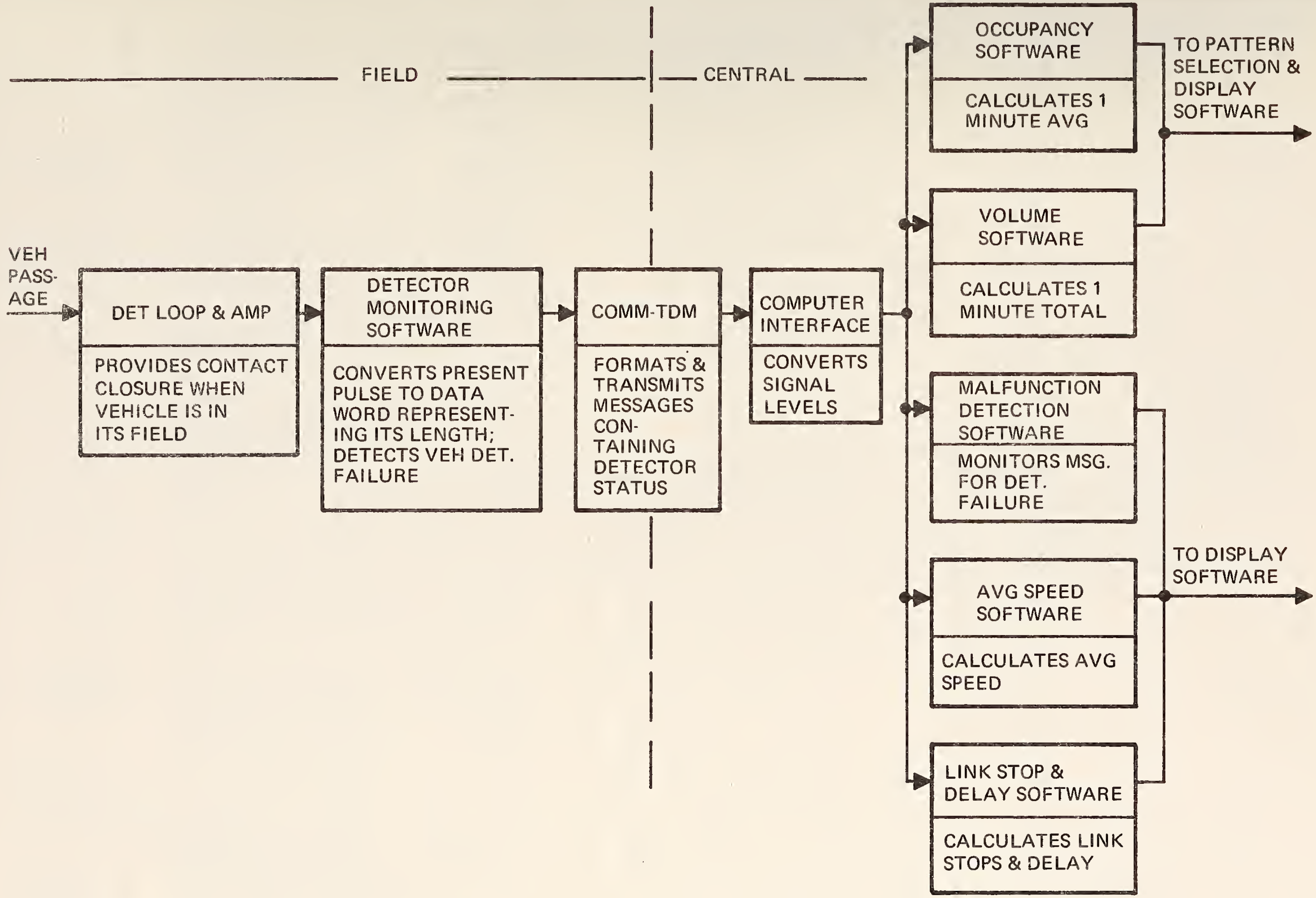


FIGURE 5-4. BELLEVUE SURVEILLANCE BLOCK DIAGRAM

5.3.2.2 Controller Monitor Function

Figure 5-5 is a block diagram of the controller monitoring function. Software subroutines are utilized to:

- Detect errors in incoming messages through a reasonableness check. The reasonableness check is based upon pre-established bounds on the magnitude of control parameters.
- Monitor signal lamp status by monitoring the load switch status of each signal phase and generating an encoded 5-bit message corresponding to the interval number.
- Detect power loss in excess of one-half second.
- Detect a controller malfunction through a self-check routine.

Hardware is provided to detect a green conflict and to monitor the local manual switch and relays for preemption commands, local flash, and one special function. The communication system formats and transmits to central a status message when interrogated at the rate of once per second. The computer interface at central converts the incoming signals to a level compatible with the computer, and generates computer interrupts. Status software decodes the message and checks its validity. The decoded data is utilized by the display, logging and pattern generation software.

5.3.2.3 Controller Command Function

Figure 5-6 is a block diagram of the controller command function. Central computer software is utilized to select the optimum timing parameters based on surveillance data - the pattern change time constant being determined by a variable loaded into the program. These timing parameters are utilized by other subroutines to select:

- Interval update: This software generates the identification number and time duration of each timing interval transmitted to the controller.
- Mode selection: This software provides either coordinated operation, in which timing commands generated by the command software synchronize several intersections (the controller operating non-actuated), or local operation, in which the controller runs independently as an actuated controller.
- Phase sequence: This software selects the sequence of the phases to be displayed. (This function is not utilized in local control.)

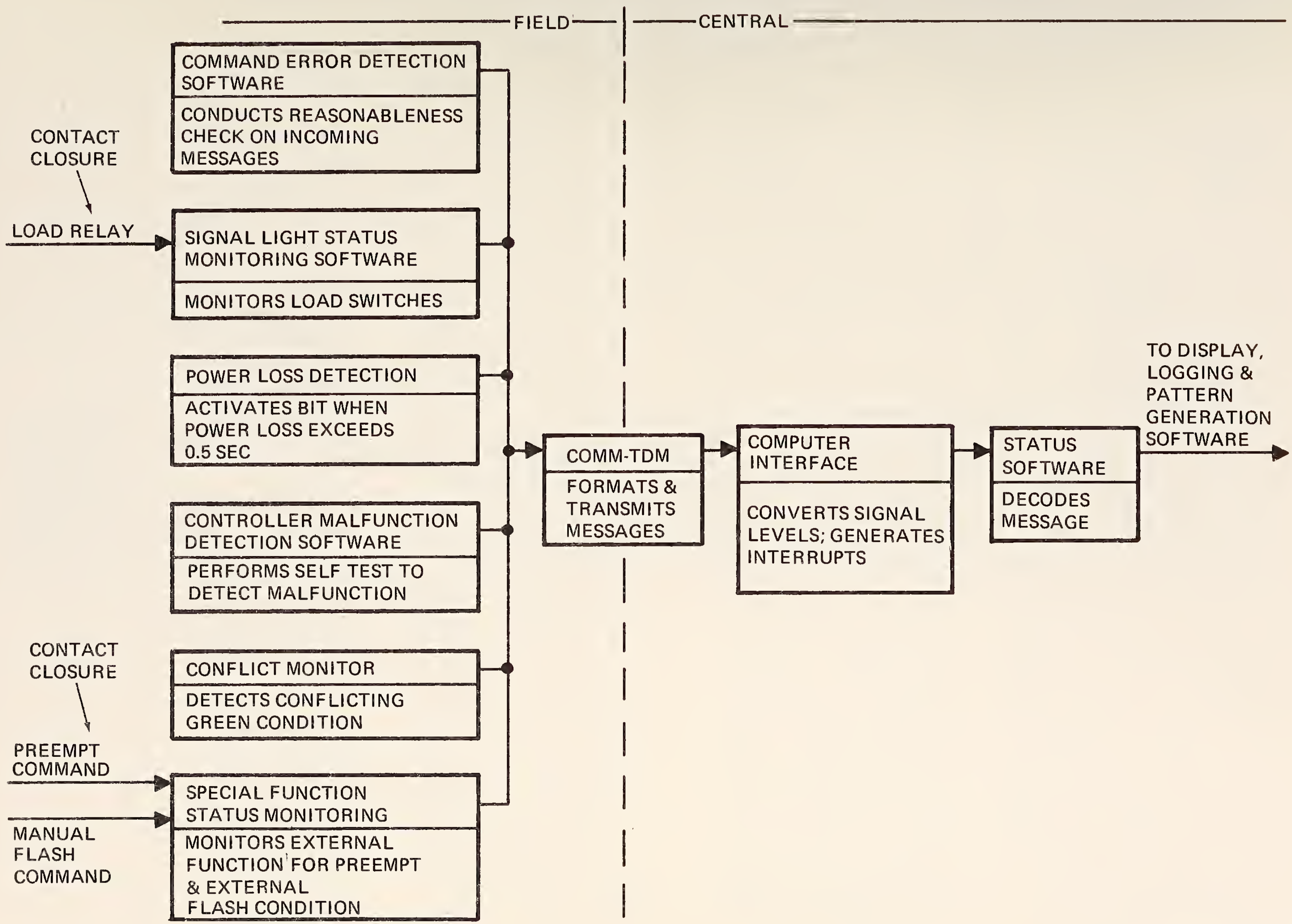


FIGURE 5-5. BELLEVUE CONTROLLER MONITORING BLOCK DIAGRAM

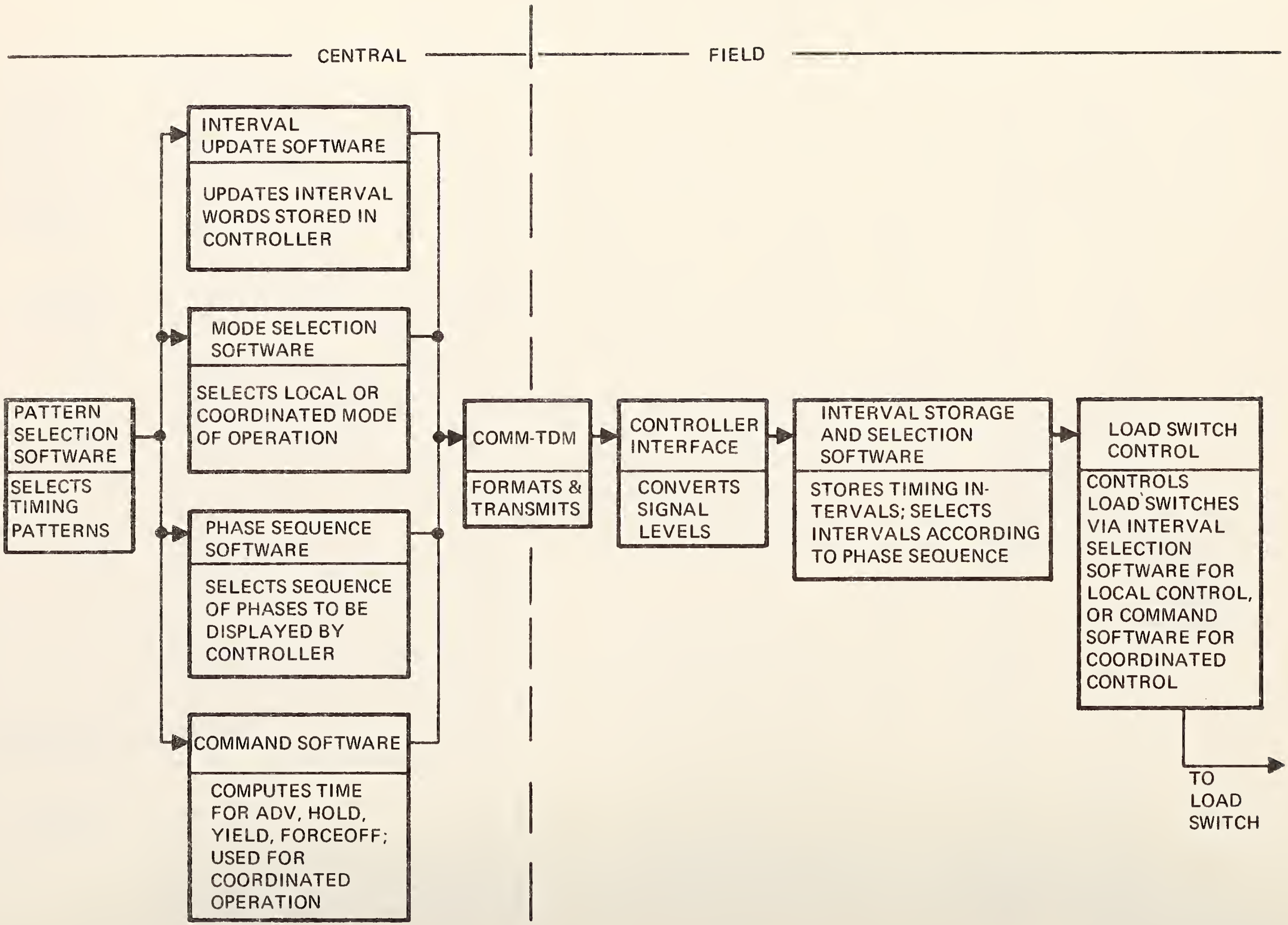


FIGURE 5-6. BELLEVUE CONTROLLER COMMAND BLOCK DIAGRAM

The command messages are formatted and transmitted from central once per second. A controller interface converts the received messages to voltage levels compatible with the controller. Controller software decodes the incoming messages, checks for parity, stores and updates the interval table and selects from the table the next timing interval in accordance with instructions from central. A programmable read-only memory (PROM) is utilized to provide backup timing information in the event that the central computer or communications link has failed. The load switch control function contains hardware and software to activate the load switches in accordance with the timing information.

5.3.3 Seattle (SR-5) System

The SR-5 system is an example of a state-of-the-art microprocessor-based network system. The system currently consists of twenty-five local microprocessor fully-actuated controllers and five local master controllers. Each local master controller has the capability to control a network consisting of ten local controllers. A central processor is utilized for pattern generation status and failure monitoring and display. City-owned cables provide the medium for communication between the local and local master, and leased channels are used between the local master and central.

5.3.3.1 Surveillance Function

Figure 5-7 is a block diagram of the surveillance function. The passage of a vehicle over the loop is detected by the amplifier and results in the amplifier relay closing. Surveillance subroutines sample the detector output 60 times per second. Subroutines are utilized to compute one-minute volume counts and one-minute occupancy averages. A vehicle detector malfunction subroutine is used for failure detection. If excessive counts or no counts have been received for a programmable period of time, a detector failure is deemed to have occurred.

The occupancy, volume and failure status data is formatted into a message and transmitted to its local master once per minute. The local master's communications buffer decodes the message and checks for parity and errors. The decoded data is routed to:

- Occupancy running-average software which computes an occupancy average over a selectable period of from one to fifteen minutes.
- Volume running-average software which computes a volume average over a selectable period of from one to fifteen minutes.
- Failure monitoring software which monitors the message for detector failure reports.

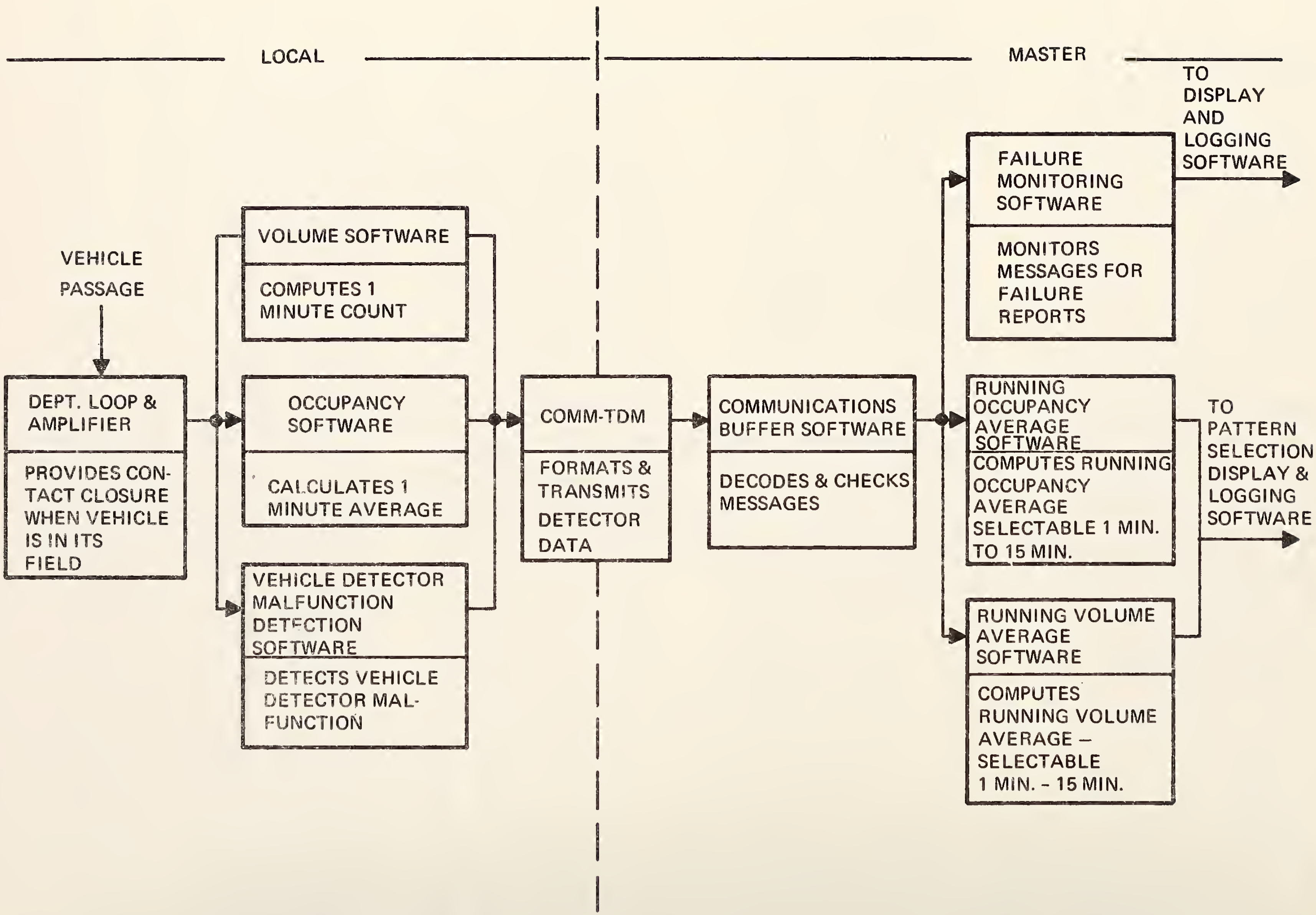


FIGURE 5-7. SR-5 SURVEILLANCE BLOCK DIAGRAM

The outputs from the volume, occupancy and failure software is utilized by the local master to select a traffic pattern and for display. These outputs are also transmitted to central for logging and display.

5.3.3.2 Controller Monitor Function

Figure 5-8 is a block diagram of the controller monitor function. The local controller contains the following software routines used for controller monitoring:

- Lamp failure detection software monitors current sensors connected to each load switch. When the sensed level falls below a programmed threshold, a lamp failure is deemed to have occurred. Appropriate bits are then set in the status word.
- Conflict monitor software monitors an external hardware green conflict monitor and the load switch control software for a green conflict. When a conflict is detected, a preassigned alarm bit in the status word is set. The hardware conflict monitor indicates a conflict by a contact closure to ground.
- Preemption monitoring software monitors external preemption hardware for a preempt condition indicated by a contact closure. When this occurs, the appropriate bits in the status word are set indicating preempt condition by phase, and the controller software executes a preprogrammed preemption pattern.
- Communication failure detection software examines all incoming command messages for proper format, parity, and timing. When a malfunction is detected, the communications failure bit is set in the status word.
- Signal status monitor software monitors the load switches to determine the current phase of the signal. The state of the manual switch and the manual flash relay are also monitored. Appropriate bits are then set in the status word.
- Watchdog timer software continuously triggers a resettable one-shot circuit. Failure to be retriggered indicates a microprocessor failure and causes appropriate bits to be set in the status word.

The communication block formats the status and alarm message, and transmits it over the city-owned cable network to the local master.

The communications buffer software decodes the incoming message and checks for transmission errors. The data is utilized by the local master for pattern selection and display and is retransmitted to central for display and logging.

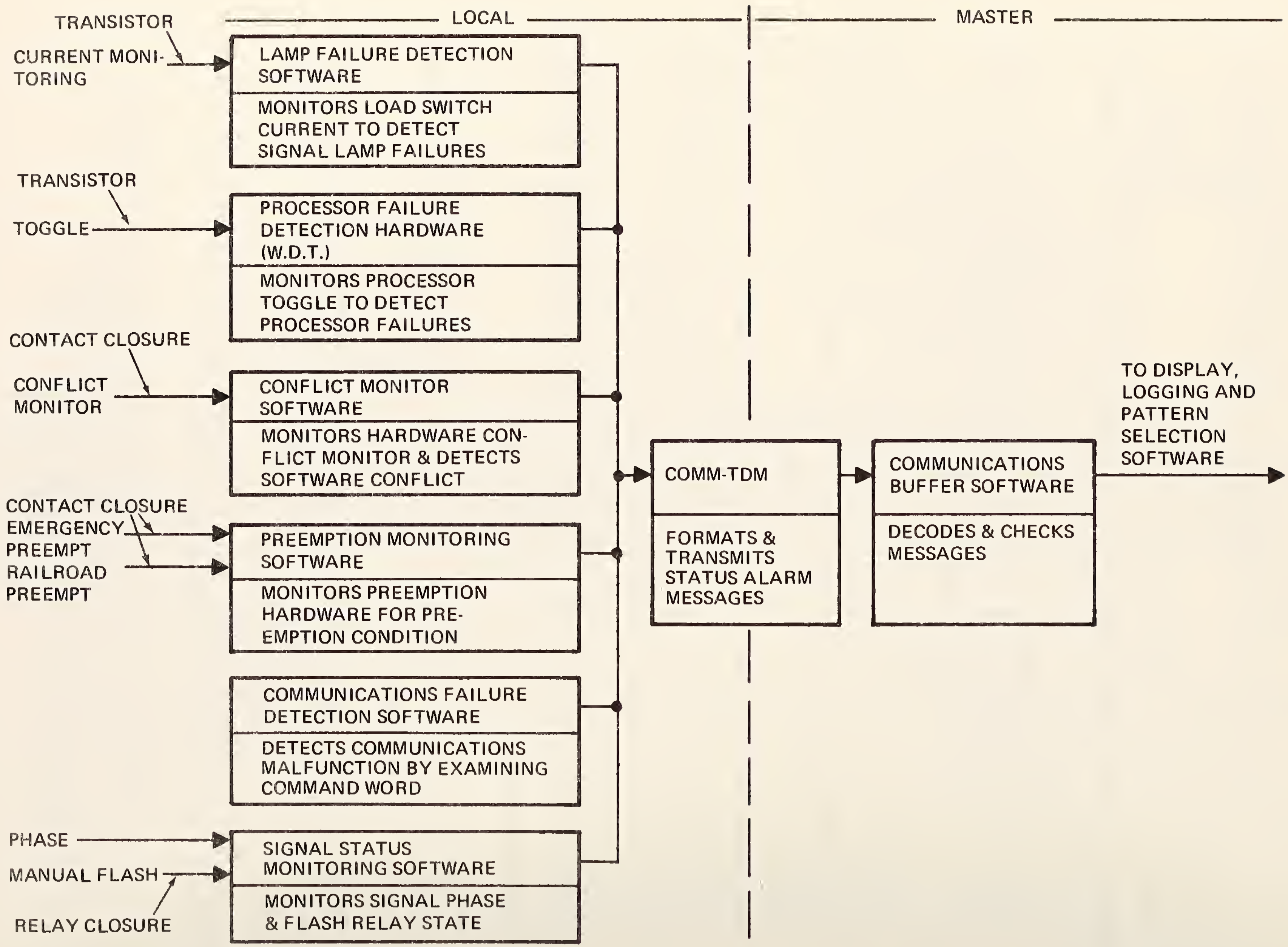


FIGURE 5-8. SR-5 CONTROLLER MONITOR BLOCK DIAGRAM

5.3.3.3 Controller Command Function

Figure 5-9 is a block diagram for the controller command function. The local master has the capability to store ten patterns in its random-access memory (RAM). Each pattern consists of: cycle, offset, sequence, force off and hold, and timing data for each of ten intersections. Three modes of pattern selection are utilized: traffic responsive (TR), time of day (TOD), and manual. In the traffic responsive mode, the pattern selection is based upon the volume and occupancy averaged over the previous one to fifteen minutes. In the time-of-day mode, the pattern selection software selects the appropriate pattern based upon the time of day and day of the week. The time of day is kept by a clock, synchronized to central, which generates sync pulses for the local controllers in its network. In the manual mode, the pattern is selected either via the local master's CRT keyboard interface or via a command from central.

The timing parameters for each local controller are formatted and transmitted over the communication network. A command message is transmitted once per second. A synchronization bit is inserted in the message once each minute.

The local controller's communications buffer decodes and checks the incoming message. If an error is detected by the communications failure-detection software (Figure 5-8), an error message is sent to the local master. The timing pattern is stored in the local controller's RAM and the synchronization bit is used to synchronize the local clock. A backup timing pattern is stored in a PROM. This pattern is utilized when either the local master or communications has failed. The local controller then operates as an independent fully-actuated controller. The timing command generation software generates load-switch control signals in accordance with the stored pattern and vehicle or pedestrian service calls as modified by local preempts.

Load switch control hardware provides the signal level interface between the microprocessor and load switches.

5.4 MULTIPOINT NETWORK COMPUTATIONS

5.4.1 General

To size a communication system it is necessary to know how many data channels or wire pairs are required. These quantities depend upon the multiplexing scheme selected. The following paragraphs illustrate the procedure used to compute the multipoint capability of the wire pair communication methods for which costs are estimated in Section 4.

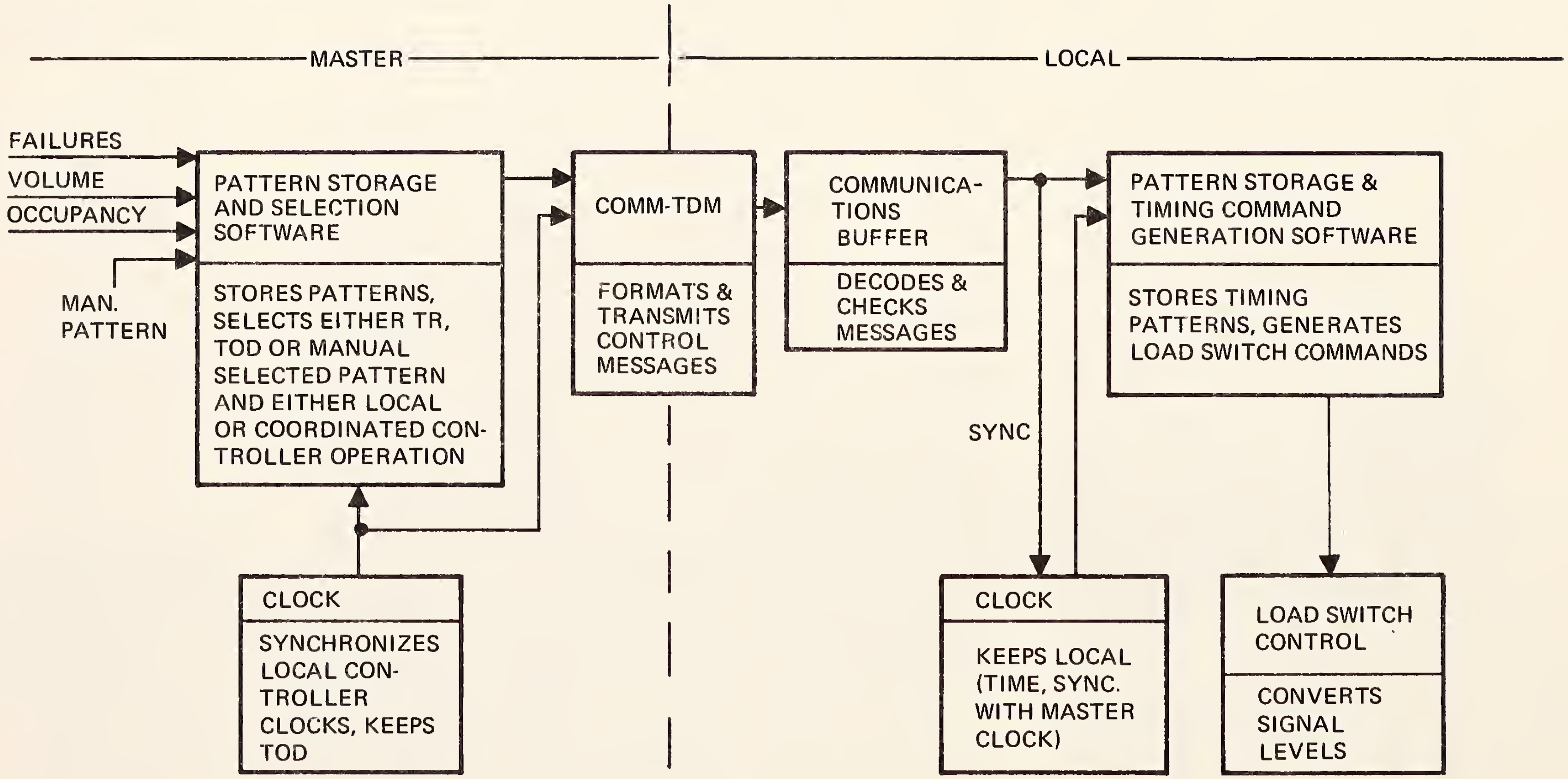


FIGURE 5-9. SR-5 CONTROLLER COMMAND BLOCK DIAGRAM

5.4.2 Central TDM System

For the wire pair TDM configurations examined in Section 4, a 1,200 bit per second TDM system utilizing the three-byte check sum message format is used (two data bytes, one error-check byte). It is assumed that the command message contains four address and four data bits in the first word and eight data bits in the second word.

The controller monitor message has the same format as the command message, with detector messages being appended to the controller monitor message as required. The status of up to two detectors can be transmitted in each message following the monitor message.

The number of messages required for transmission in both directions between the master and local as a function of the number of detectors are listed as follows:

No. of detectors	Number of 3-byte messages
0	2
2	3
4	4
8	6
16	10

Assuming the use of 4-wire full duplex channels, up to 25 messages can be transmitted each second based upon the following calculation: Time for each message = (32 bits/message)/1200 bps plus 10 milliseconds (ms). Request-to-send/clear-to-send (RTS/CTS) remote modem delay, or 30 + 10 = 40 milliseconds per message (25 messages per second).

For an average of two detectors per intersection, three messages are required per intersection, namely, controller command, controller monitor, and detector monitor; thus, an average of 8 intersections can be accommodated on each communication channel, with a once-per-second polling rate.

5.4.3 Distributed Processing (Hierarchical or Network) TDM System

A message structure consisting of 32-bit words with 10 ms RTS-CTS remote modem delays is used for these architectures in the examples of Section 4. With this message structure, a 1200 bps modem can transmit at the following rate:

$$R = \frac{60 \text{ sec/minute}}{32 \text{ bits/1200 bps} + 10 \text{ msec}}, \text{ or 1600 words/minute.}$$

Making the following assumptions:

a. Local to master and master to local words contain 16 data bits, 6 address bits, 1 start and 1 stop bit, 3 control bits, 5 BCH error check bits.

b. The detector monitor word does not contain any address bits, since it always appears in a message containing a controller monitor status word, thus having 22 data bits available.

c. Worst case transmission occurs when a pattern change is transmitted, with the following number of words required:

Master to local	Number of words/minute
2-phase	4
4-phase	5
8-phase	7
Local to master	
2-phase	6
4-phase	7
8-phase	9
Detector monitor	2

As a worst case, if all intersections on a two-pair channel had 8-phase controllers and 16 detectors, the channel could handle 1600/(7 + 9 + 2 x 16), or 33 drops; however, a maximum of 20 drops on two pair will be used in the cost analysis to avoid excessive line loading and difficulty in troubleshooting.

5.4.4 Central FDM System

The following data requirements are assumed:

1 channel per phase

1 channel per advance command

1 channel per hold command

1 channel per detector

A maximum capacity of 18 channels per pair is also assumed.

5.5 EFFECTS OF LEASING COST INCREASES

5.5.1 Computation of Escalated Leasing Cost Estimates

The current cost of leasing communication lines is often used as the basis for a trade-off analysis. In recent years, however, leased-line costs have escalated dramatically in certain parts of the country. While the escalation cannot, in any given instance, be predicted in advance with certainty, it is nevertheless useful for the traffic system designer to understand the trade-offs involved in tariff escalating environments so that he may better formulate his policies.

Figure 5-10 shows the effects of escalating leasing costs and can be used to determine how various increases in leasing rates affect present-worth cost estimates. The curves in this figure show the escalation factor to be applied for various service life assumptions (10, 15, 20 years) and for various expected leasing charge escalation rates (up to 40 percent per year).

As an example of the use of these curves, assume a 15 year service life and a 10 percent interest rate (the values used for all of the computation examples in Section 4) and assume a yearly fractional escalation rate of 0.1 (10 percent per year). Then by noting the point at which the 15 year 10 percent curve (dashed middle curve) intersects the 0.1 yearly escalation rate, it is seen that the corresponding escalation factor on the ordinate has a value of approximately two. That is, the present worth estimate should be double the amount that would be used if no escalation occurred. In the example computation for the centralized leased-line wire pair TDM case (Section 4), the original estimated leasing cost present worth is $214,000, and therefore, this value must be increased to $214,000 x 2, or $428,000, raising the total communication cost from $904,000 to $1,118,000. Similarly,

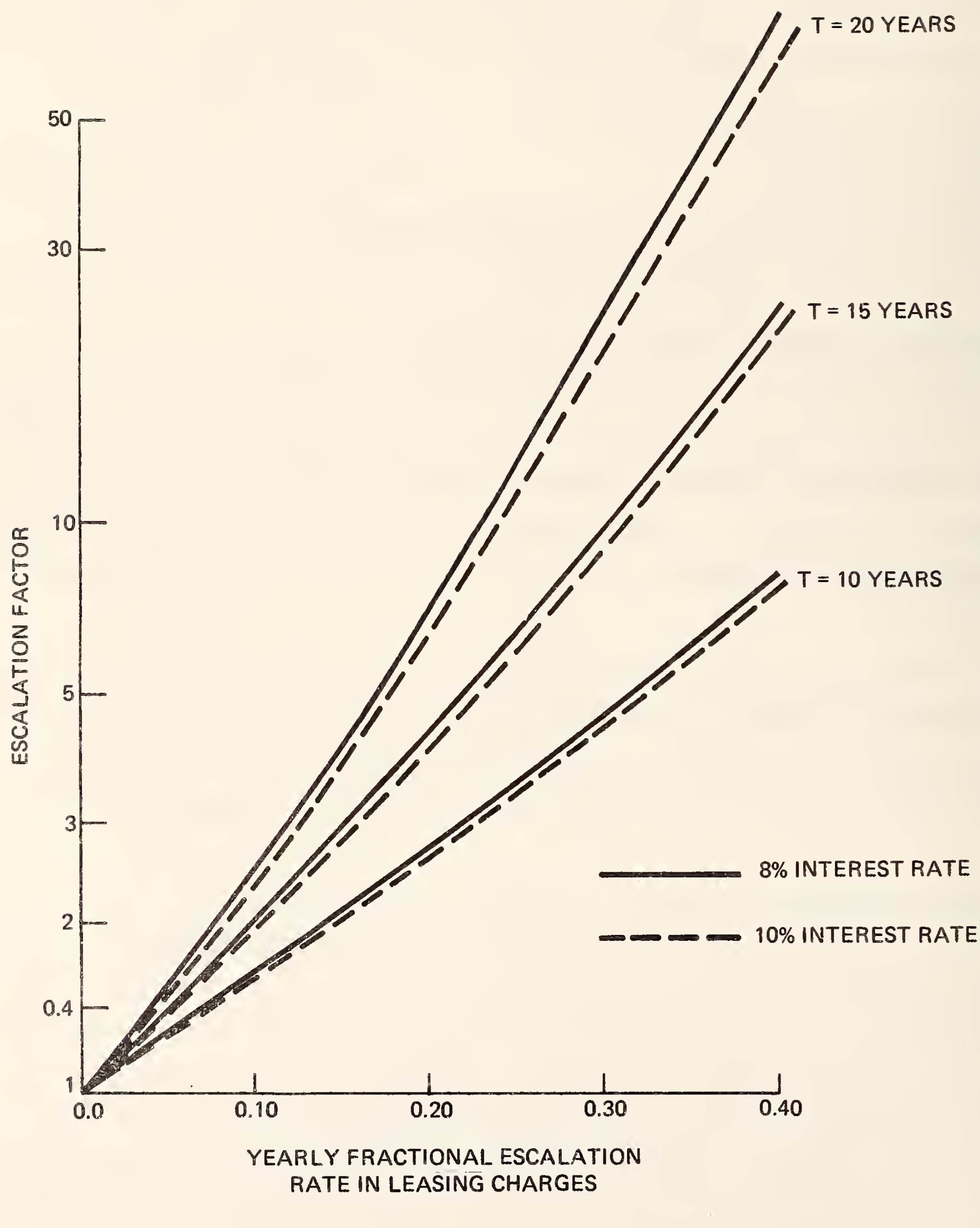


FIGURE 5-10. EFFECT OF LEASING CHARGE ESCALATION

for the centralized TDM case, the leasing rate is doubled from \$158,000 to \$316,000 and the total from \$1,086,000 to \$1,244,000.

With a yearly escalation rate of 0.05 (5 percent per year), the escalation factor is seen to be about 1.4 (using the same curve) and therefore the leasing cost present worth is increased from \$214,000 to \$214,000 x 1.4 or \$300,000, raising the total from \$904,000 to \$990,000. Similarly, for the FDM case, the total is increased from \$1,086,000 to \$1,149,000.

5.5.2 Derivation of Escalation Factor Relationships

The escalated present worth of that portion of the system cost attributable to leasing charges is representable by the equation

$$EP = \sum_{t=1}^{T} \frac{Ct}{(1+i)^t} \qquad (5\text{-}1)$$

where Ct is the yearly leasing cost paid at the end of year t; i is the interest (discount) rate; T is the service life of the system.

If a yearly fractional increase in the leasing rate over the previous year (designated E) is assumed, the leasing cost for year t is

$$Ct = Co(1+E)^t \, . \qquad (5\text{-}2)$$

Substituting 2 into 1 yields

$$EP = \sum_{t=1}^{T} \frac{Co(1+E)^t}{(1+i)^t} \, . \qquad (5\text{-}3)$$

It can be shown that

$$EPF = \frac{EP}{Co} = \frac{\frac{(1+E)^T}{(1+i)^T} - 1}{1 - \left(\frac{1+i}{1+E}\right)} \qquad (5\text{-}4)$$

where EPF is a normalized escalated present worth factor.

The present worth under non-escalation conditions can be obtained by setting E = 0 in equation (5-4). This yields the uniform series present worth factor (uspwf) commonly used in economic studies. An escalation factor can then be defined as equation (5-4) divided by the uspwf or

$$EF = \frac{EPF}{uspwf} = \frac{\dfrac{\left(\dfrac{1+E}{1+i}\right)^{T} - 1}{1 - \dfrac{1+i}{1+E}}}{uspwf} \tag{5-5}$$

This equation is plotted in Figure 5-10 for two different interest rates and three different assumed periods of useful system life.

Equation (5-5) and Figure 5-10 can be used to estimate the equivalent capitalization costs in an environment of increasing leasing rates. They can similarly be used to assess the value of the rate increase which will equalize the leased and owned system costs.

5.6 CABLE COST COMPUTATION

5.6.1 Introduction

This subsection contains a detailed procedure for computing wire pair cable costs using examples of the following types of systems: Central processing architecture with TDM and FDM communications, and hierarchical processing architecture using TDM communications.

This cost computation procedure would only be used for situations where cable cost is likely to be a large part of total communications cost. Otherwise, the simplified procedure given in Section 4 provides sufficiently accurate results.

5.6.2 Central Architecture, TDM Example Computation

To determine the cable cost for TDM communications, the following steps are performed:

a. The cable network is layed out on a scaled map as shown in the example system (Figure 5-11).

b. The intersections are numbered, starting with the outermost branches, and branches and intersections are listed in columns A and B of Table 5-2*. (A branch is defined as a

*Table 5-2 lists some of the intersections for the left side non-CBD area only. Identical tables are used for the remainder of the left side and for the right side non-CBD and CBD areas.

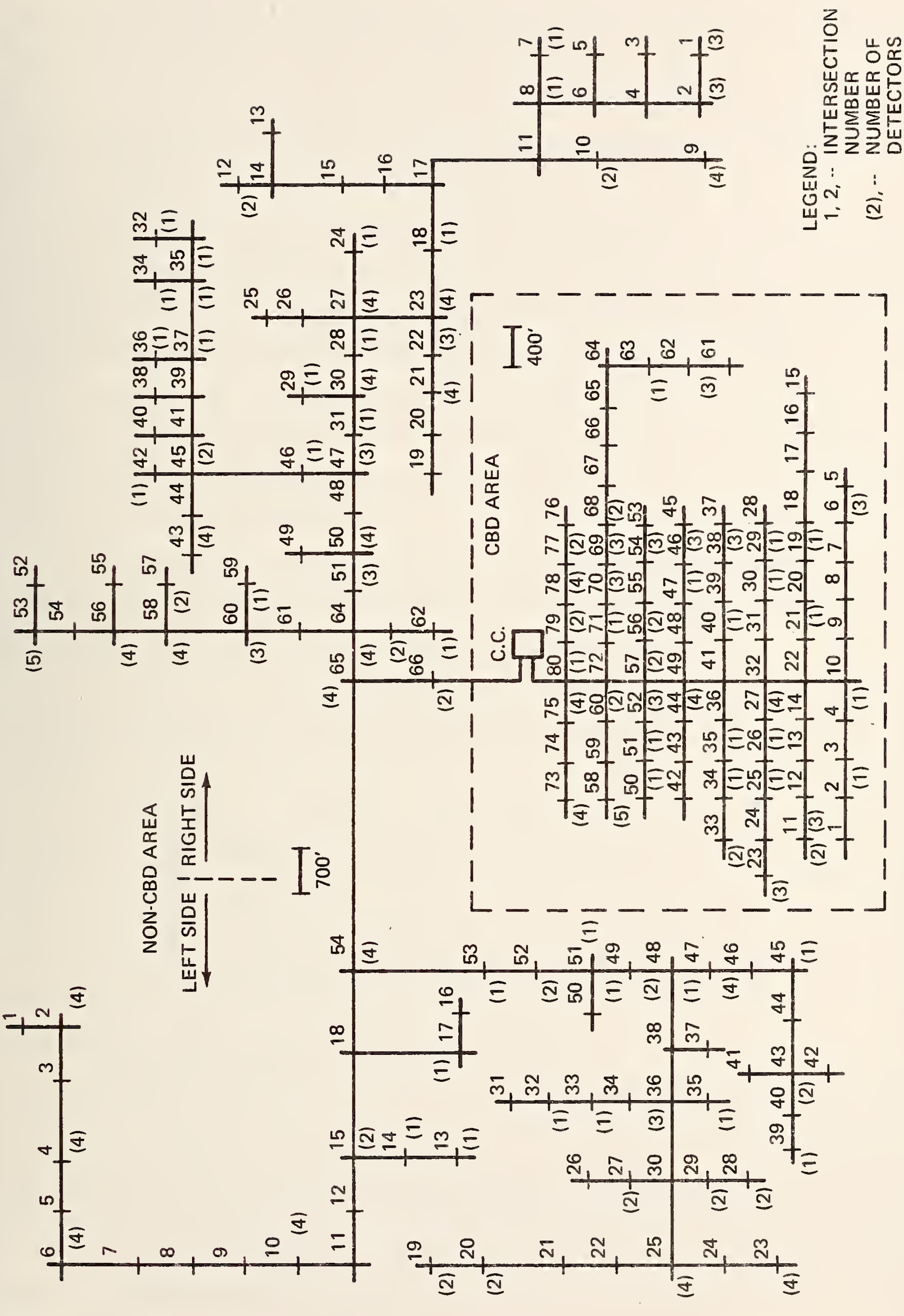


FIGURE 5-11. CENTRALIZED SYSTEM CABLING

TABLE 5-2. CABLE COST DATA (NON-CBD, LEFT SIDE)

A. Branch	B. Inter-section	C. Detector	D. TDM messages	E. Cum. messages	F. Data pairs	G. Total pairs	H. Std. pairs	K. FDM channels	L. Cum. channels	M. Data pairs	N. Total pairs	O. Std. pairs
1	1	-	2	2	2	6	6	3	3	1	5	6
	2	4	4	6	2	6	6	7	10	1	5	6
	3	-	2	8	2	6	6	3	13	1	5	6
	4	4	4	12	2	6	6	7	20	2	6	6
	5	-	2	14	2	6	6	3	23	2	6	6
	6	4	4	18	2	6	6	7	30	2	6	6
	7	-	2	20	2	6	6	3	33	2	6	6
	8	-	2	22	2	6	6	3	36	2	6	6
	9	-	2	24	2	6	6	3	39	3	7	12
	10	4	4	28	4	8	12	7	46	3	7	12
	11	-	2	30	4	8	12	3	49	3	7	12
	12	-	2	32	4	8	12	3	52	3	7	12
2	13	1	3	3	2	6	6	4	4	1	5	6
	14	1	3	6	2	6	6	4	8	1	5	6
	15	-	2	40	4	8	12	3	63	4	8	12
3	16	-	2	2	2	6	6	3	3	1	5	6
	17	1	3	5	2	6	6	4	4	1	5	6
	18	-	2	45	4	8	12	3	73	5	9	12
4	19	2	3	3	2	6	6	5	5	1	5	6
	20	2	3	6	2	6	6	5	10	1	5	6
	21	-	2	8	2	6	6	3	13	1	5	6
	22	-	2	10	2	6	6	3	16	1	5	6
15	54			134	12	16	18		223	15	19	25

list of all intersections on a cable, counting inward toward the control center, up to, but not including, the junction with an uncounted branch.)

c. The number of detectors at each intersection are listed in column C of Table 5-2.

d. The number of messages required at each intersection is determined from subsection 5.4.2 above, and is entered into column D.

e. The cumulative number of messages is determined by summing each branch and adding to the previous sum at each branch junction. These values are entered into column E. (For example, at intersection 15, the junction of branches 1 and 2, the 8 messages of branch 2 are added to the 32 messages of branch 1 to give a total of 40).

f. The number of wire pairs required for data in each segment of the network is determined by using a maximum value of messages per dual pair, and the number is entered into column F. (In this example, a maximum of 25 messages are used.) The 25 message figure is derived in subsection 5.4.

g. A single "order wire" pair (for use with a plug-in field telephone) and at least 10 percent spare pairs (minimum of three spare pairs) are added to obtain the total number of pairs for each segment. This number is entered into column G.

h. The standard cable size (number of pairs) that accommodates the total number of pairs for each segment is selected and entered into column H. (The standard cable sizes contain the following number of pairs: 6, 12, 18, 25, 50, 75, 100, 150, 200, ---.)

i. The total length of each size cable is determined from column I and entered into Table 5-3. In the example, the average intersection spacings are 400 feet (122 m) for the Central Business District (CBD) area, and 700 feet (213 m) for the non-CBD area.

j. The cable costs are computed using cable price figures in Table 5-4, and the results are entered into Table 5-3. The cable cost for this example is $9.7K.

5.6.3 Central Architecture, FDM Communications

The cable cost computation procedure for FDM communications makes use of the basic data listed in Table 5-2, columns A, B, and C, and includes the following steps:

a. The number of FDM channels is computed for each intersection, and consists of three channels for each controller - hold (yield), advance (force-off), and one phase monitor - plus one channel for each detector electronics unit that is located in the intersection cabinet. This information is entered into column K of Table 5-2.

TABLE 5-3. TDM SYSTEM CABLE COST

Std. cable pairs	Cable lengths (K feet)				Cost (K$)[a]
	Non-CBD (left) (table 5-2)	Non-CBD (right)	CBD	Total	
6	28	32	28	88	6.2
12	9	9	2	20	2.0
18	0.7	3.5	1.2	5.4	0.9
25	-	-	0.8	0.8	0.2
50	-	1.4	-	1.4	0.4
					Total 9.7
NOTE: 1000 feet = 305 meters					

[a] 19 AWG, PE-22, Filled

TABLE 5-4. TYPICAL CABLE PRICES[a]

Cable pairs	Unit cost ($/1000-ft.)	Cable pairs	Unit cost ($/1000-ft.)
6	70	75	580
12	100	100	1100
18	170	150	1600
25	230	200	2000
50	310	300	3000
NOTE: 1000 feet = 305 meters			

[a] 1977 prices for #19 AWG, PE-22, filled cable

b. The cumulative number of channels is determined by summing each branch and adding to the previous sum at each branch junction (column L).

c. Using a figure of 18 FDM channels (maximum) per wire pair, the number of pairs required for data in each segment of the network is determined and entered into column M.

d. As in the TDM case, a single order wire pair (for maintenance) and at least 10 percent spare pairs (minimum of 3 spares) are added to obtain the total number of pairs required for each segment, and this total is entered into column N.

e. The standard cable size (see subsection 5.6.2) that accommodates these totals is entered into column O.

f. The total length of each size cable is determined from column O (number of intersections having each size multiplied by the average intersection spacing in that group) and entered into Table 5-5.

g. The cable costs are then computed using Table 5-4, and the results are entered into Table 5-5.

TABLE 5-5. FDM SYSTEM CABLE COST

Cable pairs	Cable lengths (K feet)				Cost (K$) [a]
	Non-CBD (left) (Table 5-3)	Non-CBD (right)	CBD	Total	
6	26	33	28	87	6.1
12	13	7	2	22	2.2
18	-	4.2	0.8	5.0	0.9
25	0.7	1.4	0.8	2.9	0.7
					Total 9.9K
NOTE: 1000 feet = 305 meters					

[a] 19 AWG, PE-22, filled

5.6.4 Hierarchical Architecture, TDM Communications

To determine the cable cost for TDM communications, the following steps are performed:

a. The cable network is layed out on a scaled map (figure 5-12), and the intersections are numbered starting with the outermost branches as for the central system.

b. The branches and intersections are entered into columns A and B of Table 5-6.

c. The number of detectors at each intersection is entered into column C.

d. The number of words per intersection is determined and entered into column D. (For example, at intersection 1, two words are required for the basic intersection data, and four monitor words are required to handle the 12 detectors, giving a total of six).

e. The cumulative number of messages is determined by summing each branch and adding to the previous sum at each branch junction. These values are entered into column E.

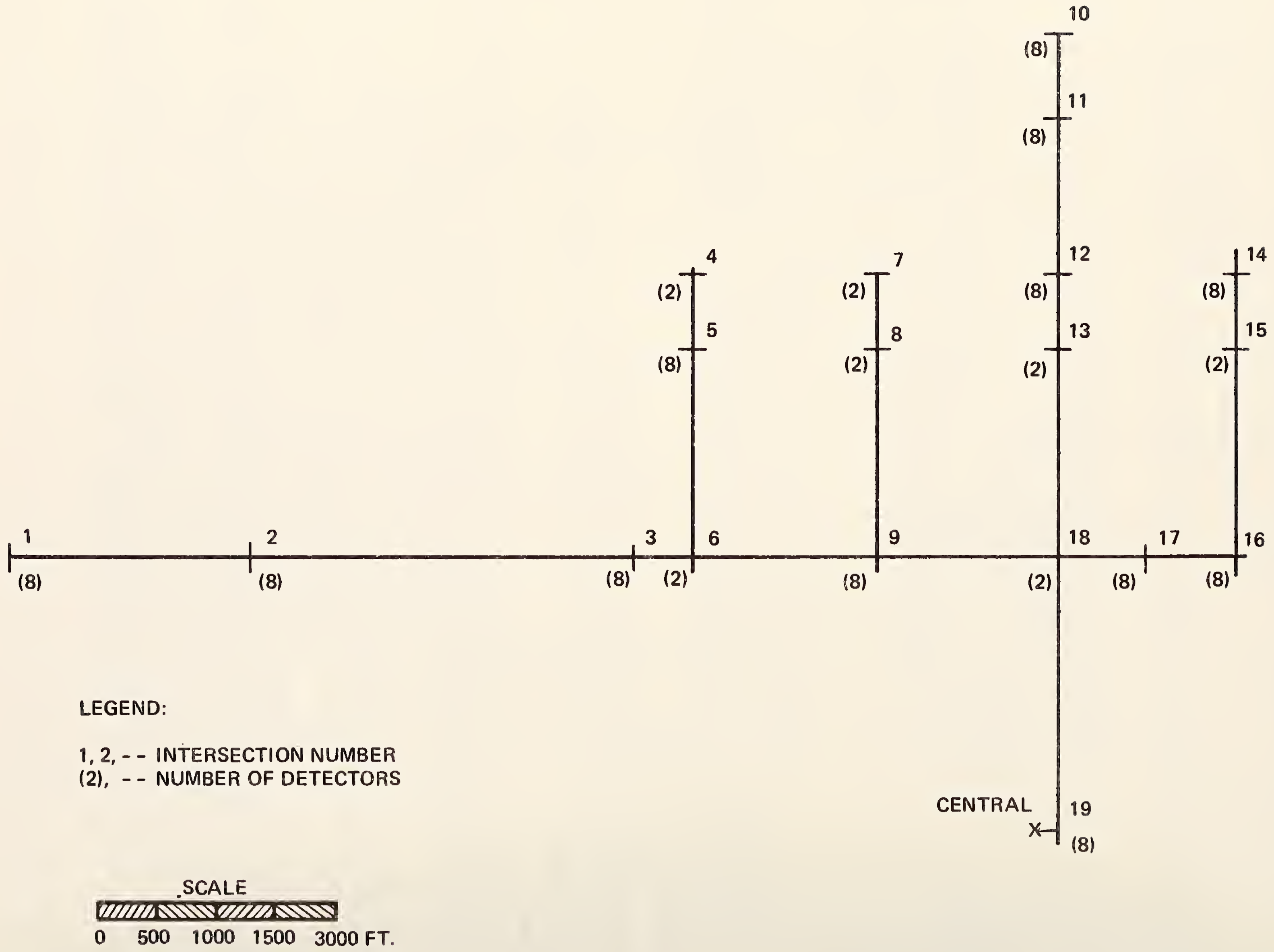


FIGURE 5-12. HIERARCHICAL SYSTEM CABLING

TABLE 5-6. CABLE COST DATA

A. Branch	B. Inter-section	C. Detectors	D. TDM word	E. Qum. word	F. Data pairs	G. Total pairs	H. Std. pairs
1	1	12	6	6	2	6	6
	2	12	6	12	2	6	6
	3	12	6	18	2	6	6
2	4	2	3	3	2	6	6
	5	12	6	9	2	6	6
	6	2	3	30	4	8	12
3	7	2	3	3	2	6	6
	8	2	3	6	2	6	6
	9	12	6	42	4	8	12
4	10	12	6	6	2	6	6
	11	12	6	12	2	6	6
	12	12	6	18	2	6	6
	13	2	3	63	6	10	12
5	14	12	6	6	2	6	6
	15	2	3	9	2	6	6
	16	12	6	15	2	6	6
	17	12	6	21	2	6	6
	18	2	3	24	2	6	6
	19	12	6	93	6	12	12

f. The number of wire pairs required is determined by adding one dual pair for each point requiring more than 28 messages, and entering this number into column F.

g. A single "order wire" pair and at least 10 percent spare pairs (minimum of three spare pairs) are added to the number in column F and entered into column G.

h. The standard cable size that accommodates the total number of pairs is selected and entered into column H.

i. The total length of each size cable is determined from column H and the network dimensions, and the cost is computed using the unit prices in Table 5-4. For this example, the results are:

Cable pairs	Cable lengths (ft)	Cost
6	16,000 (4,877 m)	$1,100
12	7,000 (2,134 m)	700
	Total	$1,800

5.7 INFORMATION FLOW DIAGRAMS

5.7.1 General

A set of information flow diagrams is contained in this subsection which shows the relationship between the communication system and the informational flow process leading up to the selection of the controller timing pattern. These diagrams describe the key functional and system parameters for typical systems having centralized and distributed-processing types of architecture. In each case, the system is assumed to utilize the UTCS first generation software control algorithm.

These diagrams are explained in the following paragraphs. The following listing provides a general definition of many of the symbols used in the diagrams.

Symbols for Information Flow Diagrams

δ_N = spurious noise

C = traffic cycle

K_C, K_T, K_S, K_{SIG}, K_V = constants

U = unity weighted pulse

U_b = unity weighted pulse generated by vehicle b

T = detector sampling time for initial detector sampling device

T_1 = TDM equipment message transmission period (central system)

T_2 = TDM equipment message transmission period (network system)

h = subscript index for cycle-based computations

d = subscript index for 15-minute-based computations

p = subscript index for computations based on T_2 period.

5.7.2 Central System Architectures

Figure 5-13 describes the functional operation of the surveillance and control paths in a typical FDM system.

The traffic detector presence state is described by a logical one or zero. The FDM transmitter communicates this state by a frequency shifted tone over a communication line which is subject to noise inputs δ_N. The FDM receiver demodulates the signal to recover the traffic detector wave-shape (as distorted by noise and line propagation effects). This signal is sampled at a rate T by a multiplexer which is often a portion of the computer equipment. The computer analyzes the signal state changes and provides a signal τ_b which indicates the time period of the presence of a vehicle and a counter index change U_b with each additional vehicle. These signals are accumulated over the period of the traffic cycle C and are each weighted by this value. The indications of raw volume V_h and occupancy ϕ_h which result are used for the following purposes:

a. for historical data accumulation;

b. to compute raw speed S_h;

c. as inputs to first order digital filters.

The digital filters shown are the formulations used in the first generation UTCS software.[1]

The remainder of the computations shown in Figure 5-13 describes how the filtered (smoothed) values of volume and occupancy are used to select the controller timing plans from a prestored set. The computations represent the operation of the UTCS first generation control algorithm.

The filtered occupancy value of each sensor location is weighted and summed with filtered volume. This signature is then compared, on a location-by-location basis with a member of a set of stored signatures (each stored signature is associated with a stored timing plan). The absolute value of the signature difference, E_{dAL}, is then summed over all of the detectors in a control area, and the stored signature, L, which yields the minimum sum of the absolute differences is identified. The first generation software has certain signature admissibility criteria not shown in the diagram.

1. Urban Traffic Control & Bus Priority System Software Manual; Vol. 1 - Functional Description & Flow Charts, Sperry Systems Management, Report No. FHWA-RD-76-185, June 1976.

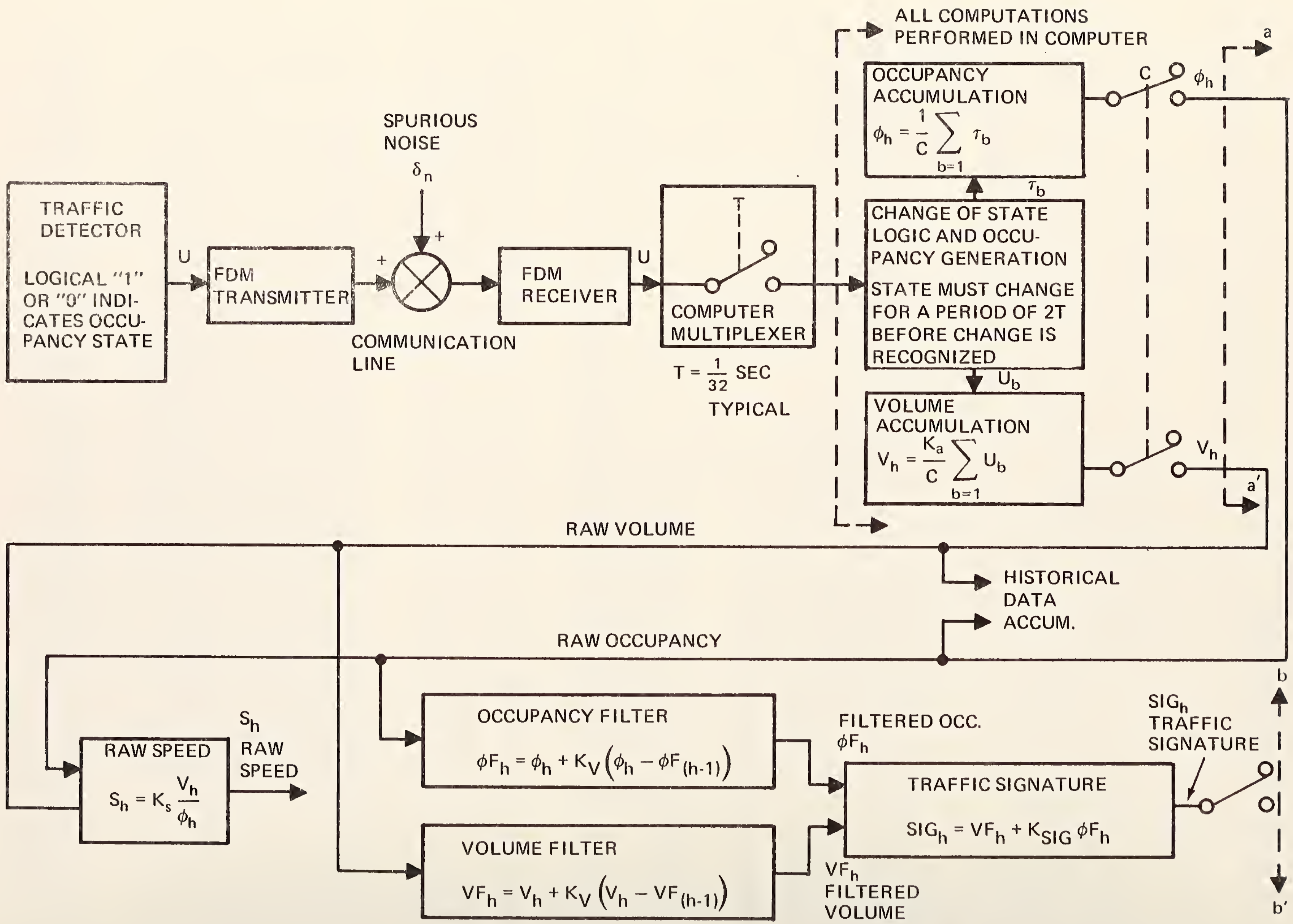


FIGURE 5-13. RELATIONSHIP OF FDM COMMUNICATIONS TO SURVEILLANCE AND CONTROL ALGORITHMS FOR CENTRAL SYSTEM ARCHITECTURE (SHEET 1 OF 2)

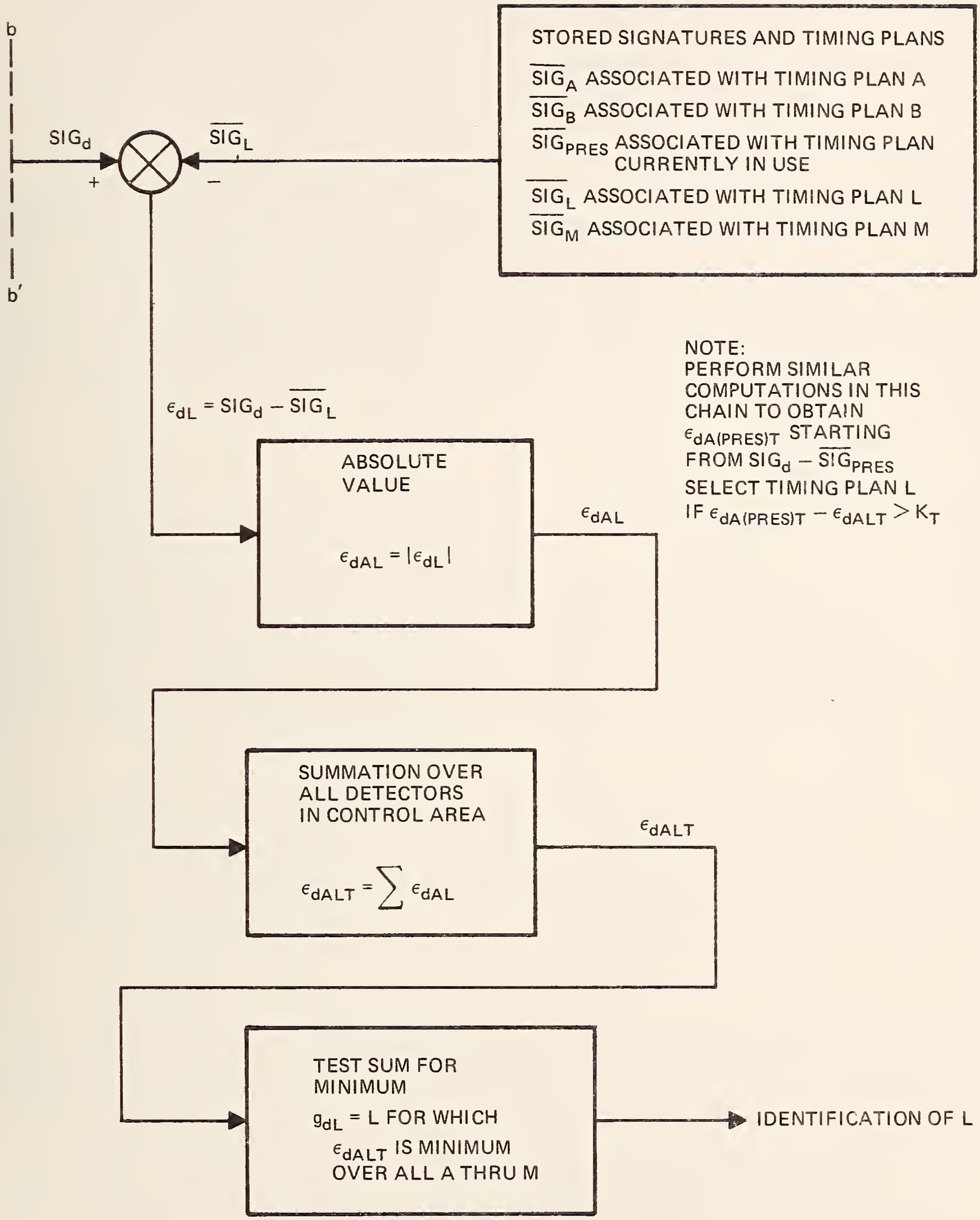


FIGURE 5-13. RELATIONSHIP OF FDM COMMUNICATIONS TO SURVEILLANCE AND CONTROL ALGORITHMS FOR CENTRAL SYSTEM ARCHITECTURE (SHEET 2 OF 2)

Figure 5-14 describes the functional operation of a typical TDM system. The TDM field transceiver equipment samples the detector at interval T and preprocesses the data as shown. The preprocessing is performed for each transmission interval T_1 and results in an occupancy indication ϕ_j and (depending on the interval T_1) a vehicle count or detector state indication D_j.

This information is then transmitted over a communications line which may be subject to noise δ_N, plus propagation losses and distortion. The control center communications unit recovers these signals. Volume and occupancy for the traffic cycle period are then obtained using summation algorithms which are similar to those used for the FDM case. These quantities are then processed in a way which is identical to the FDM case and this is represented in Figures 5-13 and 5-14 by the use of the match line a-a' in these figures.

5.7.3 Network System Architecture

TDM is widely used in distributed processing architectures such as hierarchical or network system architectures. Although the communications equipment and data processing algorithms are generally similar to those used for the central system architecture, the use of field microprocessors with the hierarchical or network type architecture offers the opportunity of distributing the data processing burdens and generally reducing the communication burdens. This is shown in Figure 5-15 by the use of one minute as the typical data transmission period (T_2) as compared with central architecture which uses a period closer to one second.

Since the data transmission periods for this architecture are generally of the same order as the cycle length (e.g., 50-150 sec), the data is directly used at this T_2 interval in the computation of smoothed occupancy and volume as shown in Figure 5-15.

5.8 DISTRIBUTED PROCESSING

5.8.1 Introduction

This section discusses distributed processing forms of computerized traffic control, with emphasis on those characteristics which affect communications. The discussion includes the following topics:

- A definition of distributed processing systems.
- The processing functions which affect communications.
- The characteristics of the data to be transmitted.

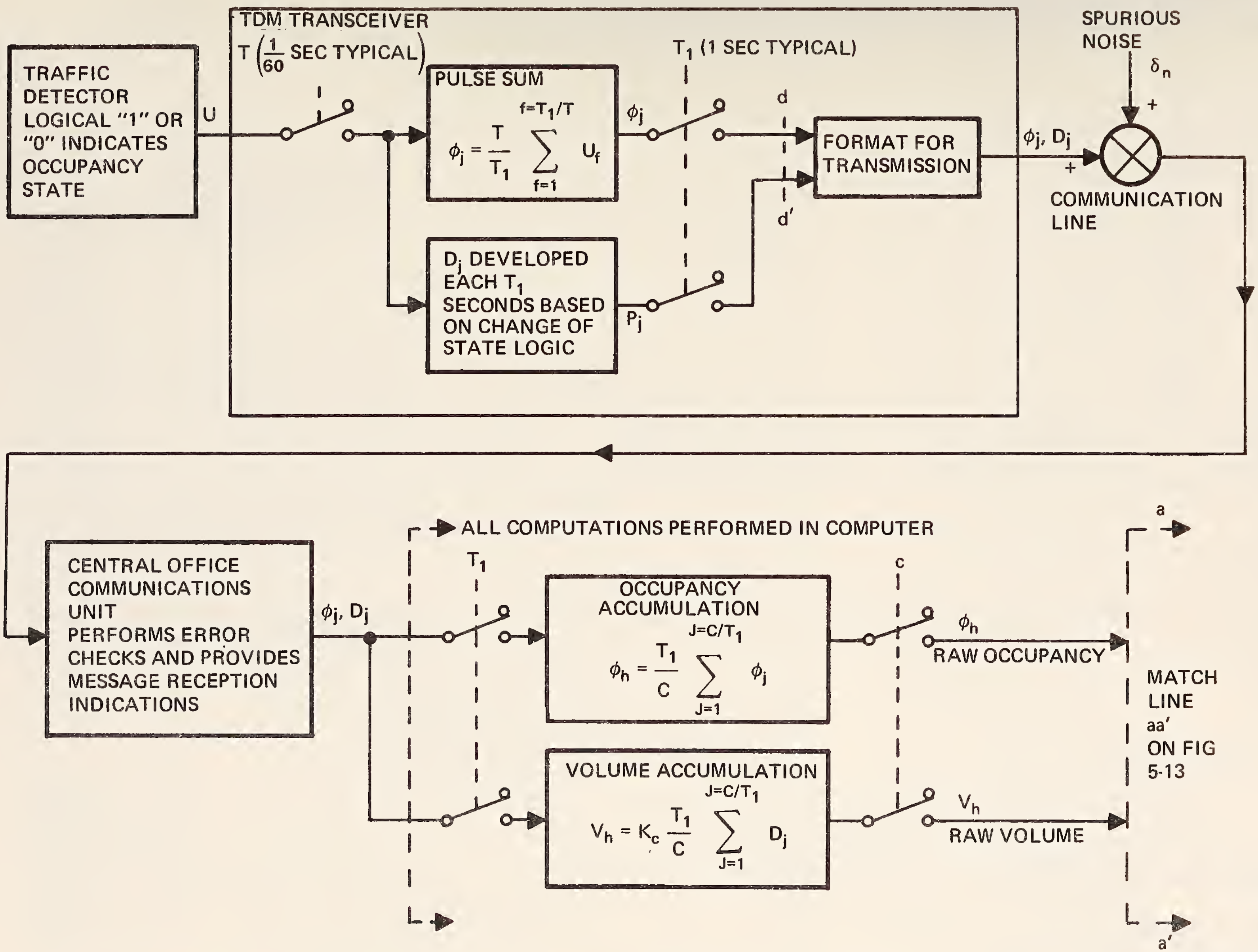


FIGURE 5-14. RELATIONSHIP OF TDM COMMUNICATIONS TO SURVEILLANCE AND CONTROL RELATED ALGORITHMS FOR CENTRAL SYSTEM ARCHITECTURE

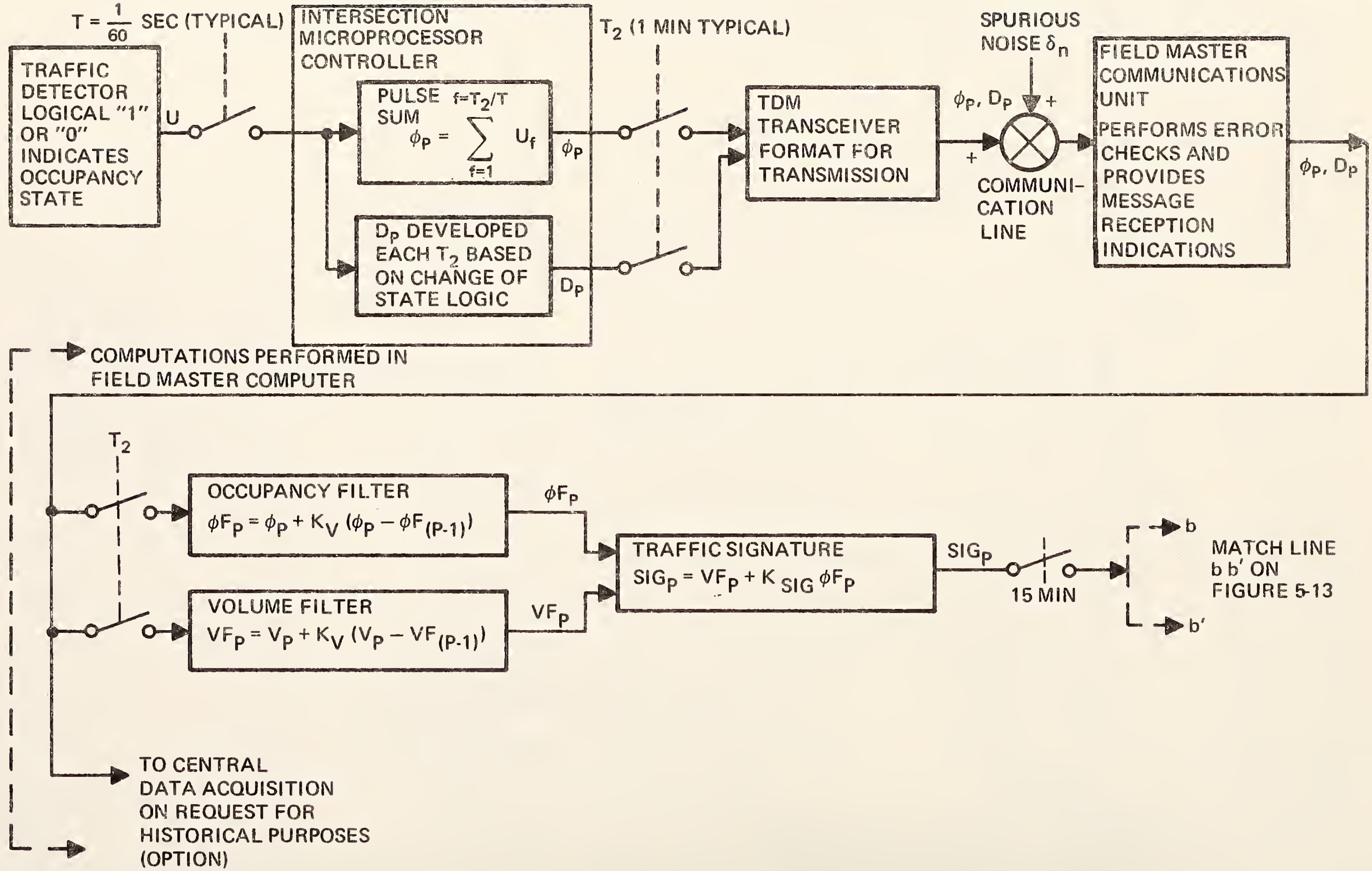


FIGURE 5-15. RELATIONSHIP OF TDM COMMUNICATIONS TO SURVEILLANCE AND CONTROL RELATED ALGORITHMS FOR NETWORK SYSTEM ARCHITECTURE

- Hardware and software computer/communication interfaces.
- Computer characteristics required to provide the necessary communication functions.

5.8.2 Distributed Processing Definition

For the purposes of this discussion, a distributed processing system is defined as one which includes "local" computers in each intersection controller cabinet, a communications subsystem, and a master or central computer which may be located at an intersection or in a control center. Microcomputers are used for the roadside locations, and either minicomputers or microcomputers at the control center. The master or central computer provides the processing for area traffic control, operator interface, and communications, and the local computers provide processing of vehicle detector data, controller data, and communications.

Although, in practice, the amount of processing and the division of processing between local and master may vary from system to system, a particular processing configuration is described in this subsection for simplicity of explanation. This configuration consists of a master computer at a control center connected via a single multipoint voiceband channel (300 to 3,000 Hz) to an unspecified number of microcomputers (local computers) at each controlled intersection. The transmission medium for the voiceband channel may consist of leased or owned wire pairs (4-wire channel) or the optical spectrum of the atmosphere. The local computers interface with up to eight system detectors and eight controller-actuation detectors as well as with the signal controller, which is assumed to be an 8-phase NEMA type[1] having the maximum number of options. It should be noted that the local computer does not provide the traffic signal controller functions directly as in some distributed processing systems which employ a single microprocessor such as the Model 170 Processor[2] to provide both traffic control functions and signal controller functions directly.

The system is assumed to provide traffic control functions based on first generation UTCS software. These functions are divided between the master and local computers.

The master computer commands and monitors the local computers, coordinates control and mode of operation, accumulates data, formats printed reports, and responds to

1. Defined as a controller conforming to Standards Publication No. 1-1976, "Traffic Control Systems", National Electrical Manufacturers Association.
2. This processor is defined in "Traffic Signal Equipment - Microcomputer Specifications", New York State Department of Transportation, Division of Traffic & Safety, March 9, 1978.

operator requests. A printing terminal located in the control center inputs all operator commands for the system and outputs all printed reports.

The local computers time the controller intervals when under computer control, accumulate detector data, interface with all specified controller functions, perform failure evaluation for all equipment reporting to the local computer, and communicate with the master upon command.

In other sections of this report, two basic types of distributed processing architecture have been defined - a hierarchical type in which a single central computer provides the area traffic control processing, and a network type, in which roadside master computers provide the area control for a group of locals. Because the communications requirements for both types are essentially the same, most of the discussion in this subsection is pertinent to both, and differences are noted as applicable. In the following discussion, the term "master" computer is used to represent either the master (network) or central (hierarchical) computer, and the term "computer" is used to represent either a minicomputer or a microcomputer.

5.8.3 <u>Functions Affecting Communications</u>

The amount and type of data to be transmitted between the master and local computers depends on the complexity of the intersection and the way in which the processing load is apportioned between the two computers. The apportionment of the processing load for the example configuration is defined by the following lists of functions provided by the master and local computers.

5.8.3.1 Master Computer Functions

The master computer performs the following functions:

- Provides the master time reference for all of the local computers.
- Establishes the operational mode as a function of the most recent operator request and the operability of equipment.
- Provides a master time-of-day, day-of-week timing pattern scheduler.
- Accumulates system detector data required for responsive control and for the performance report.
- Maintains all tables required for reporting.

- Generates the current traffic pattern for each section. This pattern is used in selecting the best available controller timing for the section.
- Updates the signal timing pattern in the local controller.
- Provides the interface with the local computers through the communications system.

5.8.3.2 Local Computer Functions

The local computer performs the following functions:

- Samples system detectors and accumulates one-minute samples of vehicle count, occupancy, speed, stops and delay.
- Times all intervals necessary to coordinate the controller according to the selected timing plan and safety interval set.
- Issues force offs and yields to actuated controllers and issues advances to pretimed controllers.
- Enacts preempts.
- Performs failure evaluation of the controller, detectors, and communications.
- Responds to master commands.
- Locally controls the entire NEMA interface.
- Enacts CIC control when enabled.
- Performs smooth transitions from one timing pattern to another.
- Provides a local time-of-day, day-of-week scheduler with four local timing plans plus flash and standby modes.

5.8.4 Characteristics of Data to be Transmitted

For the distributed processing configuration defined as an example in this subsection, the data interchanged between the master and local computers consists of a serial-data command message from the master followed by a serial-data reply message from the particular local whose address was contained in the command message. Each such interchange between the master and all locals takes place once per minute.

The command message contains the following elements:

- Address of local to be interrogated.
- Format word whose bits provide the following functions:
  - Define the contents of the remainder of the message if the message contains "set" commands for the local computer; that is, commands which change the values of information stored in the local computers.
  - Request that the local computer transmit certain types of information to the master; this is termed a "monitor command".
- "Set" commands for the local computer.
- Error check bits associated with each of the following: address word, format word, each command, and each 8-bit byte within each of these elements.

The set command categories and the parameters within each category for the example system are listed in Table 5-7. The particular categories contained in any one message (if there are any) are indicated by the pattern of bits in the format word. The data within the message is divided into 8-bit bytes representing each parameter, and transmitted as 11-bit asynchronous "frames" as described in Section 2.

The reply message from the local computer (Table 5-8) has essentially the same format as the command message from the master. If it receives set commands from the master, it returns the command exactly as received, for confirmation, and stores the new data. If it receives monitor commands, which appear as bit patterns in the format word, it returns the current stored value of the category requested. All information categories are subject to monitoring (including those which may have previously been received as set commands) as indicated in Table 5-8.

The format word in the reply message indicates which information categories are contained in the message and also indicates when a malfunction in controller, detector, or computer has been detected by the local computer, thereby alerting the master.

In addition to the information content listed in Tables 5-7 and 5-8, the command and reply messages also contain bits representing address, message length (in bytes), and results of error check operations. In the example of this subsection, the address and message length strings are assumed to consist of one 8-bit byte each (maximum of 255 items each). The error check bits are assumed to be obtained by first taking the logical exclusive OR (XOR) of successive 8-bit bytes for all elements of each information category, as well

TABLE 5-7. COMMAND MESSAGE INFORMATION CONTENT

Information category	Parameter	No. of data bits Required	Transmitted	Comment
Format		9	16	Defines content of command message, requests specific reply message
Set mode of operation	Phase hold	8	8	Any combination of phases on hold
	Phase omit	8	8	Any combination of phases omitted
	Pedestrian omit	8	8	Any combination of pedestrian phases omitted
	Actuated modes	8	8	Red rest, omit red, inhibit max. time, nonactuated
	Other NEMA modes	8	8	Pedestrian recycle, stop timing, vehicle call, max II timing, walk rest, external start
	Major mode	8	8	Pattern number, local TOD mode, pattern, preempt, CIC enable, flash
	Total	48	48	
Set time	Day	7	8	1 bit per day of week
	Hour	5	8	$2^5 = 32$ to cover 24 hours
	Minute	6	8	$2^6 = 64$ to cover 60 minutes
	Second	6	8	$2^6 = 64$ to cover 60 seconds
	Sync	32	32	Synchronization for four time-of-day clocks
	Total	56	64	

TABLE 5-7. COMMAND MESSAGE INFORMATION CONTENT (Cont.)

Information category	Parameter	No. of data bits		Comment
		Required	Transmitted	
Set timing pattern	Cycle	8	8	Cycle length (2^8 seconds max)
	Offset	8	8	Offset length
	Splits	64	64	Splits for 8 phases
	Yield	8	8	1 bit per phase each ring
	Force off	8	8	1 bit per phase, each ring
	Total	96	96	

TABLE 5-8. REPLY MESSAGE INFORMATION CONTENT

Information category	Parameter	No. of data bits		Comment
		Required	Transmitted	
Format		12	16	Defines content of reply; indicates malfunction of controller, detector, or computer
Monitor mode of operation	Phase hold	8	8	Current value of all parameters in local computer. Same parameters as listed in command message
	Phase omit	8	8	
	Pedestrian omit	8	8	
	Actuated modes	8	8	
	Other NEMA modes	8	8	
	Major mode	8	8	
	Total	48	48	
Monitor time	Day	7	8	Current values of time clocks. Same parameters as listed in command message
	Hour	5	8	
	Minute	6	8	
	Second	6	8	
	Sync	32	32	
	Total	56	64	

TABLE 5-8. REPLY MESSAGE INFORMATION CONTENT (Cont.)

Information category	Parameter	No. of data bits Required	No. of data bits Transmitted	Comment
Monitor timing pattern	Cycle	8	8	Current values. Same parameters as listed in command message
	Offset	8	8	
	Splits	64	64	
	Yield	8	8	
	Force off	8	8	
	Total	96	96	
Monitor safety intervals	Intervals per phase	64	64	2^8 seconds per interval; 8 intervals
Monitor local pattern	Cycle	8	8	Current TOD pattern cycle length
	Offset	8	8	Current TOD pattern offset
	Splits	64	64	Current TOD pattern splits for 8 phases
	Total	80	80	
Monitor controller state		8	8	1 bit per phase; "1" signifies green phase
Monitor controller failure status		8	8	Bit pattern indicates failure type
Monitor averaged detector data	Occupancy	9	16	Accumulated value for preceding one-minute period (per detector) (a)
	Volume	6	8	
	Speed	7	8	
	Stops	6	8	
	Delay	10	16	
	Total	38	56	

[a] See paragraph 5-1.

TABLE 5-8. REPLY MESSAGE INFORMATION CONTENT (Cont.)

Information category	Parameter	No. of data bits		Comment
		Required	Transmitted	
Monitor smoothed detector data	Smoothed occupancy	10	16	Smoothed value updated once per minute (optional) (a)
	Smoothed volume	10	16	
	Total	20	32	

[a]See paragraph 5-1.

as the address byte and format word, and then transmitting the result of this operation after the last byte of each of these elements.

The particular categories contained in any one command message from the master will vary as a function of traffic conditions, time-of-day/day-of-week, or operator intervention. For example, the entire message may consist of address plus format word, which simply requests that the local send only the current detector data (the most common type of command message). Or, it may provide a new traffic control timing pattern in addition to monitoring detector data, in which case the format word would indicate that the "set timing pattern" category is contained in the message. In this case, the local would return the same timing pattern values that it received in addition to current detector data values.

Because the message lengths can change, and may not be the same for all intersections, the amount of time required for any particular polling sequence is indeterminate. However, enough time must be made available for the longest sequence, which in this example consists of the timing pattern set command plus monitoring of mode, time, timing patterns, and detectors. This exchange results in the following numbers of bits transmitted per intersection:

	Transmitted bits	
Master-to-local message:	Information	Total
Address (one byte, repeated)	16	22
Format (two bytes)	16	22
Set timing pattern (8 bytes)	64	88
Message length (one byte)	8	11
Error check (4 XOR sums)	32	44
Total (master-to-local)	136	187
Local-to-master-message:		
Address	16	22
Format	16	22
Monitor mode	48	66
Monitor time	56	77
Monitor timing pattern	64	88
Monitor detectors (average of 2)	56	77
Message length	8	11
Error check (7 sums)	56	77
Total (local-to-master)	320	440

The total number of bit positions required for two-way message transmissions, then, 187 + 440 = 627.

For a given transmitted data rate (number of bits per second) and a given polling period, this maximum number of bits that must be transmitted imposes a limit on the number of intersections that can be interconnected on a single multipoint channel. For example, with a data rate of 1,200 bits per second and a 60-second polling period, the above maximum number of bits (627) results in a limit of 1,220 x 60/627 = 116 intersections. In practice, other factors such as circuit loading, mode turn-on and turn-off delays, or difficulty in fault isolation would probably limit the number well below this value.

5.8.5 Communications/Computer Interface

As noted in the preceding paragraphs, the information exchanged in a distributed processing multipoint communication system requires data rates which can easily be accommodated on a single voiceband channel (300 to 3,000 Hz bandwidth). Consequently, asynchronous data transmission techniques employing either wire pairs (owned or leased) or air path optics can be considered for such systems. With wire pairs as the transmission medium, standard two-wire or four-wire medium speed modems can provide the necessary carrier modulation and demodulation (transmission and reception) at data rates of 1,200 bits per second or less. With air path optics as the transmission medium, low-cost pulsed lasers and photodiodes can be used as the energy sources and receivers, respectively, at similar data rates. In either case, interfacing with a local intersection microcomputer can be accomplished using a standard asynchronous receiver/transmitter microcircuit plus associated timing and level-changing circuits as shown in Figure 5-16.

5.8.5.1 Asynchronous Receiver/Transmitter Circuits

Single-chip asynchronous receiver/transmitter microcircuits are available either from the microprocessor manufacturer as part of a microprocessor "family" of chips, or from manufacturers of chips that are applicable to any computer or terminal device. A standard form of the latter type of chip is called a Universal Asynchronous Receiver/Transmitter unit or UART.

Both the dedicated computer family units and the UART's have as their primary purpose the conversion of parallel data to serial data and vice-versa. Because their operation is described in detail in manufacturers' literature and technical articles,[3] only a summary of their principal features is presented here.

For transmitting data, the receiver/transmitter chip first accepts control signals from the microcomputer directing turn-on of the modem carrier (for wire line operation). Then it accepts 5 to 8 bits of parallel data from the microcomputer data bus, converts it to serial form having a selectable pre-set data rate, and generates the start bit, parity bit and one or two stop bits to form a transmitted "frame". When the data word is 8-bits wide, as is assumed throughout this report, the standard transmitted frame is eleven bits long (start, 8 data, parity, stop). The data rate is set by an auxiliary clock circuit which is usually selected as 16 times the desired data rate.

3. Des Rochers, G., "Choosing IC's for Serial Data Communication", Electronic Products magazine, December 16, 1974.

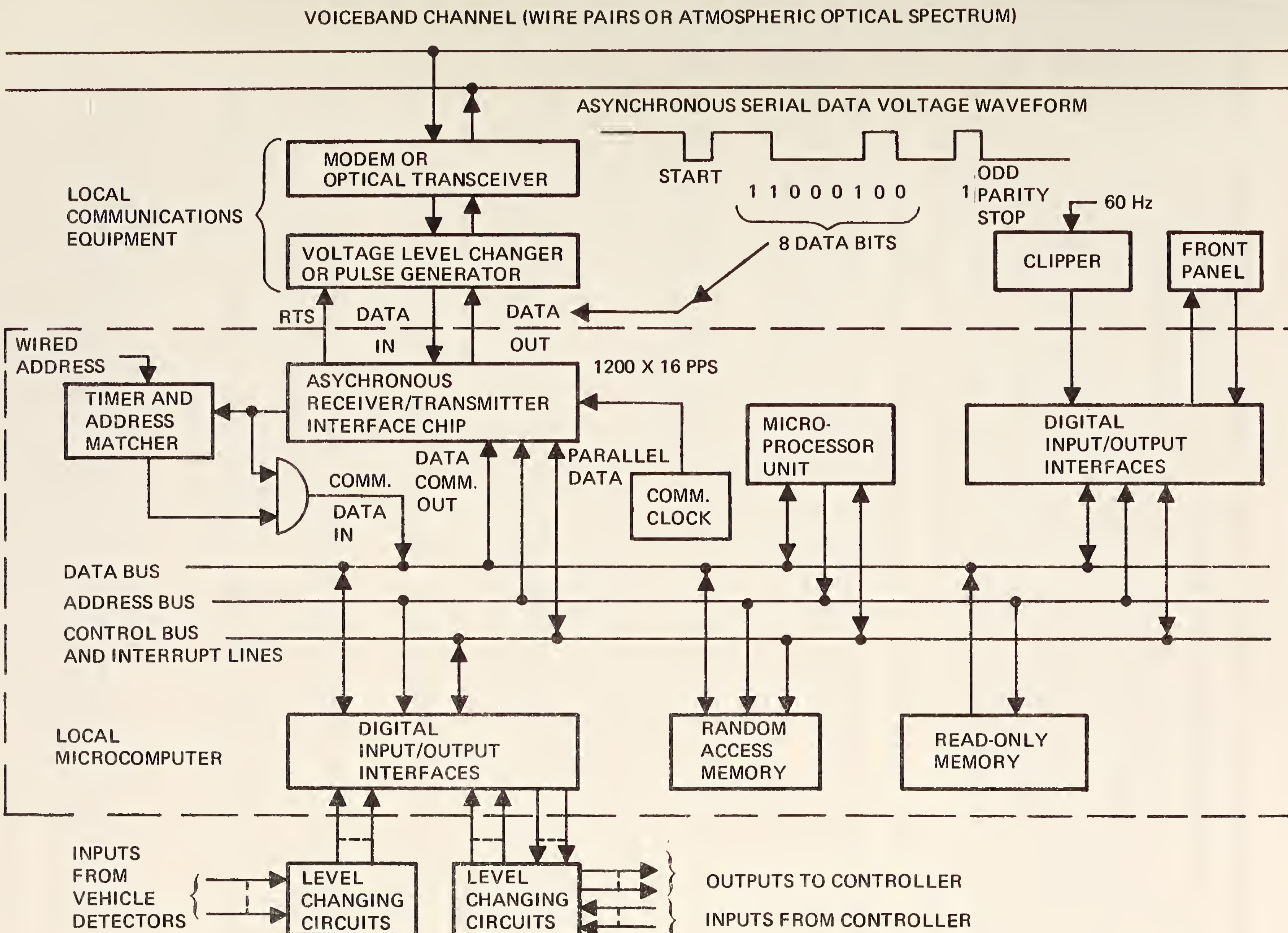


FIGURE 5-16. LOCAL INTERSECTION COMPUTER/COMMUNICATIONS BLOCK DIAGRAM

This frequency provides a convenient means of sampling the center of each received bit by counting multiples of 8 clock pulses from the start bit leading edge.

The two-state serial data output of the unit consists of high and low DC levels (Figure 5-16), where, for example, the high level is present when no data is being transmitted. The start of transmission is then defined as the transition from a high to a low level (beginning of start bit), and the end of the frame is defined as the transition from low to high level (beginning of stop bit). The eight data bits (and the parity bit) produce a transition from low to high or high to low whenever the data changes from zero to one or one to zero, respectively. This output signal feeds either a voltage level-changing circuit (for standard wire-line modems) or feeds a pulse generating circuit (for air path optics transmission). The standard modem levels are usually specified as conforming to the EIA RS-232-C or RS-449/422/423 interface standards,[4] which require specific minimum positive and negative voltage levels rather than the typical TTL standard-logic levels.

For receiving data, the incoming data enters the receiver/transmitter unit as two-state logic levels (after being level-shifted from its RS-232-C values, if required). This unit removes the start, stop and parity bits, and feeds the eight data bits into the computer in parallel via the computer's data bus. The receiver/transmitter also checks for parity error and framing error (stop bit not valid) and provides a logic level indication of such errors on separate lines of the computer control bus.

Additional functions which are available on some receiver/transmitter units include modem control signals such as "clear-to-send", "request-to-send", and "data carrier detect".

Other single chip computer/communication interface circuits are also available for implementing standardized data link controls, which form one level of control within a hierarchy of data communication protocols.[5] Such protocols are used primarily for long-distance commercial data processing applications, and usually

4. EIA Standard RS-232-C, "Interface Between Data Terminal Equipment & Data Communication Equipment Employing Serial Binary Data Interchange", August 1969. Electronic Industries Association, EIA Standards RS-449, RS-422, RS-423 are intended to gradually replace EIA Standard RS-232-C.

5. Weissberger, A.J., "Data Link Control Chips", Electronics, June 8, 1978.

employ synchronous, rather than asynchronous transmission techniques. The standard frame format adopted by the American National Standards Institute (ANSI) for such data link control provides for a variety of communication options and includes a specific error checking technique. This frame format consists of the following fields (bit strings): 8-bit start and stop "flags", 8-bit address, 8- or 16-bit control field, undefined length information field, and 16-bit cyclic redundancy code error checking field. This type of data link control appears to offer potential advantages in standardization of software and hardware. However, at the time of this writing, the techniques had not yet been used in traffic control applications.

5.8.6 Communications Processing Requirements

The local intersection microcomputer processes controller and detector data, and also performs the following communications related actions:

- Recognize the start of each message transmitted from the master computer.
- Recognizes its address when it appears in a message, and ignores messages containing all other addresses.
- Exchanges control signals with the asynchronous receiver/transmitter interface unit to determine when a received byte of data is ready to be entered.
- Accepts each parallel 8-bit byte of the message provided by the asynchronous receiver/transmitter interface unit, and stores the data in specific memory locations.
- Recognizes parity and/or framing errors when they are indicated by the receiver/transmitter interface unit.
- Processes the error check words in the messages and ignores the commands in the message if an error is found.
- Initiates the actions required by the commands from the master.
- Formats the data to be transmitted in the reply message and stores it in specific memory locations.
- Exchanges control signals with the asynchronous receiver/transmitter interface unit to determine when a byte of data may be transmitted.

- Sends the reply message in the form of successive 8-bit bytes to the asynchronous receiver/transmitter interface unit at the rate established by the interface unit.
- Accepts a 60 Hz AC power input which serves as the basic real-time clock.

The recognition of message start and local address can be accomplished by providing a non-message time interval (gap) between messages, which computer hardware can measure before activating either hardware or software address matching circuitry.

The acceptance of the incoming message can be initiated by means of an interrupt signal from the receiver/transmitter interface unit when it has completed reception of a byte of information in serial form, and is ready to transfer the information to the computer in parallel form. This interrupt causes the computer program to jump to a routine which stores the 8-bit byte from the receiver/transmitter unit. The transmission of the reply message can also be initiated by means of an interrupt from the receiver/transmitter unit when it has completed the serial transmission of the previous byte and is ready to start transmitting the next one. This interrupt causes the computer to jump to a routine that transfers the next byte from memory to the receiver/transmitter interface unit.

The processing and error checking of the received information is accomplished as part of the main processing sequence which includes detector and controller processing. The design of the over-all program is part of the system design task, and therefore the manner in which the communication routines are incorporated will depend on the particular characteristics of the computer selected and other factors related to system design.

Microcomputers which are capable of performing all of the local intersection functions described above are readily available from a number of sources. The original model 6800 microprocessor and associated memory and interface units (introduced in 1974) has been successfully programmed to provide the functions required by the configuration defined in this subsection. Therefore, it is reasonable to expect that the more recent, higher-performance models of microcomputers based on this family of microprocessors and other families such as the 8080-series and the Z80-series, will be able to handle all foreseeable local processor requirements. These microprocessors, microcomputers, and associated support chips are described in detail in the technical literature[6, 7] and manufacturer's manuals, and therefore only a few of the main features of microcomputers based on the 6800, 8080, and Z80 series of microprocessors are listed here to provide an indication of their capabilities:

Data word size (bits)	8
Memory addressing range (words)	65,000
Number of instructions	80 to 150
Short instruction time range (microseconds)	1 to 2
Long instruction time range (microseconds)	4 to 6
On-chip interrupt levels	1 to 4
Input-output chips available	Yes
Direct memory access (DMA) available	Yes
Prototype development system available	Yes
High level languages available	Yes

Several different microcomputer models based on each of these microprocessors are available as assembled units. However, additional circuitry or modifications to the existing models must usually be provided to obtain all of the traffic control functions of a typical local intersection computer.

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6. Third Annual Microcomputer System Directory, EDN magazine, November 20, 1977 - pg. 104.

7. Microcomputer Data Manual, Electronic Design magazine, May 24, 1978, pg. 65.

SECTION 6

EXAMPLE OF COMMUNICATION SYSTEM SPECIFICATION

6.1 INTRODUCTION

This section contains an example of the communication system portion of an overall traffic control system specification. The overall specification is assumed to include all the non-communication elements of the system, as well as general and special provisions regarding such elements as construction and installation practices which would be unique to a particular locality. These general and special provisions are referred to, as applicable, in the communication system specification.

A traffic control system having a hierarchical type of processing architecture is used for this example. With this type of architecture, local computers at each controlled intersection, and a computer at the control center share the data processing load, as discussed in Section 2. The communication method selected for this example employs polled time division multiplexing (TDM), using a combination of air path optics and user-owned wire pair communication media.

In a hierarchical type of traffic control system, the borderline between communication-related functions and non-communication functions is not easily defined, because the degree of local (streetside) processing of traffic control information determines what data must be transmitted and how frequently it must be updated. For this specification, most of the local processing functions are considered to be related to communications and are used to establish the quantity and type of information transmitted and the information transfer rate. Therefore, the equipment defined as communication equipment includes the local computers as well as the wire and optical modems together with their related interfaces and mounting hardware. For an actual implementation, this set of equipment would be provided by a single supplier to meet the requirements of the specification.

The physical features of the traffic control system which are pertinent to the communication system specification are listed in Table 6-1.

The communication system specification consists of an Equipment Specification, a Software Functional Specification, and a Statement of Work. These items are presented in the following paragraphs.

TABLE 6-1. TRAFFIC CONTROL SYSTEM FEATURES

Parameter	Parameter quantities
Number of intersections	35
Number of controllers:	
2-phase	24
4-phase	7
8-phase	4
Number of CIC intersections	4
Number of system vehicle detectors	55
Maximum number of detectors per intersection	8
Number of intersections with existing cable	15
Length of new cable and conduit (ft)	1,500
Maximum cable lengths (ft)	9,000
Number of intersections suitable for air path optical communication	20
Maximum distance between intersections (ft)	3,000
1 foot = 0.305 m	

6.2 EQUIPMENT SPECIFICATION

6.2.1 General

The communication system shall consist of the following equipment:

- A local computer in each controller cabinet which performs traffic control as well as communication functions.
- An air path optical communication modem at each of the twenty intersections designated for optical communications.
- A wire communications modem at each of the fifteen intersections designated for wire communications.
- An air path optical modem or a wire type modem at the control center interfacing with the central computer.

6.2.2 Functional Requirements

a. Computer Functions

Each local computer shall perform the following functions:

- Sample system detectors and accumulate one-minute samples of vehicle count, occupancy, speed, stops and delay. (Volume and occupancy shall be computed and exponentially smoothed for each link.)
- Time all intervals necessary to coordinate the controller according to the selected timing plan and safety interval set.
- Issue force off and yield commands to actuated controllers.
- Enact locally-supplied or centrally-supplied preempts and return to the desired control upon completion.
- Perform extensive failure evaluation of the controller, detectors and communications, and automatically disconnect the computer from the street equipment in the event of a computer failure.
- Measure the duration of all controller intervals.
- Respond to central commands by accepting messages having the appropriate address, and outputting messages having the proper format and timing for transmission over the TDM link.
- Locally control the traffic signal controller via the NEMA interface.
- Enact CIC control when enabled.
- Perform smooth transitions from one timing plan to another.
- Provide a local time-of-day, day-of-week scheduler, with four time-of-day timing plans.
- Automatically start up when power is supplied.
- Return the controller to standby when power is removed.

The central computer shall perform the following functions:

- Monitor each local computer once per minute.
- Accumulate volume, occupancy, speed, stops and delay for each system detector for selectable periods of time.

- Respond to operator commands.
- Provide a master time-of-day, day-of-week scheduler.
- Provide traffic responsive area control based on smoothed volume, occupancy and speed.
- Generate the following reports:
  - Performance
  - Controller Status
  - System Status
  - Failure Status
  - Detector Status
  - Intersection Status
  - Controller Timing
  - System Log
- Automatically start up when power is supplied, with the correct time, day-of-week, and date.

Detailed descriptions of the local and central computer functions are contained in the overall traffic control system specification.

b. <u>Communication Functions</u>

The central computer shall transmit command messages addressed to individual local computers and shall wait for a response from the addressed computer before interrogating the next one. This polling operation shall be repeated once per minute for all intersections.

The command message length shall be variable, depending on the nature of the command. The command message shall contain the address of the local controller plus format information defining the command message contents which shall include one or more of the following types of information:

- Time set (DOW, hour, minute, second, tic, local cycle clocks).
- Time monitor.
- Timing pattern set (cycle, split, offset).
- Timing pattern monitor.

- Mode set - this command permits the remote control of the NEMA interface. It provides a means for remote selection of a local pattern, remote selection of local time-of-day mode, preempt, flash, and standby.
- Mode monitor.
- Local pattern monitor, to supply required information for the intersection report.
- Controller failure status monitor.
- Safety interval monitor, to supply required information for the intersection report.
- Detector data monitor.
- Sync set to lock a master-supplied pattern to the master clock.

In addition to the above, the operator shall be able to select one intersection to be monitored each second, to provide information for the controller timing report. Sufficient information shall be returned to the master to monitor all controller intervals.

When a local computer receives a monitor command, it shall respond with the desired information. When the local computer receives any of the set commands, it shall initiate the action and return the received message to the master to confirm correct reception. Extensive error checking shall be provided in the local and central computers to guard against undesired actions.

(1) Command Message.

The monitor command shall contain the following functions:

Monitor detector data
Monitor controller failure
Monitor mode
Monitor time
Monitor current pattern
Monitor controller intervals (Max I, yellow, etc.)
Monitor local patterns (0-4)
Monitor signal state

The mode command shall contain the following functions:

Hold (8 phase max)
Phase omit (8 phase max)
Pedestrian omit (8 phase max)
Red rest ring 1
Red rest ring 2
Omit red ring 1
Omit red ring 2
Inhibit max time ring 1
Inhibit max time ring 2
Nonactuated
Pedestrian recycle ring 1
Pedestrian recycle ring 2
Stop timing ring 1
Stop timing ring 2
Vehicle call all phases
Max II timing
Walk rest
Pattern number (TOD1, TOD2, TOD3, TOD4, Master)
Local TOD mode
Preempt
CIC enable
Local TOD pattern
Flash

The timing command shall contain the following functions:

Day of week (0-6)
Hour of day (0-23)
Minute of hour (0-59)
Second of minute (0-59)
Sync Time of Day Clock 1 (second of cycle)
Sync Time of Day Clock 2 (second of cycle)
Sync Time of Day Clock 3 (second of cycle)
Sync Time of Day Clock 4 (day, hour, minute, second)

The timing pattern command shall contain the following functions:

Cycle length: 240 seconds maximum, in 1 second increments

Offset: 240 seconds maximum, in 1 second increments

Split (for each of 8 phases): 240 seconds maximum, in 1 second increments

Early yield

(2) Response Message. The response message shall contain any synchronization bits required, the address of the responding (commanded) local computer, identification of any communications errors detected by the local computer, and identification of the functions(s) included in the response message. The types of errors shall include, but not be limited to, the following:

Carrier detect

Inconsistent data

Receiver overrun

Parity error

The response message functions which correspond to the command set functions shall contain the same amount of information as the set commands. These functions include time, mode and pattern.

The local pattern function shall be transmitted when the local pattern monitor command is received. The following data shall be transmitted for each of the four TOD patterns and one master pattern, all with a resolution of one second and a maximum value of 240 seconds:

Cycle

Offset

Split 1

Split 2

.

.

.

Split 8

The signal state function shall be transmitted when the signal state monitor command is received. The message shall identify the state of all phases and calls at the time of command reception.

The detector data function shall be transmitted when the detector data monitor command is received. The following data shall be transmitted for each detector:

Volume (0 to 127)

Speed (0 to 60 in one mph increments)

Occupancy 1 (0 to 255/30 seconds in 1/30 second increments)

Occupancy 2 (0 to 255/30 seconds in 1/30 second increments)

Delay 1 (0 to 255 seconds in one-second increments)

Delay 2

Total Stops (0 to 127)

The controller failure function shall be transmitted when the controller failure monitor command is received. A minimum of four failure types shall be capable of being transmitted.

(3) Error Control. Error checking codes and automatic procedures shall be provided to achieve an undetected error rate of one error in 10^8 messages in a noise environment identical to that for the Bell System switching network as described in Appendix C.

The traffic control system shall take no action when an error is detected, and automatic message re-transmission techniques shall be used to obtain correct information after errors are detected.

(4) Test Procedures. Test equipment and test procedures shall be provided for isolating problems to the printed-circuit board level.

6.2.3 Modem Characteristics

a. Wire Communications

A modem at each controlled intersection designated for wire communications and at the control center shall be used to provide data transmission and reception. The modems shall be cabable of transferring data at rates that meet the functional requirements given in subsection 6.2.2, using a single 4-wire circuit interconnecting the 15 intersections, and shall meet all of the general requirements given in subsection 6.2.4 below.

The transmission characteristics of each of these modems shall be as follows:

- Data rate: Up to 1,200 bits per second.
- Data format: Asynchronous, binary, serial by bit.

- Modulation method: Frequency shift keying (FSK).
- Multiplexing method: Polled TDM, half duplex, 4-wire.
- Interconnection: Unattended, private-line, 15-point multidrop.
- Interface: TTL logic-level compatible.
- Transmitter output level: Adjustable between - 2 dbm and + 2 dbm.
- Transmitter driving impedance: 600 ohms ± 10% resistive.
- Clear-to-send delay: 15 ± 5 milliseconds.
- Receiver dynamic range: 0 to - 40 dbm.
- Receiver load impedance: 600 ohms ± 10% resistive.
- Line isolation: Transformer coupling.
- Power requirements: 115 VAC, 2 watts maximum.
- Physical dimensions: 2" H x 8" W x 10" D maximum (5 x 20 x 25 cm).

b. Air Path Optical Communications

An optical modem consisting of one or more transceivers at each controlled intersection designated for air path optical communication shall be used to provide transmission and reception. The transceiver electronics shall consist of a single unit interconnected to one or two optical heads and shall be contained within one of the optical heads.

The air path optical modems shall meet all of the general requirements given in subsection 6.2.4 below.

The transmission chacteristics shall be as follows:

(1) Transmitter:

- Two gallium arsenide laser diodes (one for each direction of a repeater modem).
- Peak power output per optical head: 4-7 watts.
- Pulse width: 80 nanoseconds.
- Maximum pulse repetition frequency: 2 KHz*.

*Set at this value to meet BRH, Class I, laser safety standards.

(2) Receiver:

- Detector: Silicon avalanche photodiode.
- Minimum detectable power: 3×10^{-11} watts for 7 MHz video bandwidth.
- Automatic gain control dynamic range: 90 db.
- Data threshold signal/noise ratio: 10 db.
- False alarm rate due to photon noise: 10^{-7}.

(3) Optical Head:

- Transmitter/receiver optics: 6 inch* diameter plastic fresnel lens.
- Transmitter beam angle and receiver field-of-view: 4.5 milliradian -3 db intensity points.
- Fiber Optics - length of transmit/receive branches: 50 inch* to remote head; 21 inch* to local head.

(4) Measured fade margin: 37 db above data threshold at R=2,000 ft.*

(5) Power: 115 v @ 60 Hz 250 watts (with heaters on).

(6) Size - Optical head: 27 1/2 inches* long, 8 inch* diameter.

(7) Weight of one optical head (with electronics): 20 lbs*

(8) Approximate volume of optical head (less sun shield): 980 in^{3}*

Safety Standards. The optical transceiver units shall meet Bureau of Radiological Health, H.E.W., Class I Safety Standards as described in BRH Standards 21CFR1002 and 1002.12 and in compliance with standards 1040.10 and 1041.11.

Mounting Bracket. The optical head mounting bracket shall provide the means for secure mounting of the optical head and quick installation and alignment. The bracket, as shown on Figure 6-1, shall consist of two horizontal steel plates held together by two steel side pieces. Two banding brackets shall mount to the top plate and secure the mounting bracket to the mast arm by means of stainless steel bands. The top plate once installed shall be stationary and the bottom plate shall be adjustable in elevation through 60° (30° either side of the horizontal).

*1 in = 2.54 cm
1 ft = 0.3048 m
1 lb = 0.4536 kg
1 in^3 = 16.3871 cm^3

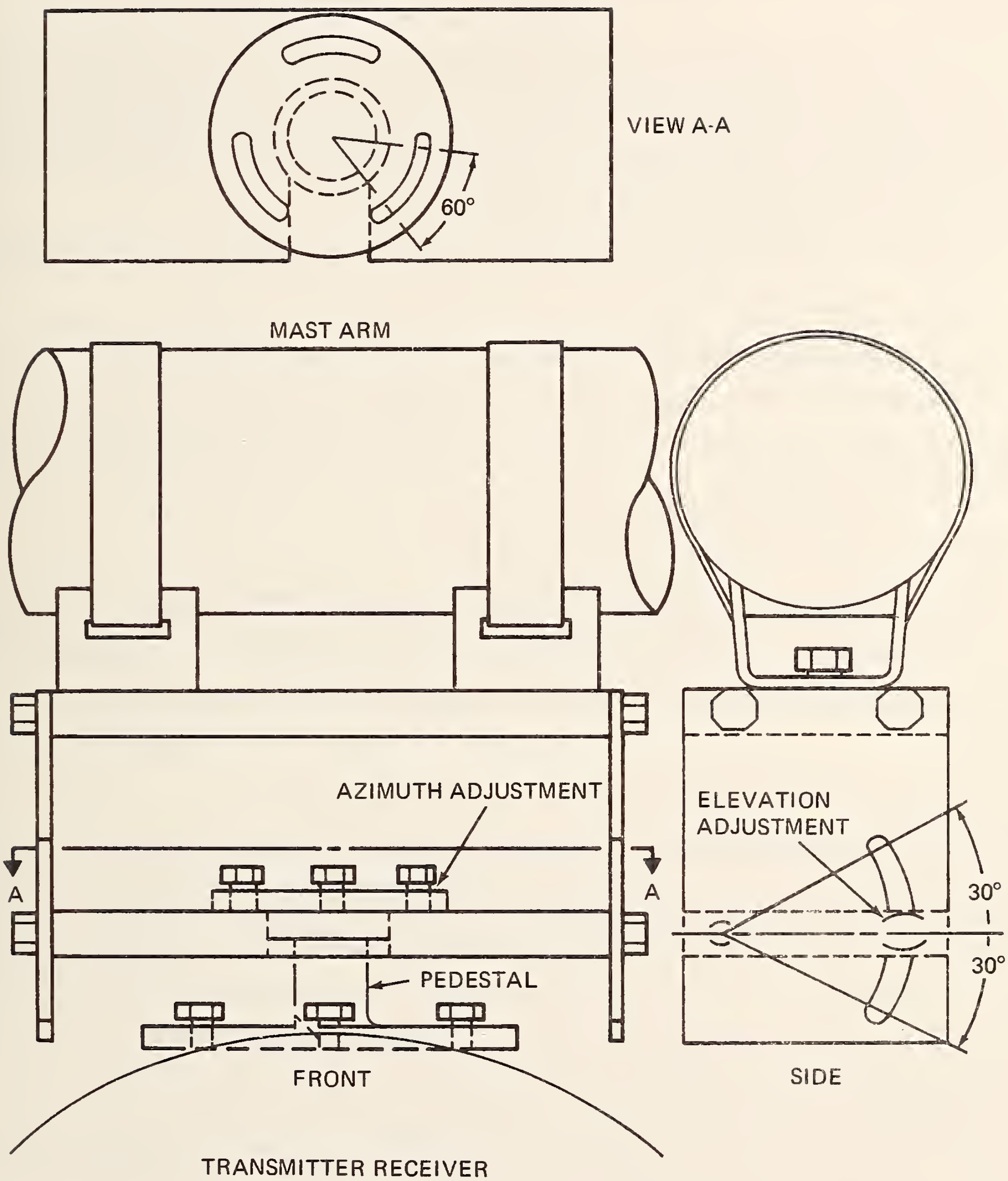

FIGURE 6-1. MAST ARM/OPTICAL HEAD MOUNTING DETAIL

c. Communication Interface

The interface signals which are transferred between the modems (both the wire type and air path optics type) and the central and local computers shall consist of asynchronous serial data signals having the following voltage and current levels, format, and data rate characteristics.

The voltage levels shall be TTL compatible (0.8 volts logic low; 3.2 volts logic high). The modem receivers shall be capable of driving the equivalent of one TTL logic load (1.6 milliamperes) and the modem transmitters shall present a load to the interface of no greater than the equivalent of one TTL logic load.

The formal shall consist of a start bit, 8 data bits, a parity bit and a stop bit.

The data rates of all units (locals and central) shall be settable to within ± 1 percent of each other and shall remain stable to within ± 1 percent of the initial value over the entire temperature/humidity range without adjustment. Nominal data rate shall be 1,200 bits per second or less in order to achieve compatibility with the wire communications specification of paragraph 3.1.

d. Communication Verification Unit (CVU)

A communication verification unit shall be provided which shall be capable of conducting a complete GO/NO-GO functional test of all the communication equipment. This unit shall not require special operator skills and shall be self-contained and easily transported.

6.2.4 General Requirements

The following paragraph defines the general requirements that shall apply to all equipments unless the requirement is specifically deleted in the section defining the specific requirements for a particular type of equipment. In cases where design tests are specified herein, documentation may be provided indicating that such tests have previously been satisfactorily completed. In the latter case, additional tests will not be required.

6.2.4.1 Definition of Special Terms

Procuring Activity: The term "procuring activity" is used in this specification to mean the State or its authorized representative.

Contractor: The term "Contractor" is used to mean the party that is responsible for furnishing, installing and testing the various items of equipment.

6.2.4.2 Parts and Material

In the selection of parts and materials, fulfillment of the requirements of this specification shall be of prime consideration. The equipment design shall utilize the latest available techniques, minimum number of different parts, subassemblies, circuits, cards and/or modules, to maximize standardization and commonality.

a. Electronic Components

Components used shall generally be a type, model, or a family currently recommended for new design by major manufacturers of such components and easily obtainable from industry sources. In order to assure reliable operation of the various equipments, the following practices, specifications and tests, or approved alternates, shall be complied with.

(1) Capacitors. Capacitors shall be marked with EIA approved color code, or the capacitance in microfarads (mF) or picofarads (pF). The voltage rating and tolerance shall be printed in legible characters on the body of the capacitor. In lieu of voltage and tolerance, the generic type (in an EIA code) may be used which indicates the above information.

Electrolytic capacitors shall be rated for at least 85°C operation. If subjected, or possibly subjected, to ripple voltage in excess of 10 percent of the actual DC voltage across the capacitor, the capacitor shall have a specific ripple or AC voltage rating.

An aluminum electrolytic capacitor shall be used only in an application where it is continually energized.

(2) Connectors. Unless otherwise specified, all external connections shall be made by means of connectors. The type and location of the connectors are specified in the specific requirement section for each equipment. The connectors shall be keyed to preclude improper hookups. All wires to and from the connectors shall be color coded and/or appropriately marked.

(3) Diodes. Diodes shall be marked with JEDEC part number, using either an industry approved color code or clearly legible printing. Polarity of diode shall also be indicated on the case by the use of the diode symbol or the 360° band on the cathode end, or the shape of case.

(4) Indicators. All indicators shall be solid state (LED) except for lamps, which are to be incandescent. The solid state indicators shall be clear, i.e., shall not have colored lens. The solid state indicators shall have a minimum useful life of 25,000 hours.

Minimum useful life required for lamps is specified later in this specification. The useful life shall be interpreted here as the length of time required for the light output, measured in lumens, to diminish below 70 percent of its value as measured after the first one hundred hours of operation. Indicators and lamps shall be marked with the manufacturer's part number or the generic type part number (where practical).

(5) Integrated Circuits. Every integrated circuit shall be subjected to at least one of the tests in each group shown below:

Group 1

- Stabilization bake.
- Temperature cycling.
- Power burn-in.

Group 2

- Functional test with the device at the manufacturer's maximum specified temperature.
- Static and dynamic test per manufacturer's data sheet.

The manufacturer's part number and any information required to properly install the integrated circuit assembly shall be clearly and legibly printed upon the package of all integrated circuits.

(6) Potentiometers and Rheostats. Potentiometers and rheostats shall be enclosed and shall be derated 50 percent from their maximum power ratings.

(7) Printed Circuit Boards. Printed circuit boards shall be designed to facilitate identification of components. Identification shall be made either by part identification markings or by providing a pictorial diagram in the maintenance manual showing physical location and identification of each component. Each printed circuit board shall have the following quality requirements: NEMA Grade G-10 cloth base epoxy resin board, 1/16-inch (1.5 mm) minimum thickness, and gold-plated contacts. Inter-component wiring shall be copper track, with a minimum weight of 2 ounce* per square foot*, with adequate cross-section for the current to be carried. Printed circuit design shall be such that components may be removed and replaced without permanent damage to board or tracks. The printed circuit board assembly shall be coated with a protective coating to combat mildew, moisture, and fungus. Holes which carry electrical connections from one side of the board to the other shall be completely plated through.

*1 oz = 28.35 g
1 ft^2 = 0.0929 m^2

(8) Relays. Relays shall be replaceable without the use of special tools. Solder connections will not be permitted.

(9) Resistors. Resistors shall be marked with EIA approved color code or the value in ohms and the tolerance in percent shall be printed on the body of the resistor in legible characters.

(10) Semiconductor Devices. Semiconductor devices shall be derated 50 percent from the device manufacturer's absolute maximum ratings for any one of simultaneous combination of parameters under any reasonably foreseeable operating conditions.

(11) Switches. Switch contacts shall be derated 50 percent from their maximum current ratings.

(12) Terminal Blocks. Terminal Blocks shall be molded screw type terminal blocks adequate for a specified number of external connections, with at least 20 percent spares.

AC terminal blocks shall be Underwriter's Laboratory approved for 125 volts AC minimum and shall be suitable for equipment located outdoors.

DC terminal blocks shall be barrier type rated for at least 600 volts RMS.

(13) Transistors. Transistors shall be JEDEC registered devices. The JEDEC part number shall appear clearly evident on the case. Either the emitter or collector must be designated as such by use of an industry approved marking technique.

(14) Component Mounting and Identification. Operating circuit components mounted on circuit boards shall be identified by either identifying characters which shall be legible and permanently printed on the circuit boards or by the use of complete assembly drawings showing all components with values or JEDEC numbers. The identifying characters shall be referenced to their respective components in the schematic diagram and in the parts list.

b. Mechanical Components

(1) Hardware. All external screws, nuts and locking washers shall be stainless steel; no self tapping screws shall be used unless specifically approved by the engineer. All screws, nuts and locking washers used internally shall be of corrosion resistant material, or suitably plated to resist corrosion. All material furnished shall be new, first quality and used in accordance with the highest industry practices.

(2) Material. All parts shall be made of corrosion resistant material, such as plastic, stainless steel, aluminum or brass; or shall be treated with corrosion resistance such as cadium plating or galvanizing.

6.2.4.3 Design and Construction

The various equipments shall conform with all applicable requirements of good engineering practices for design, construction, and workmanship. Construction shall be such that performance will not be impaired after the equipments have been subjected to shock and vibration caused by normal installation, transportation, and maintenance handling.

a. <u>Electrical</u>

(1) Design Life. All components in their normal circuit applications shall be designed to operate continuously for at least 5 years unless otherwise specified in the specific requirements section for each equipment.

(2) Power Requirements. The equipment shall meet all of its specified performance requirements when the input power is AC power, 60 ± 0.5 Hz, single phase, 115 volts ± 15 percent. The maximum power required for operation of the equipment is specified in the specific requirements section for the equipment.

(3) Primary Input Power Interruption. In the event of a momentary power failure, proper operation of the equipment shall commence immediately after restoration of power without creating false information.

(4) High-Frequency Interference. The equipment operation shall be unaffected by line voltage spikes of up to 150 volts amplitude and 10 microseconds duration.

(5) Line Voltage Transients. The equipment operation shall be unaffected by voltage transients of plus or minus 20 percent with a maximum duration of 50 milliseconds from any point within the plus or minus 15 percent steady-state tolerance band which return to the final steady-state tolerance band within 2 seconds.

(6) Wire Size. All wiring shall be of such size to satisfy good engineering practices and meet the requirements of the National Electric Code.

(7) Sleeving. All wiring connected to terminal strips shall be identified by the use of insulated pre-printed sleeving slipped over the wire before final attachment, or other suitable identification.

(8) Wire Dressing. All wires shall be cut to proper length before assembly. No wire shall be doubled back to take up slack. Wires shall be neatly laced into cables with nylon lacing or plastic straps. Cables shall be secured with suitable clamps.

(9) Transient Suppression. All DC relays, solenoids and holding coils shall have diodes across the coils for transient suppression.

(10) Protection. The equipment shall contain readily accessible, manually resettable or replaceable circuit protection devices (such as circuit breakers or fuses) for equipment and power source protection.

(11) Fail Safe. The equipment shall be designed such that the failure of the equipment shall not cause the failure of any other.

b. Mechanical

(1) Modular Design. The equipment shall be modular in design such that major portions may be readily replaced in the field.

(2) Keying. Modules of unlike function shall be mechanically keyed to prevent insertion into the wrong socket or connector.

(3) Identification. All modules and assemblies shall be clearly identified with name, model number, serial number and any other pertinent information required to facilitate equipment maintenance.

(4) Maintenance Provisions. All equipment shall be designed for ease of maintenance. All component parts shall be readily accessible for inspection and maintenance. Test points utilizing test jacks or equivalent shall be provided, if required, to enable test and troubleshooting with the equipment operating. The only tools and test instruments required for maintenance by city personnel shall be simple hand held tools, basic meters, and oscilloscopes.

c. Static, Lightning, and Surge Protection

(1) Static Effects. Unit shall be fully protected from damage due to static electricity accumulation and/or discharge during unpacking, normal handling, and installation. This shall be accomplished in the following two ways:

The material of which the case is constructed and the type of finish used shall not permit the accumulation of static electric charge.

Lines entering or leaving the equipment which might be subject to damage shall be protected with bleeder resistors, current limiting resistors, zener diodes or other suitable means of limiting monetary current surges.

(2) Lightning and Surge Protection. Unit shall suffer no damage from lightning-induced surges or other commonly encountered power line transients. The unit shall also withstand application of a 1,000 volt transient (a 15 MF paper capacitor charged to 1,000 volts) recurring once every two seconds on the primary power input leads.

d. Radio Frequency Interference (RFI) Requirements

The electronics unit shall be adequately shielded against external electromagnetic fields so that no spurious output signals shall occur as the result of the presence of electromagnetic (RFI) emissions in close proximity to the operating site. Such control measures include the use of RFI filters in the incoming power line, and other interconnecting cables, as is found necessary.

The aforementioned RFI emissions shall hold for an effective radiated power of 100 watts cw, or less, over a frequency range of 1-20,000 MHz. No spurious output signals shall occur for the source of these emissions located as close as 10 feet (3 m) from an electronics unit.

6.2.4.4 Environmental Conditions

Two types of equipment are described in this specification and they have different environmental requirements.

- Field equipment - Consists of the equipment packaged in the field cabinets. This equipment is exposed to the ambient environmental conditions indigenous to the area of the system installation.
- Central equipment - This equipment is located in a central control room whose ambient environmental conditions are controlled.

The equipment shall meet all of its specified requirements during and after subjection to any combination of the following requirements.

a. Field Equipment

(1) Ambient temperature range of - 30°F to + 165°F (- 34°C to + 74°C).

(2) Temperature shock of 5°F (3°C) per minute over any 70°F (39°C) portion of the full temperature range (equipment non-operating during temperature shock).

(3) Relative humidity range of 5 percent to 95 percent.

(4) Moisture condensation on all surfaces caused by temperature changes.

b. Central Equipment

(1) Temperature 40°F (4°C) to 110°F (43°C).

(2) Relative humidity up to 90 percent.

6.2.4.5 Quality Assurance Provisions

In cases where design tests are specified herein, documentation may be provided indicating that such tests have previously been satisfactorily completed. In the latter case, additional tests will not be required. The equipment covered by this specification shall be subjected to factory demonstration tests and design approval tests at the contractor's facility to determine conformance with all the applicable requirements. Unless otherwise specified, the contractor is responsible for all inspection requirements prior to submission to the procuring activity for inspection and acceptance. The procuring activity reserves the right to have its representatives witness all factory demonstration tests and design approval tests. The results of each test shall be compared with the requirements specified herein. Failure to conform to requirements for any test shall be counted as a defect, and the equipment shall be subject to rejection by the procuring activity. Rejected equipment may be offered again for retest provided all non-compliances have been corrected and retested by the contractor. Final inspection and acceptance of equipment shall be made after delivery at destination specified unless otherwise stated.

It is the policy of the Department of Roads to performance test all materials not previously tested and approved. If technical data is not considered adequate for approval, samples will be requested for test. Neither the State nor the City shall be responsible for time lost or delays caused prior to final approval of any item.

a. Factory Demonstration Tests

The contractor shall furnish all equipment and shall be responsible for accomplishing the demonstration tests. The engineer shall be advised a minimum of ten (10) calendar days before the start of tests. All tests shall be conducted in accordance with the approved test procedure of paragraph 4.1.5.4. The contractor shall furnish test reports, as required showing quantitative results for all demonstration tests. The reports shall be signed by an authorized representative of the contractor. Factory demonstration tests shall consist of individual tests.

b. Individual Tests

Unless otherwise specified herein, each equipment shall be subjected to the individual tests. As a minimum, each equipment accepted shall have passed the following tests:

Examination of product
Continuity
Operational test

(1) Examination of Product. Each equipment shall be examined carefully to verify that the materials, design, construction, markings, and workmanship comply with the requirements of this specification.

(2) Continuity Test. The wiring shall be checked to determine conformance with the requirements of the appropriate paragraph in the specific requirements section.

(3) Operational Test. Each equipment shall be operated long enough to permit equipment temperature stabilization, and to check and record an adequate number of performance characteristics to assure compliance with the requirements of this specification.

c. Design Approval Tests

Unless otherwise specified, design approval tests shall be conducted by the contractor on one or more sample equipments of each type to determine if the design of the equipment meets the requirements of this specification. The tests shall be conducted in accordance with the approved procedure of paragraph 4.1.5.4. The procuring activity shall be advised a minimum of ten (10) calendar days in advance of the time when tests are to be conducted. The contractor shall furnish test reports, showing quantitative results of all tests required. The reports shall be signed by an authorized representative of the contractor. The data obtained by the contractor in conducting these tests shall be submitted to the procuring activity.

(1) Tests. The design approval tests specified in the specific requirements paragraph shall include one or more of the following:

Temperature (Central Equipment)
Temperature and Condensation (Field Equipment)
Power Variation
Relative Humidity
High-Frequency Interference

(a) Temperature (central equipment). The equipment operational test specified in paragraph 6.2.4.5.b.(3) shall be successfully performed under the following conditions in the order specified below:

- The equipment shall be stabilized at + 40°F (4°C). After stabilization at this temperature, the equipment shall be operated for two hours.
- The equipment shall be stabilized at + 110°F (43°C). After stabilization at this temperature, the equipment shall be operated for two hours.

(b) Temperature and Humidity (field equipment). The equipment operational test specified in paragraph 6.2.4.5.b.(3) shall be successfully performed under the following conditions in the order specified below:

- The equipment shall be stabilized at - 30°F (- 34°C). After stabilization at this temperature, the equipment shall be operated for two hours.
- Moisture shall be caused to condense on the equipment by allowing it to warm up to room temperature in an atmosphere having relative humidity of at least 40 percent and the equipment shall be operated for two hours while wet.
- The equipment shall be stabilized at + 165°F (74°C). After stabilization at this temperature, the equipment shall be operated for two hours.

(c) Primary Power Variation. The equipment shall meet the specified performance requirements when the input voltage is plus or minus 15 percent from the nominal value of 115 volts. The equipment shall be operated at the extreme limits for at least 15 minutes during which the operational test of paragraph 6.2.4.5.b.(3) shall be successfully performed.

(d) Relative Humidity. The equipment shall meet its performance requirements when subjected to a temperature and relative humidity of + 165°F (74°C) and 95 percent, respectively. The equipment shall be maintained at the above conditions for 48 hours. At the conclusion of the 48-hour soak, the equipment shall meet the requirements of the operational test of paragraph 6.2.4.5.b.(3) within 30 minutes.

(e) High-Frequency Interference. The equipment shall meet the requirements of the operational test of paragraph 6.2.4.5.b.(3) when subjected to the high-frequency interference specified in paragraph 6.2.4.3.a.(4).

d. Test Procedures

The procedures used for conducting factory demonstration tests and design approval tests shall be prepared by the contractor and submitted to the procuring activity for approval. The contractor shall have obtained approval from the procuring activity prior to submission of equipment for tests. The test procedures shall include the sequence of conducting the tests.

e. Workmanship

The equipment, including all parts and accessories, shall be constructed in a thoroughly workmanlike manner and in accordance with best commercial practice. Particular attention shall be given to neatness and thoroughness of soldering, wiring, welding and brazing, plating, riveting, finishes, and machine operations. All parts shall be free from burrs and sharp edges or any other defect that could make the part or equipment unsatisfactory for operation.

6.2.4.6 Communications System Acceptance Test

The contractor shall submit to the engineer, thirty days prior to start of testing, a communications system acceptance test procedure. This procedure shall describe the step-by-step operations for verifying that the communications system meets all the functional and operational requirements promulgated in this specification. Descriptions of all test fixtures and special test equipment required, as well as samples of all data sheets and performance records, shall be included in this submittal.

The contractor shall furnish, at his expense, all test fixtures and special test equipment required for this test.

6.2.4.7 Standard Specifications

All electrical equipment shall conform to the standards of the National Electrical Manufacturers Association (NEMA). In addition to the requirements of these special provisions and the plans, all material and work shall conform to the requirements of the National Electrical Code (NEC); the standards of the American Society for Testing and Materials (ASTM); the American Standards Association (ASA); the specifications of the International Municipal Signal Association, Inc. (IMSA); the Insulated Power Cable Engineers Association (IPCEA); the American Institute of Steel Construction (AISC); the American Association of State Highway and Transportation Officials (AASHTO); the State Department of Roads Standard Specifications for Highway Construction hereinafter referred to as the "Standard

Specifications"; the Manual on Uniform Traffic Control Devices (MUTCD); and the ordinances of the City insofar as they apply. Wherever reference is made in these special provisions to the code in the standards mentioned above, the reference shall be construed to mean the code, or standard that is in effect on the date of advertising of these specifications.

6.2.4.8 Material Tests and Certification

Material test reports or Certificates of Compliance will be required per the Standard Specifications for all materials incorporated into the work. The following materials are to be added to the list of equipment in the Standard Specifications:

- Adapters.
- Communications equipment.
- Conduit.
- Loop vehicle detectors.
- Controller coordination and pre-empt units.

When any reference is made in the specifications to any standard specification, such as ASTM, IPCEA, IMSA, etc., or a related specification referred to by reference therein, which states that a certain test is to be made only at the request of the purchaser, it shall be considered that the City does request that such test be made. The tests shall be made at the contractor's expense and a certified copy of each test shall be submitted to the engineer prior to the installation of such material.

6.2.5 Communication Cable Material and Installation

a. Excavation and Backfill

Excavation and backfill required by the removal or installation of conduit, foundations, pull boxes and poles shall conform to the plans and these special provisions.

In general, all excavation shall be made in open cut from the surface of the ground and at the width and to the depth necessary for the proper construction of the utility and its appurtenances according to the plans and these special provisions. The sides of the excavation shall be cut as nearly vertical as possible. All necessary precautions must be made to prevent slides and cave-ins. Bracing or sheeting, if necessary, shall be provided to maintain the sides and bottom of the trench in wet or unstable material. The excavated material shall be handled at all times and in such a manner as to cause a minimum of inconvenience to public travel and to permit safe and convenient access to public and private property along the line of work. Trenches shall not be opened more than 300 feet (91 m) in advance of the finished utility. Unless otherwise specially permitted, all excavated material shall be placed on the roadway side of the trench.

Where shown on the plans or directed by the engineer, the excavation may be made by means of bore holes. Generally, these bore holes shall be made using equipment having mechanical augers and using low pressure water. The equipment and methods used shall be approved by the engineer. The filling of the annular space between the pipe and the excavation shall be done as directed by the engineer.

Excavation below subgrade with subsequent refilling with earth will not be permitted. Should the contractor inadvertently excavate below subgrade, such over excavation shall be filled and brought up to grade with compacted sand or gravel.

If the existing utility or structure foundation is not satisfactory, the engineer shall order over excavation to the necessary depth and, with select foundation materials, the contractor shall stabilize the foundation.

The bottom of all excavations shall be finished to the true profile grade, of full width, and cleared of any rocks, clods, roots or other material that may interfere with properly placing the pipe, conduit, or structure.

The contractor shall maintain all excavations during construction so as not to injure the pipe or any other work. He shall take all reasonable precautions to prevent movement of the sides of such excavations and shall remove, at his own expense, any material sliding into them. The contractor shall protect all excavations from storm water by the construction of adequate dikes. He shall furnish and put in place such sheeting and bracing as may be required to support the sides of the excavations and he shall remove such sheeting and bracing as the trenches or excavations are filled. The engineer may order the sheeting left in place if, in his opinion, the utility or structure might be damaged by its being removed.

The contractor may, if approved by the engineer, use a trench box of adequate design during the construction of the utility to protect the utility and his personnel.

All trenches or other excavations shall be backfilled with select material up to the original surface of the ground, unless otherwise indicated on the plans. Backfilling of trenches shall follow as closely after the construction as permitted by the engineer. No utility or structure shall be backfilled unless inspected and approved by the engineer. No backfill shall be made with material containing stone, frozen earth or debris of any kind. Backfilling shall not be done in freezing weather, except by permission of the engineer, nor shall any fill be made where the material already in the trench is frozen. Care shall be exercised in backfilling so as not to damage any finished work. The backfill shall be brought up evenly on both sides of the utility or structure.

The backfill of the utility or structure, not under pavement, driveways or sidewalks, shall be performed with equipment and by methods approved by the engineer. Care shall be taken to insure that the utility is properly bedded with material of an approved density. The bedding operation shall extend up to the spring line of the pipe. The remaining trench backfill material and structure backfill material shall be consolidated to a density at least equal to that of the undisturbed soil adjacent to the trench or structure. Excavations, after backfilling, shall be kept well filled and maintained in a smooth and well-drained condition, until permanent repairs can be made.

Where the utility or structure is to be located under pavement, driveways or sidewalks, all of the backfill shall be compacted to at least 90 percent of the maximum density of the material as determined by AASHTO Standard Method T-99. The moisture content of the soil shall be $\pm$ 3 percent of the "optimum moisture content" as determined by the above test. Such compaction shall extend 3 feet (0.9 m) on either side of the pavement, driveway or sidewalk.

Backfill in tunnels shall be made by blowing dry clean sand into the space between the pipe and the sides of the tunnel using compressed air. This operation shall be so conducted as to solidly fill the bore holes.

The contractor will dispose of all surplus excavated material, not needed for fills or other designated purposes, to locations designated by the engineer.

Surplus materials, whether placed on public or private property, shall be spread and finished to grades as designated by the engineer. Where possible, the surfaces shall be bladed straight and smooth.

For excavations in all unpaved areas, and for any unpaved area disturbed by the construction, sodding shall be required unless otherwise indicated by the engineer. The sodding shall conform in all respects to the Standard Specifications. Sodding shall be considered a part of the backfill or restoration of the site; no direct payment will be made for sodding.

b. Pull Boxes

Pull boxes shall be installed at the locations shown on the plans, and when runs are more than 300 feet (91 m), at additional points ordered by the engineer. The Contractor may install, at his own expense, any additional pull boxes that may be desired to facilitate the work.

Pull boxes shall be of the type and size shown on the plans, or as directed by the engineer. The bottom of the pull box shall rest firmly on a bed of crushed rock with a minimum depth of twelve (12) inches (30 cm) below the bottom, and not beyond the outside edges of the pull box, unless otherwise specified by the engineer.

In the case of the Type PB-2 pull box, cast iron frames and covers shall conform to the design as shown on the plans and shall conform to the requirements of "Standard Specifications for Gray Iron Castings", ASTM Designation A48, Class 30. Covers shall fit properly in frames and shall not rock. Castings will not be accepted that are warped, cracked, plugged, or filled or that have swells. Castings shall be thoroughly tar coated at the foundry with an approved coal tar varnish.

In some cases, cast iron frames and covers for Type PB-4 and Type PB-2 pull boxes shall be relocated from pull boxes shown to be removed on the plans. Frames and covers shall be carefully removed and cleaned and in proper condition for reuse, as determined by the engineer, before they are installed as part of the new pull box.

Concrete for Type PB-2 and Type PB-4 pull boxes shall be Class "47B" Portland cement concrete conforming to the requirements of the Standard Specifications. The conduit shall be in place before the concrete pull box is poured and the concrete pull box shall be poured so that the conduit is imbedded through the wall of the pull box.

In the case of the Type PB-5 pull box, the shape and dimensions shall be as shown on the plans. The body of the Type PB-5 pull box shall be one piece, molded of high density polyethylene, shall be open top and bottom, and shall be molded with integral reinforcing ribs for added strength. The body shall have a flange around the perimeter of the base, of sufficient size and shape to prevent overturning or up-heaving due to freeze-thaw cycles. The galvanized steel cover plate shall be firmly attached to the body with a captive, recessed, top pentahead bolt. After final installation, the Type PB-5 pull box shall be capable of withstanding a top load of 3,000 pounds (1,361 Kg), minimum.

The Type PB-5 pull box shall be installed to the depth necessary to allow the conduit to be installed directly through the wall of the pull box. Holes shall be cut in the wall of the pull box, using methods as approved by the engineer, to allow the conduit to be so installed. The top of the pull box shall be sufficiently below final grade to assure a sufficient depth of earth to support the growth of grass, unless otherwise directed by the engineer.

Each pull box, in place and accepted by the engineer, shall be measured, by type, as a single unit. Necessary crushed rock, frame, and cover are considered part of the item "pull box" and will not be measured separately.

Payment for each type of the item "Pull Box Type ***" or "Pull Box Type *** (Frame and Cover Relocated)" shall be made for the measured quantity at the contract unit price per each; which price shall be full compensation for furnishing, pouring, transporting, and installing all materials; for all excavation and backfill; and for all labor, equipment, tools, materials, and incidentals necessary to complete the work in accordance with the plans and these special provisions. Payment will be made only upon satisfactory completion, testing and approval of the "Work Unit" of which the pull box is a part.

c. Conduit

(1) General. Conduit shall be Type "A", Type "B", Type "C" or Type "D" and of a size as called for on the plans. Type "A" conduit shall be direct burial. Type "B" conduit shall have concrete encasement. Concrete used to encase conduit shall be Class "47B" Portland cement concrete conforming to the requirements of the Standard Specifications. Type "C" conduit shall be pushed or augered. Type "D" conduit shall consist of a section of rigid steel conduit of sufficient diameter to envelope a conduit of the size shown, which will first be pushed or augered for the length shown, and then the smaller conduit shall be inserted through it.

Unless otherwise noted on the plans, Type "A" and Type "B" conduit shall be plastic conduit; Type "C" conduit shall be rigid steel conduit; Type "D" conduit shall be a rigid steel conduit encasing a plastic conduit, and risers shall be rigid steel conduit. No asphaltic conduit shall be allowed for any installation.

(2) Rigid Steel Conduit. Steel conduit and fittings shall be galvanized and shall conform to the requirements of Underwriters Laboratories, Inc. "Standards for Safety" Rigid Metallic Conduit, UL 6. Conduit shall be furnished in suitable lengths and each length shall be clearly and durably marked at least every ten (10) feet* with Underwriters Laboratories label. Galvanized rigid steel conduit and fittings shall have minimum zinc coating of 0.0008 inch (.02 mm). Installation shall conform to the NEC. The use of roll type cutters in cutting conduits to proper lengths is acceptable if the cut ends are adequately reamed to remove burred or rough edges. All conduit ends must be square and true so that the ends will butt squarely together when the coupling is tightened. Conduit connections must be good electrically.

The ends of each conduit run shall be threaded and capped with standard pipe caps as soon as conduit is placed, and shall remain so until the contractor is ready to install the cable. Before installing cable, these pipe caps shall be replaced with galvanized, bakelite or plastic bushings, or galvanized conduit entrance fittings with bakelite or plastic wire entrance bushings.

All threads shall be treated with red or white lead before couplings, caps or fittings are placed thereon. Where the coating of conduits has been injured in handling or installing, such exposed places shall be thoroughly painted with rust-preventive paint.

Where two pieces of conduit are to be jointed together, a coupling shall be used, making the joint water tight. Running threads or the use of threadless connectors or threadless couplings will not be allowed.

Where the conduit crosses an expansion joint in a structure, expansion fittings, as detailed on the structure plans, shall be installed. Each expansion fitting shall be provided with a bonding jumper of #6 AWG copper wire, or equal, and approved clamps.

(3) Plastic Conduit. Plastic conduit and couplings shall be heavy-wall rigid polyvinyl chloride conforming to the requirements of Underwriters Laboratories, Inc. "Standards for Safety" Rigid Non-metallic Conduit, UL 651 and approved for use in concrete; or shall be polyvinyl chloride duct suitable for use as power or communications duct, conforming to NEMA Standard TC-6.

In the case of the heavy-wall rigid polyvinyl chloride duct, standard plastic couplings must be used to join conduit ends. The conduit may be formed or bent by warming until it is flexible and pliable enough to work easily. Wrinkles or buckling will not be

*1 ft = 0.3048 m

permitted. Conduit must not be heated to the point of deteriorating or damaging the material.

In the case of the polyvinyl chloride duct conforming to NEMA Standard TC-6, it shall be of a type intended for use as direct burial or concrete encased, as required. Conduit ends shall be joined using methods and materials as recommended by the manufacturer. Field bending of this duct may be accomplished through hot bend or cold bend techniques as recommended by the manufacturer.

(4) Installation. All conduit back of the curb shall be laid not less than twenty-four (24) inches below the curb grade of the street. When installed in roadway, the conduits shall be laid not less than twenty-four (24) inches (61 cm) below the flow line of the gutter. Unless otherwise shown on the plans, the conduit shall be laid parallel with the back face of the curb. Conduit shall be laid not to exceed thirty-six (36) inches (91 cm) below the grade of the improvement except when approved by the engineer.

Conduits terminating in poles shall not be transposed. Conduits shall terminate as near to the handhole of the poles as possible with the end of the conduit below the lower edge of the handhole. The last eight (8) inches (20 cm) of the conduit shall be straight and so placed that the prolongation of said eight (8) inch (20 cm) length shall pass through the handhole. Conduits shall be secured in their permanent position during the pouring and curing of the foundation concrete. Conduits shall extend three (3) inches (8 cm) above the top of foundations.

When provision is to be made for the installation of transformer base type poles, the conduits shall be placed as near the door opening as possible.

Conduits terminating in pull boxes shall extend at least one (1) inch (2.5 cm) into the pull box. Conduit stubouts shall extend not less than six (6) inches (15 cm) from the outer face of the foundation or pull box, and at the same distance below the top of the foundation or pull box as other conduits, in the directions shown on the plans; and shall be capped with standard pipe caps on both ends. Steel conduit stubs, caps and exposed threads shall be painted with red or white lead.

Conduit bends in a horizontal plane shall have a radius of not less than thirty (30) inches (76 cm).

Ninety (90) degree factory bends in a vertical plane shall have a radius of not less than twelve (12) inches (30 cm). Where factory bends are not used, conduit may be bent without flattening or crimping to a radius of not less than fifteen (15) inches (38 cm) for conduits of one (1) inch (3 cm) inside diameters, and not less than ten (10) times the inside diameter of all larger conduits. All radii mentioned above shall be considered as being to the centerline of the conduits.

Conduit ends projecting from foundations shall be protected in such a manner as to prevent injury to pedestrians prior to setting of the poles.

No obstruction or material shall be left in the conduit which would injure the cable when being pulled through.

Conduit to be encased in concrete must be supported above the bottom of the trench at several points to make sure that the concrete completely surrounds the conduit. Care must be taken that conduits are not damaged as concrete is placed in the trench. Concrete must be mechanically vibrated to assure that it completely encases the conduit.

When shown on the plans or approved by the engineer, the driving or pushing of conduits is to be done with hand powered jacks or other approved methods, when a constant pressure can be applied and controlled; and in accordance with approved jacking or drilling procedures. Pavement shall not be disturbed without the approval of the engineer. Upon approval of the engineer, small test holes may be cut in the pavement to locate obstructions. Jacking or drilling pits shall be kept two (2) feet (61 cm) from the edge of any type of pavement wherever possible. Excessive use of water which might undermine pavement, or soften subgrade, will not be permitted.

All conduit runs shall be of the same material and size between two terminals. The contractor may, at his option and expense, substitute a larger size of conduit in order to utilize his stock. Payment, however, will be made at the unit bid price for the size as shown on the plans, unless otherwise directed by the engineer. Where such substitution is made it shall be made for the entire length of that conduit run. No reducing fittings will be permitted.

d. Communications Cable

The cable shall consist of the specified number and size of twisted pair solid copper conductors with heat stabilized polyethylene insulation as the core assembly. This core shall be wrapped in a non-hygroscopic tape and covered with an aluminum shield. The entire cable shall have an outer jacket of polyethylene. The outer jacket of the aerial cable shall be blue in color or contain an identifying band to make the cable easily distinguishable from conventional black cable by an observer at ground level. The coloring or band shall be permanent and non-fading.

All cable furnished or installed as part of this item shall comply with the requirements set forth in the following specifications:

- IPCEA Specifications S-56-434.
- REA Specification PE-38 Aerial Cable (unfilled).
- REA Specification PE-39 Underground Duct Cable (filled).
- IMSA Specification 19-2 dated 1967 (specific section as noted herein).

The conductors shall be solid soft bare copper number 22 AWG with an insulation of heat stabilized, high density, high molecular weight polyethylene. The conductors shall be assembled in concentric construction up to 25 pairs or unit construction for more than 25 pairs using systematically varying lays in order to minimize crosstalk, and then covered with a non-hygroscopic tape.

The core assembly shall have a .008 inch (.2 mm) corrugated aluminum shield applied longitudinally with overlap with a high density, high molecular weight polyethylene jacket. The cabline shall be assembled as set forth in IMSA paragraphs 6 and 7. Fillers, if required to produce a round duct or aerial cable, shall be made of polyethylene materials as set forth in IMSA paragraphs 7 and 8. The circuit identification shall be through colored compound tracers in accordance with Table II of IMSA paragraph 5.2 or an approved equal. The cable shall be identified as required by IMSA paragraph 9.

The manufacturer shall provide certified results of all applicable tests conducted in keeping with the sampling and test methods set forth in IMSA paragraphs 13.1, 13.2 and 13.3 and REA Specification PE-38 or PE-39. Packing and shipping shall be in accordance with IMSA paragraph 14 and guarantee requirements in accordance with IMSA paragraph 15.

Unfilled aerial cable may be provided with an integral messenger cable, so that the messenger and communications cable form a figure 8 configuration.

Where communications cable is to be installed around signalized intersections, it shall be lashed to the signal support span, as specified in these special provisions.

(1) Installation. All classes of cable shall be shipped on substantially constructed reels, plainly marked as to size, type, and insulation identification. Only one length of cable will be shipped on each reel. All cable must be new. Damaged cable, or repairs on damaged cable, will not be permitted.

Prior to the installation of underground cable, the contractor shall make sure that the conduit is open, continuous, free of water, and clear of debris. The cable shall be installed in such a manner and by such methods as to insure against harmful stretching of the conductor, injury to the insulation, or damage to the outer protective covering of the cable. No splices or joints will be permitted to be drawn inside the conduit. Where more than one cable is to be installed in the conduit, all shall be pulled at the same time. No splices or joints shall be made in any cable outside of pull boxes, pole bases or traffic signal heads. All splices or joints of cable in pull boxes or pole bases shall be made waterproof using high-grade rubber splicing tape; and the finished splice or joints shall be waterproofed and covered with vinyl plastic tape to provide mechanical protection in accordance with these special provisions. An approved cable lubricant may be used to aid in pulling cables through conduit, when necessary to avoid stretching the conductor or damaging the insulation.

The contractor shall provide drip loops at all signal hangers, wire inlets, and service entrance heads in conformance with good outdoor wiring methods. All wire inlets on the poles and signal heads shall be sealed with duct seal. Cables installed on messenger cable shall be firmly and neatly attached using black nylon cable lashing specified by the manufacturer for outdoor service and approved by the engineer. This lashing shall be installed as shown on the plans but not more than twelve (12) inches (31 cm) apart, and in accordance with the manufacturer's recommendation, to insure a neat, first class appearance. The contractor may choose to install the overhead communications cable using an integral messenger type cable rather than separate messenger cable. There shall be two (2) feet of extra cable left on each lead in the base of all poles.

(2) Cable Splices and Connections for Communications Cable. Insofar as possible, communications cable is to be installed in continuous lengths between terminal boards in cabinets. Splices shall be made in the communications cable only where absolutely necessary, as determined by, and subject to the approval of, the engineer. All splices shall be made in strict accordance with the recommendations of the manufacturers of the cable, connectors, and splice enclosures.

Connectors used in splicing communications cable shall be of a type specifically intended for splicing multi-conductor telephone cable, and shall be applied with a tool of the same manufacturer. No prestripping or cutting of the wires shall be required. Rather, the applicator tool shall automatically trim the wires to proper length in the crimping cycle. The connector shall displace the wire insulation during the crimping cycle so that each wire is mechanically held in place in at least two places and has at least four electrical contact points. The connector shall be capable of either straight or butt splices, with at least two wires entering each end of the connector, for a total of four wires, minimum. Connectors shall be suitable for use with either jelly-filled or unfilled cable.

Splice enclosures shall be completely waterproof and dust tight, and shall not be affected by extremes of temperature or soil condition. Any metal parts shall be corrosion-proof. The enclosure shall, as a minumum, accommodate the diameter of the bundle of cables to be spliced. For splices in pull boxes, the overall length of the enclosure shall not be so long as to create crimping of the cables when the splice is placed in the pull box and the lid secured.

Removal of the splice enclosure cover shall be possible without the use of special tools, and shall expose all wire pairs for inspection and testing. A polyurethane resin compound shall be used to hold the cables in place and seal the cable entry hole in the enclosure, as well as saturate and seal the cable ends. Other effective means for sealing the entry and cable ends and holding the cables in place may be approved by the engineer.

The shields of the cables to be spliced shall be bonded by means of a cable bonding braid.

(3) Test of Existing Communications Cable. Existing communications cable, shown on the plans, shall be tested for continuity and insulation resistance. When a cable fails to meet the standards set forth below, the fault shall be isolated to the segment between either splice(s) and/or termination boards, and the engineer shall be notified.

Continuity resistance shall be tested by measuring the DC resistance of all conductors in the cable. This resistance shall not exceed 18 ohms per 1,000 feet (58 ohms per kilometer) at 20°C.

Insulation resistance shall be tested by measuring each insulated conductor with all other insulated conductors and the shield grounded. This resistance shall have a value of not less than 10 meg-ohm mile (16 meg-ohm kilometer) at 20°C. The measurement shall be made with a DC potential of not less than 100 nor more than 550 volts applied for one minute.

The contractor shall restore all splices after testing in accordance with paragraph 6.2.5.d.(2).

e. Typical Plan Drawings

Figures 6-2 and 6-3 are typical plan drawings which depict where and how equipment and material is to be installed.

6.3 SOFTWARE FUNCTIONAL SPECIFICATION

6.3.1 General Description

The local computer software shall consist of two basic routines, namely the hardware interrupt servicing routine (INTRUP) and the traffic control processing routine (MAIN). Each routine shall be initially entered in response to a hardware-generated signal. Routine INTRUP shall be entered when either the line-frequency clock or the serial input-output (communication) line require service, and routine MAIN shall be entered at power start up. Once started, routine MAIN shall not exit except to permit service to the INTRUP routine or to the power shutdown routine.

Each of these routines shall call subroutines which perform the real-time tasks required of the system. Logic flow diagrams and operating software for these subroutines will vary with the microcomputer selected and shall be developed during actual implementation of a system.

6.3.2 Hardware Interrupt Servicing Routine (INTRUP)

a. General

The hardware interrupt servicing routine (INTRUP) shall be entered from the MAIN routine whenever an interrupt occurs and shall return control to the MAIN routine when it has completed its task. It shall call two subroutines, namely, line frequency clock (CLOCK) and communications input-output (COMM).

The flow chart for the INTRUP routine is shown in Figure 6-4. When an interrupt occurs, the line-frequency clock shall first be examined and its servicing temporarily deferred if a communication interrupt has occurred simultaneously. After the communication interrupt has been serviced, the clock interrupt shall be serviced (if waiting) before returning to the point in the MAIN routine at which the interrupt(s) occurred.

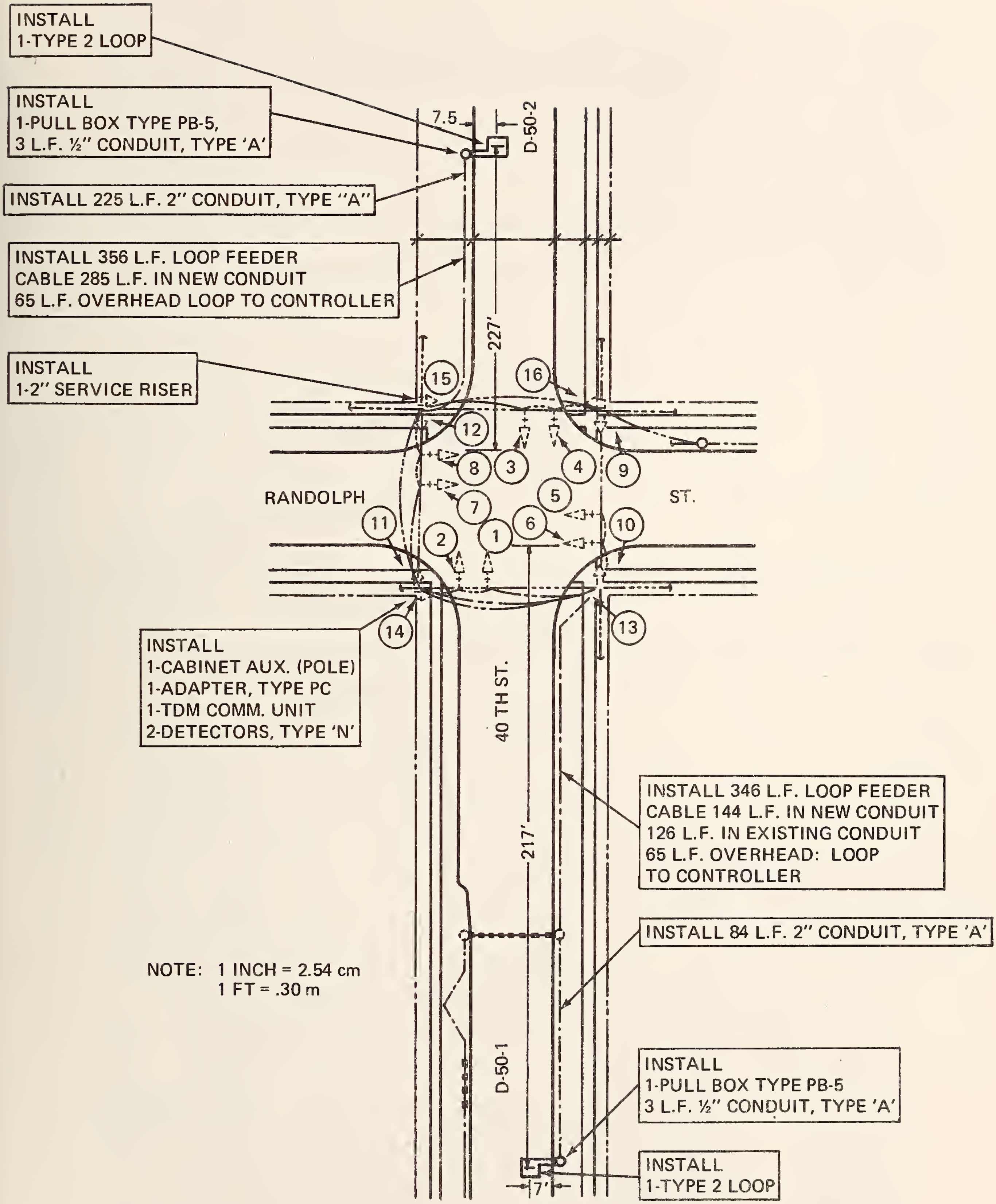

FIGURE 6-2. TYPICAL PLAN DRAWING

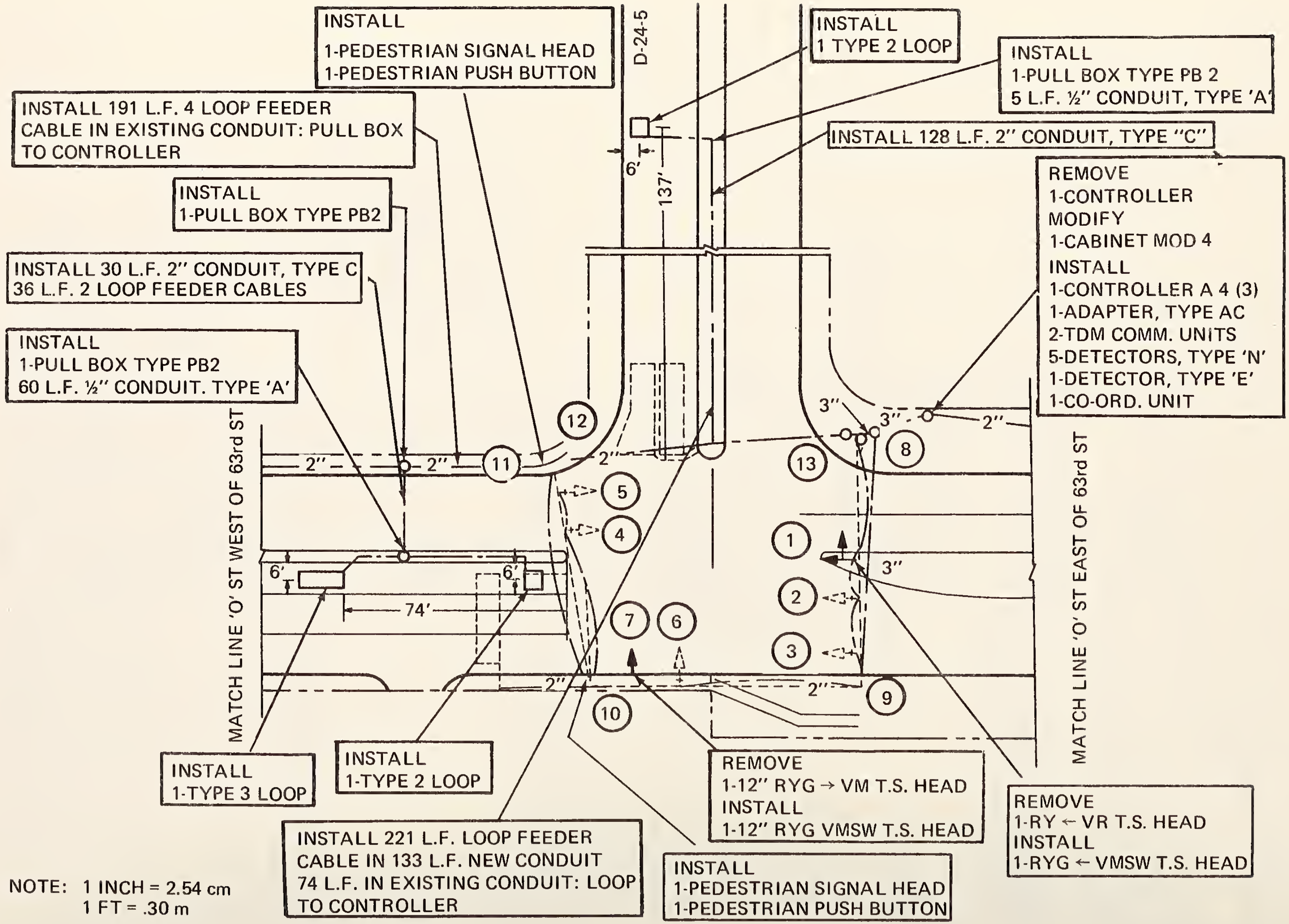

FIGURE 6-3. TYPICAL PLAN DRAWING

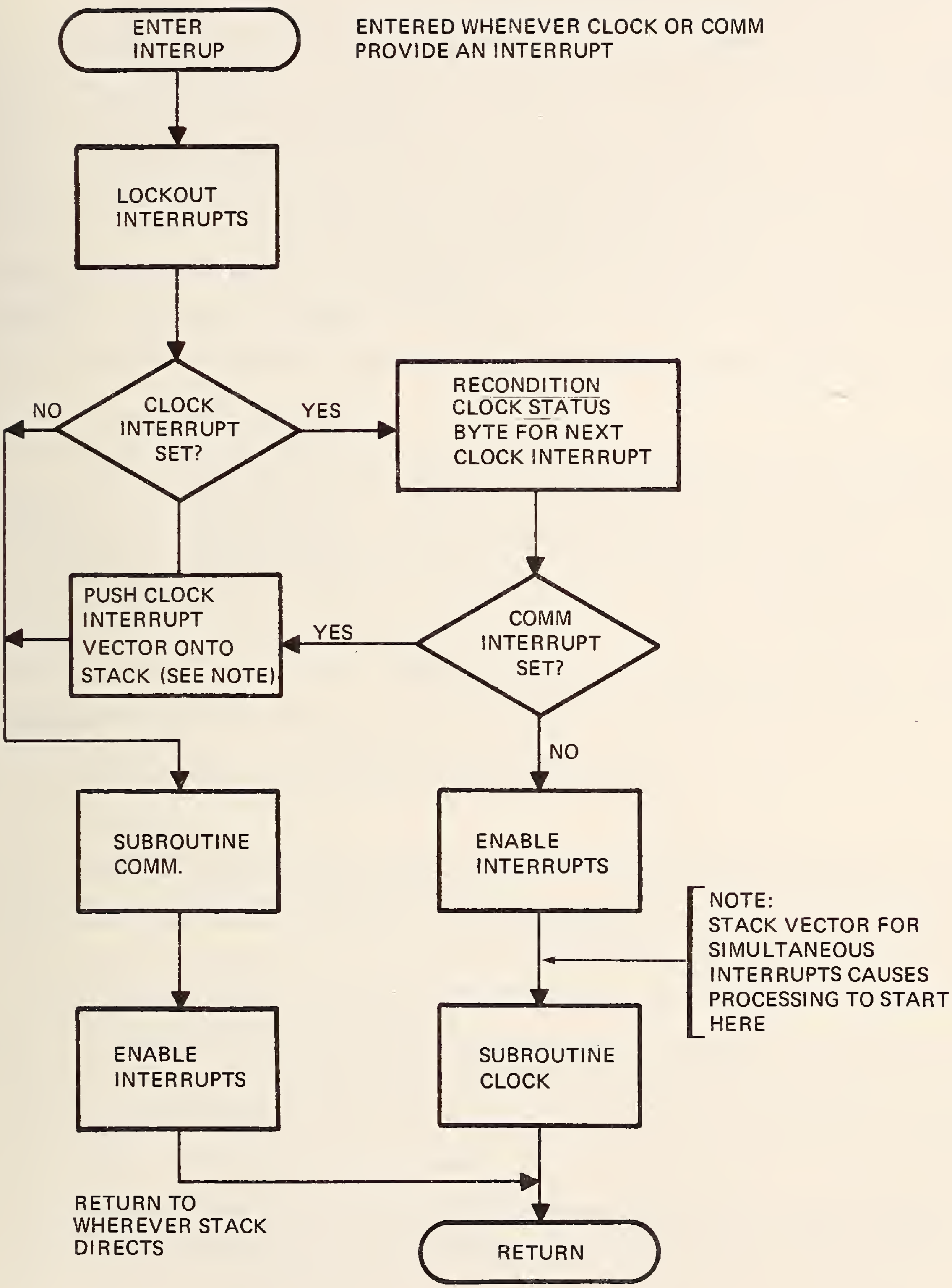

FIGURE 6-4. HARDWARE INTERRUPT SERVICING ROUTINE (INTRUP)

b. Line Frequency Clock Subroutine (CLOCK)

All of the microcomputers in the system shall be provided with line frequency clocks. These clocks generate one interrupt each AC cycle, i.e., 60 per second. Since all of the computers will, in general, be powered by the same source, the hardware provides a means to guarantee that there will be no time drift between computers, except in the case of power or equipment failure. Since the system requires that the computers not drift with respect to one another and the hardware supports this requirement, it is mandatory that the software maintain its clock without any drift as long as there is neither power nor hardware failure. This function shall be performed in the interrupt driven task INTRUP since there is not point in MAIN that clocks and time event flags can be set and still guarantee drift-free operation.

Subroutine CLOCK in routine INTRUP shall support this time-keeping function. It shall maintain the day-of-week and time-of-day, set time-driven event flags, provide no-drift timing for cycle clocks and controller timing, and synchronously sample and drive the digital inputs and outputs. The longest path through this routine shall be less than 1,000 microseconds.

c. Communications Input-Output Subroutine (COMM)

The communications input-output subroutine shall employ four registers (storage locations) to interface with the communication channel, namely, data receive, data transmit, control, and status registers.

The data receive and data transmit registers shall act as buffers for temporarily storing 8-bit bytes while awaiting the appropriate time for transfer to the serial data shift register or to computer memory respectively.

The control register shall permit the software to control the serial input/output interface. At startup, this register shall initialize the input/output logic, set the received data strobe rate, and enable the read interrupt. Whenever a transmission is to start, the control register shall lock out receive interrupts, set the transmit strobe rate and enable the transmit interrupt.

The status register shall indicate the occurrence of detected transmission errors and shall indicate when transfer of data to the transmit register and from the receive register is permissible.

A transmission shall be initiated by the input/output requesting subroutine moving a character to the transmit register. When ready for another character, the hardware shall automatically produce an interrupt at which point another character can be moved to the transmit register by subroutine COMM. This process is continued until the transmission of all characters is complete.

The receive portion of the I/O process shall be equally automatic. However, in addition to the reading of characters, the logic in COMM shall also check the input for the following attributes: local computer identifying code; command transmission errors; and expected number of characters to follow.

The longest path through subroutine COMM shall be less than 1,000 microseconds.

d. Timing Considerations

The longest path through subroutines CLOCK and COMM are specified to be less than 1,000 microseconds each. Therefore, with 1,200 baud communications and 1/60 second clock, there will never be more than two hardware interrupts in any 8,000-microsecond period. In addition, no other software, except shutdown, shall have higher priority. Thus even if the two longest paths are required sequentially in CLOCK and COMM, a safety factor of four shall exist in guaranteeing that no clock or communication interrupt will ever be lost.

6.3.3 Traffic Control Processing Routine (MAIN)

a. General

All of the user functions except input/output shall be performed in the traffic control processing routine (MAIN) which shall consist of a single activity list whose order defines the relative priority of all functions (figures 6-5 through 6-8). The highest priority tasks shall be the communication processing subroutines which are scheduled after the completion of a message transmission or reception. These subroutines are placed at this high priority position to make maximum use of the available communication facility. The priority of all the remaining functions is ordered according to frequency of processing. In descending priority order, these include subroutines processed at the following time intervals: 1/30th second; 1/10th second; once per second; once per 15 seconds; once per message; once per minute; and once per cycle. Table 6-2 shows the glossary for the MAIN routine.

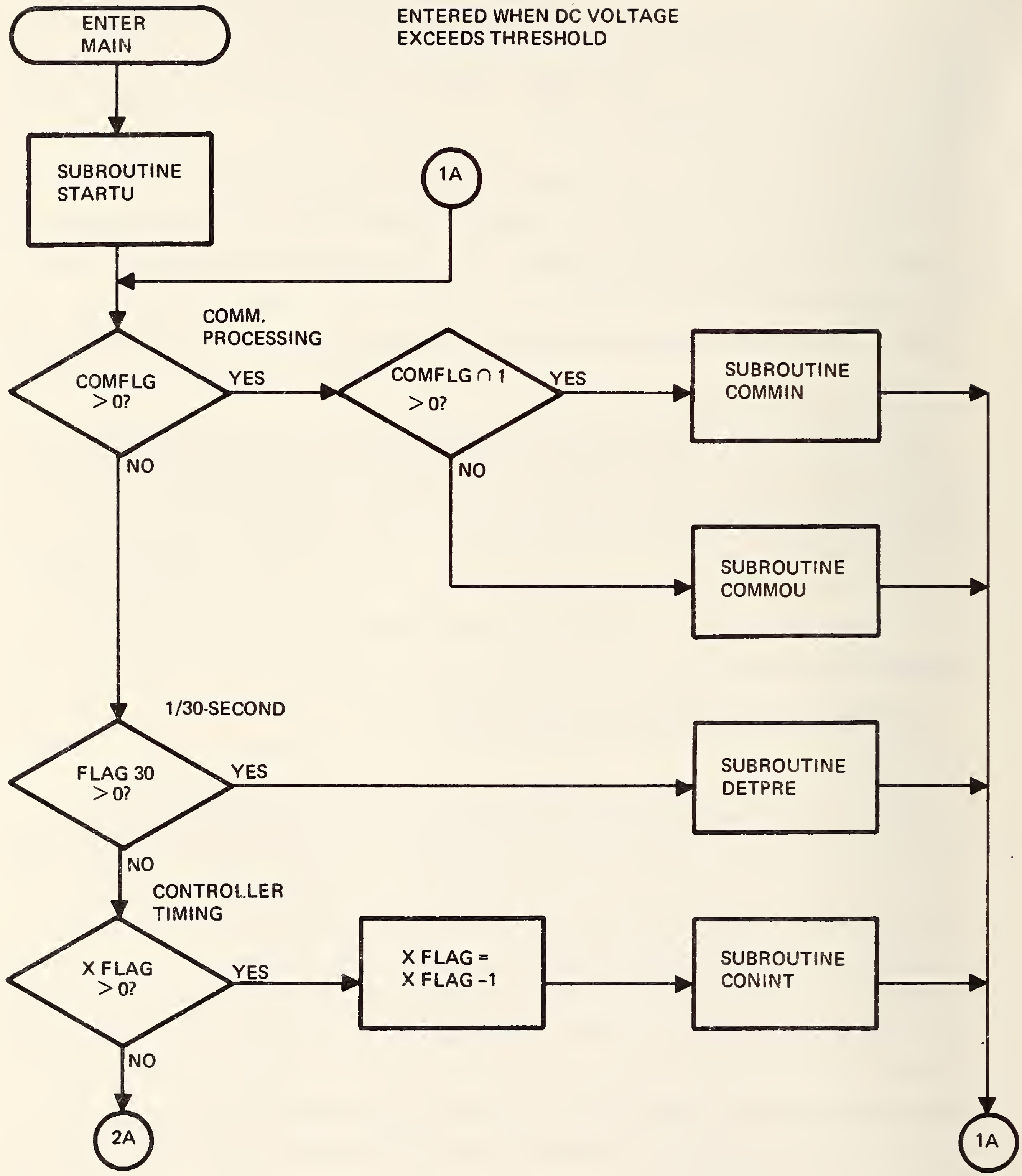

FIGURE 6-5. HIGH PRIORITY SUBROUTINES

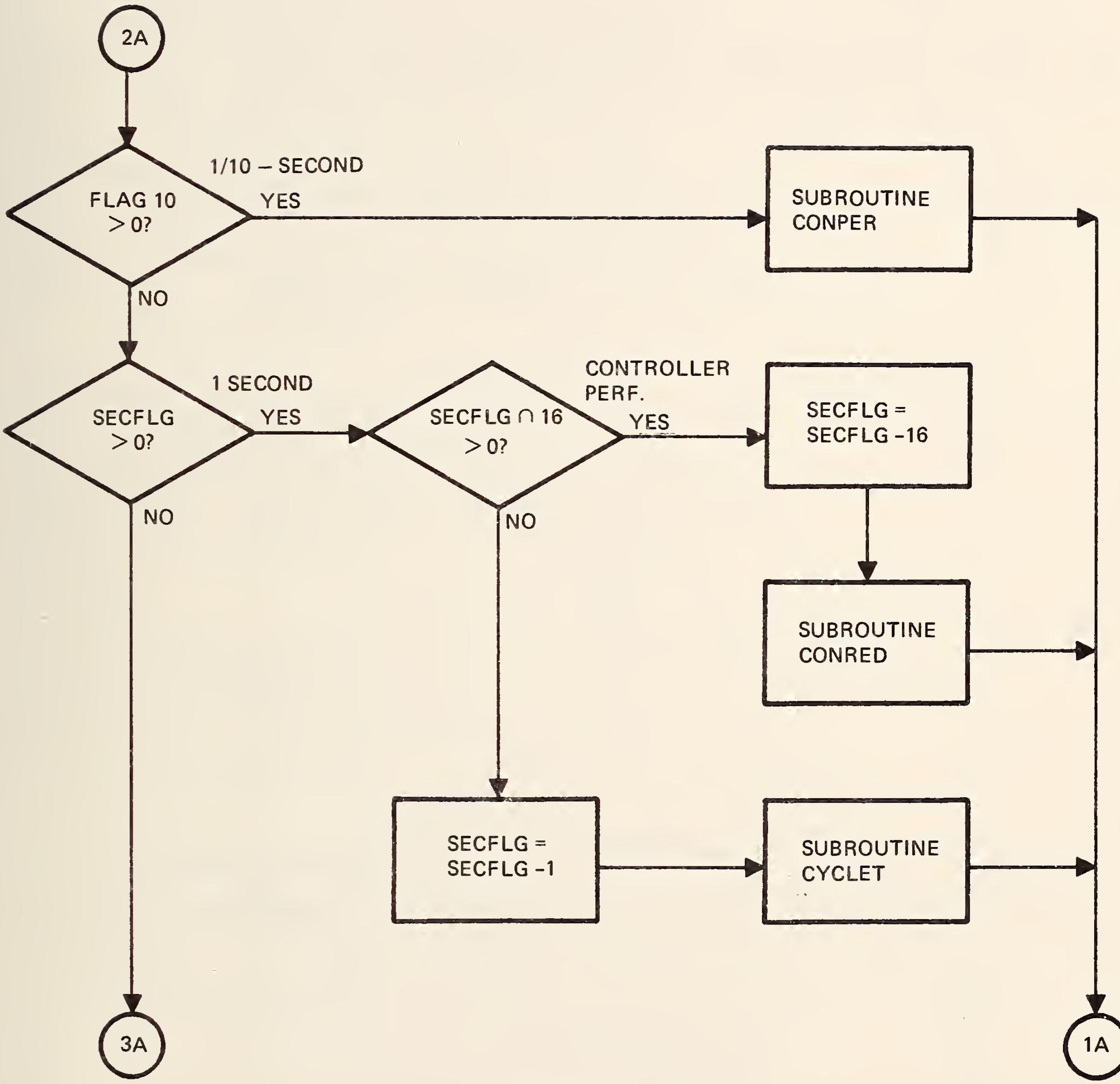

FIGURE 6-6. 1/10 SECOND AND 1 SECOND SUBROUTINES

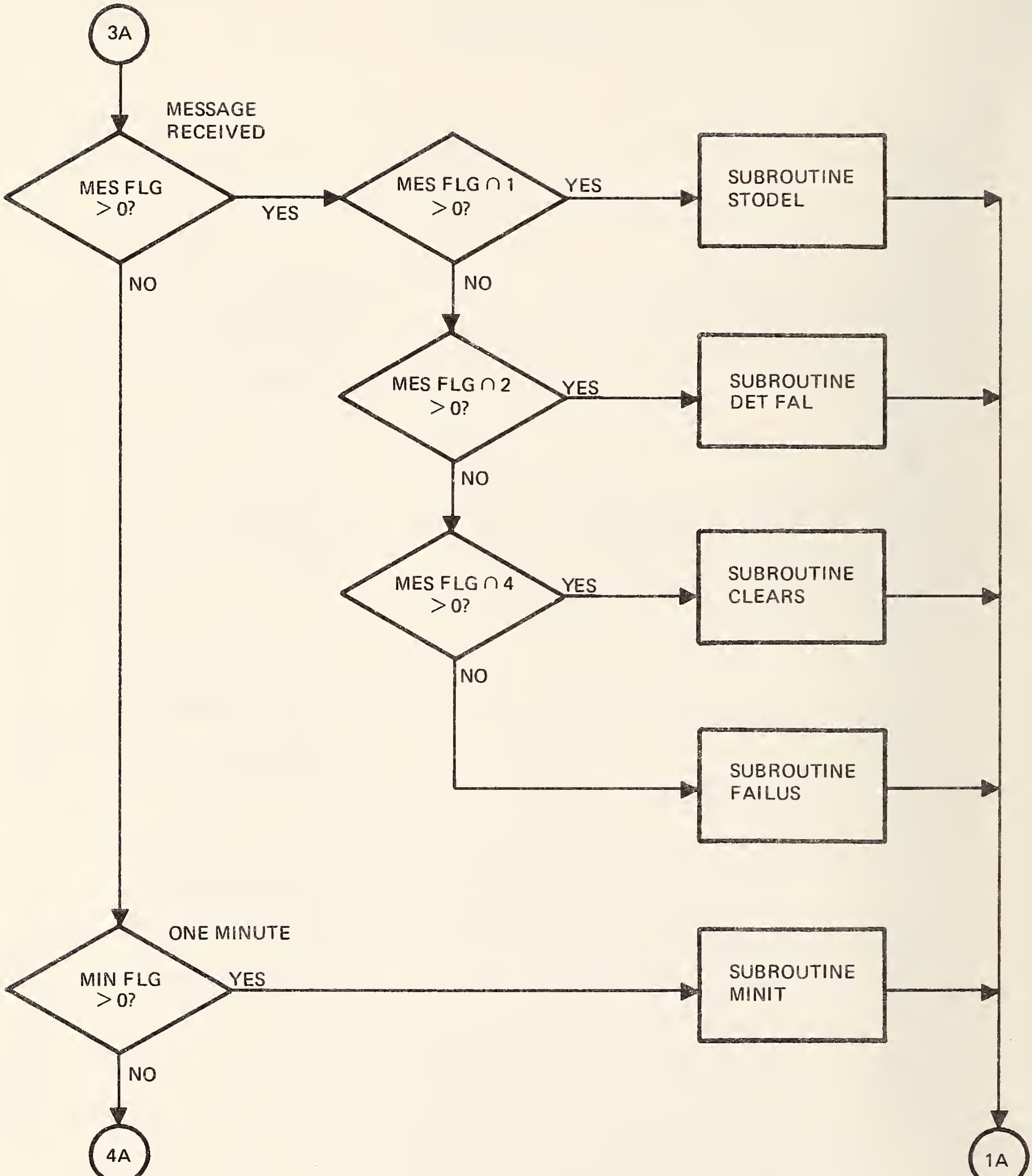

FIGURE 6-7. ONCE PER MESSAGE AND ONCE PER MINUTE SUBROUTINES

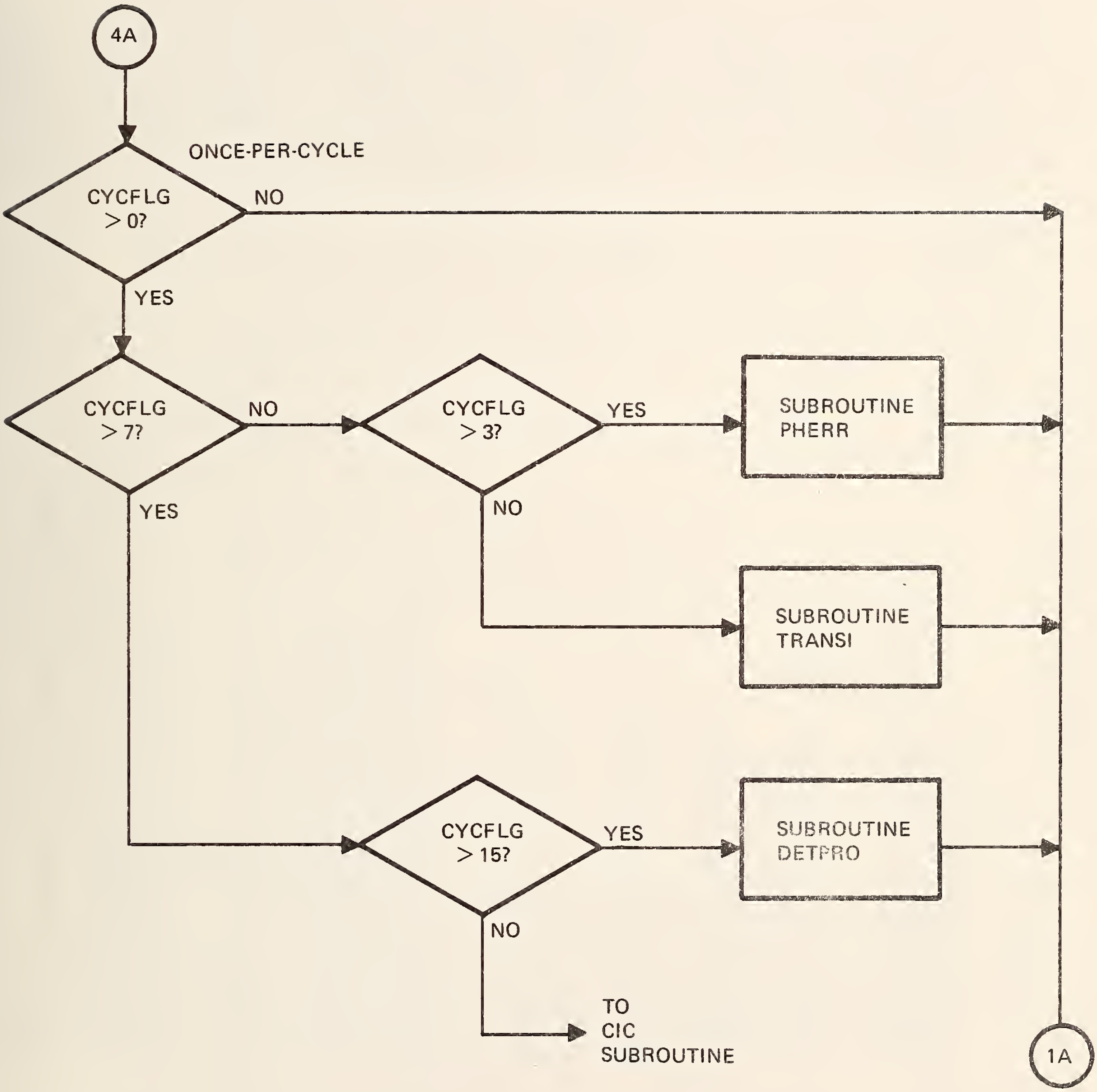

FIGURE 6-8. ONCE PER CYCLE SUBROUTINES

TABLE 6-2. SOFTWARE GLOSSARY

Variable	Description	Bytes	Memory Type	Routines	Processor
COMFLG	Communications event flags: Bit 0 = input block complete or timed out Bit 1 = output block complete or timed out	1	RA	MAIN CLOCK COMM STARTU	L
CYCFLG	Once per cycle action request flags: Bit 0: subroutine TRANSI Bit 2: subroutine PHERR Bit 3: subroutine CICADJ Bit 4: subroutine DETPRO	1	RA	MAIN TRANSI PHERR CICADJ DETPRO STARTU	L
FLAG10	1/10 second action request flag	1	RA	MAIN CLOCK STARTU	L
FLAG30	1/30 second action request flag	1	RA	MAIN CLOCK STARTU	L
MESFLG	Incoming message referenced action flags: Bit 0: execute subroutine STODEL Bit 1: execute subroutine DETFAL Bit 2: execute subroutine CLEARS Bit 3: execute subroutine FAILUS	1	RA	MAIN CLOCK STARTU	L
MINFLG	Once per minute on-the-minute action request	1	RA	MAIN CLOCK STARTU	L
SECFLG	Once per second action request counts Bits 0-3: backlog of subroutine CYCLET requests Bits 4-7: backlog of subroutine CONRED requests	1	RA	MAIN CLOCK STARTU	L
XFLAG	Backlog of controller timing subroutine CONINT calls	1	RA	MAIN CLOCK STARTU	L

After the completion of any subroutine, the list is scanned from top to bottom. The first function found that requires service is then processed. The subroutines processed include the following:

- Start-up (STARTU).
- Communication input processing (COMMIN).
- Communication output processing (COMMOU).
- Detector presence computation (DETPRE).
- Controller interval timing (CONINT).
- Controller performance evaluation (CONPER).
- Controller red green status (CONRED).
- Traffic cycle time keeping (CYCLET).
- Stops and delay computation (STODEL).
- Detector failure (DETFAIL).
- Communication buffer clearing (CLEARS).
- Controller failure status reporting (FAILUS).
- Time keeping (MINIT).
- Phase error evaluation (PHERR).
- Transition (TRANSI).
- Detector data processing (DETPRO).

b. Start-up Subroutine (STARTU)

The start-up subroutine shall be entered in any one of three ways: power turned on, restart button cycled, or test completed. It shall provide all required initialization at start up by zeroing all random access memory (RAM) and then entering the non-zero parameters and flags. Interrupts shall be locked out during the initialization process.

c. Communication Input Processing Subroutine (COMMIN)

The communication input processing subroutine shall be called after the end of each message received from the central computer. It shall perform the following functions:

- Perform input message error detection logic.
- Call subroutines having inputs to the response message to check and enact commands and format response message.
- Set up ROM and PROM tests.
- Initiate transmission of data to the central computer by enabling the transmit interrupt and transferring the first byte to the communication channel.

d. Communication Output Processing Subroutine (COMMOU)

The communication output processing subroutine shall be called after the response message has been transmitted. It shall perform the following functions:

- Reset the output watchdog timer.
- Initialize input character pointer.
- Clear communication error message.
- Initialize input/output registers.
- Set detector data transmit flag.

e. Detector Presence Computation Subroutine (DETPRE)

The detector presence computation subroutine shall be called every 1/30th second. It shall examine the detector arrays for an indication of vehicle presence. It shall then determine the start time and duration of each vehicle or pedestrian passage.

For each end of vehicle indication from a system detector, the subroutine shall compute raw car count, raw occupancy, and raw speed, corrected for bias.

f. Controller Interval Timing Subroutine (CONINT)

The controller interval timing subroutine shall be scheduled by the clock each 1/10th second, at which time the CONINT flag (XFLAG) shall be incremented. The XFLAG shall be decremented each time the subroutine is called. This routine shall time out the intervals of each controller phase, and shall issue force-offs and yields at the appropriate times and for the appropriate durations. In addition, this routine shall perform checks on the traffic signals at the beginning and end of A-phase green, as well as after each force-off. It shall issue appropriate diagnostics when the desired action fails to occur.

g. Controller Performance Evaluation Subroutine (CONPER)

The controller performance evaluation subroutine shall be called each 1/10th second by routine MAIN. It shall detect the state changes of each phase, namely, green, yellow, red, walk and don't walk, as well as system and actuation detector inputs, pedestrian actuations and controller status indications (flash, local, conflict and local test). The subroutine shall interpret this information to determine if the controller is operating properly and shall issue failure indications when deviations from normal operation are detected.

This subroutine shall also coordinate the bringing on line of controllers from standby to computer-controller operation.

h. Controller Red/Green Status Subroutine (CONRED)

The controller red/green status subroutine shall be called every 15 seconds. This subroutine shall log the red/green status of the controller associated with each on-line detector. This information shall be accumulated for each 15-second period for use by subroutine STODEL (computation of stops and delays).

For each on-line detector, the routine shall compare the actual phase green return with the expected return and shall store the resulting red/green status in the controller history array.

i. Traffic Cycle Time-Keeping Subroutine (CYCLET)

The traffic cycle time-keeping subroutine shall be called once per second. It shall time all possible cycle lengths that can be selected for on-street use. It shall up-date all cycle clocks and when the cycle length has been reached for any one, it shall reset its clock to zero and shall set the start flag for that cycle.

j. Stops and Delay Computation Subroutine (STODEL)

This subroutine shall be called at the start of each command message received from the central computer if the stops/delay bit of the MESFLAG byte has been set. It shall calculate stops and delay for each system detector by correlating the sequence of vehicle passages with the appropriate red phase display. Data to be used in these computations shall be the passage data stored by subroutine DETPRE and the red phase data stored by subroutine CONRED.

k. Detector Failure Subroutine (DETFAL)

This subroutine shall be called at the start of each command message received from the central computer if the detector failure flag bit has been set. It shall identify detector failures and shall set flags to prevent use of data from these detectors. It shall also store one-minute accumulations of car count, raw occupancy, average speed, raw stops, and raw delays into the communication buffer for all non-failed detectors.

l. Communication Buffer Clearing Subroutine (CLEARS)

This subroutine shall be called after each local response message has been transmitted. It shall clear the communication buffer in computer memory (reset all locations to zero) after transmission of each complete message.

m. Controller Failure Status Reporting Subroutine (FAILUS)

This subroutine shall be called after the end of each command message received from the central computer if the controller failure flag bit has been set. It shall compile a list of failures generated by other routines and shall group them, as applicable, for transmission to the central computer.

n. Time Keeping Subroutine (MINIT)

The time-keeping subroutine shall be called once each minute by the CLOCK subroutine. It shall perform the following functions:

- Update values for minute, hour and day of week.
- Schedule and initiate interval measurement, when required.
- Establish the priorities of conflicting requests.
- Update detector failure detection threshold pointer.
- Update TOD pattern pointer and request a TOD pattern, if required, when a time block is received from the central processor.
- Service the following mode changes when requested by the central processor: preempt on; preempt extend; preempt off; flash; standby; local TOD; local pattern; master pattern.
- Time out a requested preempt and return to the desired mode.

- Return control to local TOD if communications is missing for more than a specified number of minutes.
- Enact deferred requests.
- Initiate the bring-on-line function.

o. Phase Error Evaluation Subroutine (PHERR)

This subroutine shall be called once per traffic cycle at the beginning of A-phase green by subroutine CONINT. It shall evaluate the following aspects of controller operation:

- Green or walk displayed when it should have been bypassed.
- Green or walk bypassed when it should have been displayed.

The phase and actuation data required by this subroutine shall be obtained from subroutine CONPER.

p. Transition Subrountine (TRANSI)

The transition subroutine shall be called once per cycle if the transition flag bit is set. This subroutine shall provide the transition timing information for transitions from off-line to a selected on-line pattern, as well as from one on-line pattern to another. This shall be accomplished by appropriately initializing subroutine CONINT when the beginning of the offset reference phases are first detected.

q. Detector Data Processing Subroutine (DETPRO)

This subroutine shall be called once per cycle. It shall compute volume in vehicles per hour, occupancy in percent, and average speed in miles per hour, and shall smooth these values using exponential smoothing algorithms. If there is a detector failure, no computation shall be made.

6.4 STATEMENT OF WORK FOR THE POLLED TDM COMMUNICATION SYSTEM

6.4.1 Introduction

The supplies and services described in this Statement of Work are to be furnished as part of the Computer Traffic Control System. The objective is to provide communications between the computer center and the street equipment.

6.4.2 Invoked Documents

Purchase specification for the Communication System for the Computer Traffic Control System.

6.4.3 Description of Supplies and Services

The SELLER shall perform the tasks and provide all the supplies, documentation and services, described below and in the documents invoked in Paragraph 6.4.2, above.

The SELLER shall comply with all Sections and Paragraphs of the invoked documents except as specifically modified by this Statement of Work.

a. Item 1: Equipment Design, Fabrication and Tests

(1) Design and Manufacture. The proposed design for the Polled TDM Communications System shall be the nearest equipment which conforms to the purchase specifications. Any exception to the specifications shall be itemized and modified only by written agreement prior to the issuance of a purchase order.

(2) Experience. The SELLER must have built at least one similar type system. The SELLER shall provide data on the operational experience with these units. The SELLER shall provide the PURCHASER with the names of users of this equipment.

(3) Design Approval. The SELLER must obtain from the PURCHASER approval of his preliminary design.

(4) Design Approval Tests. The SELLER must perform tests acceptable to the PURCHASER to receive design approval.

The proposed test shall include sequence and duration of the test cycle involved.

The PURCHASER shall be advised a minimum of 15 days in advance of the time when the tests are to be conducted so that his representative may be designated to witness the tests.

(5) Factory Acceptance. That portion of the Communication System that is required in Item 6 for the first delivery, shall be completely tested as a system. The central communication modules, remote communication units and other required assemblies shall be utilized in sufficient combinations to assure that a system of up to remote units shall operate properly. The Communications System shall be tested with sufficient computer and street equipment simulation to show proper system operation. Those items scheduled to be delivered at subsequent dates shall be tested as individual units.

The PURCHASER shall be advised a minimum of 15 days in advance of the time when tests are to be conducted so that a representative may be designated to witness these tests.

(6) Installation Acceptance Test. That portion of the Communication System that is scheduled in Item 6 for first delivery, shall be completely tested as a system after delivery. After each subsequent delivery the Communication System shall be completely tested. Where there is no existing street connection the remote units shall be connected at the control center.

The SELLER shall assume, for purpose of establishing his bid price, that the computer will not be available when he delivers the Communication System. His installation technician(s) shall be required to return after the computer is installed to perform final acceptance tests.

b. Item 2: Procurement Documentation

The SELLER shall be prepared to supply documentation on some or all of the following items. Specific requirements are invoked in Item 6.

(1) Equipment Outline. All dimensions defining the outline configuration of the unit.

(2) Mounting Supports. Location and dimensions of mounting pads indicating method of mounting equipment to support structure.

(3) Power and Air Cooling Access. Location and clear identification of all cooling air connections, electrical connectors, controls and vents.

(4) Weight. Weight of unit and weight per mounting pad.

(5) Equipment Handling. Special handling and accessibility considerations.

(6) Restrictions. Any restrictions or precautions including interfacing and cable lengths which must be considered in the location or mounting of the unit.

(7) Power Consumption. The total power consumption of the equipment shall be indicated.

(8) Cooling Requirements. Air cooling requirements including temperature and required rate of flow.

(9) Reliability. Statement of reliability prediction and basis therefor.

(10) Schematics. Circuit diagrams for each type of module to be supplied.

(11) Interconnections. Equipment interconnection diagrams shall be provided.

(12) External Wiring Diagrams. The external wiring diagrams, including symbols and drawing sizes, shall conform to good engineering practices.

(13) Design Approval Proposal. The design approval proposal must include PURCHASER approval of the preliminary design and any exception to the specifications. These exceptions shall be itemized, and modified only by written agreement prior to the issuance of a purchase order.

(14) Establishment of a Product Line. The SELLER shall submit field data on the operation of representative product line equipment.

(15) Expansion Capabilities. The SELLER shall submit a statement indicating the capability of his equipment to be modularly expanded to its maximum capacity.

(16) Factory Acceptance Procedure. The SELLER shall submit 30 days prior to on-site installation his installation acceptance test procedures.

c. Item 3: Support Documentation

The SELLER shall be prepared to supply documentation on some or all of the following items. Specific requirements are invoked in Item 6.

(1) Instruction Manual. The SELLER shall provide Instruction Manual(s) containing sufficient information to operate and maintain the equipment. The manual(s) shall also include schematics and wiring diagrams where the components are clearly identified and cross referenced to electrical parts list and component layout diagrams.

(2) Installation Instructions. The SELLER shall provide instructions pertaining to the installation of his equipment including any precautions which must be considered in handling the equipment.

(3) Parts List. The SELLER shall furnish a complete parts list of the modules and components used in the equipment. The designation of parts shall correspond to the key numbers in the schematic and assembly drawings contained in the Instruction Manual. The parts list shall contain information on component identification and vendor.

(4) Recommended Spares. A list of recommended spares shall be provided by the SELLER based on estimated component reliability data and purchase lead time.

d. Item 4: Management Documentation

The SELLER shall be prepared to supply documentation on some or all of the following items. Specific requirements are listed in Item 6.

(1) Schedule Requirements. The SELLER shall prepare and furnish a chart indicating his plans for scheduling: the preliminary equipment design and procurement, design approval test, equipment manufacture, factory acceptance test, delivery milestones and installation acceptance test.

(2) Status Reports. The SELLER shall provide the PURCHASER with a monthly written status report.

e. Item 5: Operations Support

The SELLER shall be prepared to supply some or all of the following services. Specific requirements are listed in Item 6.

(1) On-Site Service. The SELLER of the equipment shall supervise and be responsible for the installation, checkout and final test of the equipment.

(2) Additional On-Site Services. The SELLER shall submit with his proposal a rate schedule for field maintenance service. This rate schedule shall consider two 1-day service calls per year to clean, lubricate and repair the equipment as necessary. These rates shall remain in effect for a 1 year period after installation. The SELLER shall also indicate the maximum response time for an emergency service call for any day of the week. This rate schedule is required for information purposes and will not be considered in the vendor qualification procedure.

(3) Warranty. The equipment furnished by the SELLER shall be guaranteed against defective material and workmanship for a period of twelve months from the date of certification. During this twelve month time period all defects shall be corrected at no cost to the PURCHASER.

f. Item 6: Deliverable Items and Scheduled Delivery

The following table defines all the items to be delivered by the SELLER, the schedule for delivery and the specification cross reference number.

TABLE 6-3. DELIVERABLE ITEMS AND SCHEDULED DELIVERY

S.O.W. item no.	Qty.	Equipment/supplies	Spec. ref. no.	Delivery months A.R.O.
6.4.1	1	Central Communication Module		4
	1	Remote Communication Unit		4
	1	Remote Communication Unit		5
	1	Remote Communication Unit		6
	1	Central Communication Cabinet		4
	1	Central Communication Chassis		4
	1	Power Supplies		4
	1	Communication Verification Unit		4
6.4.3.a.(4)	1	Design Approval Test		2
6,4.3.a.(5)	1	Factory Acceptance Test		3
6.4.3.b	5	Sets of all Procurement Documentation items		4
6.4.3.c	5	Sets of all Support Documentation items listed		4
6.4.3.d.(1)	5	Sets of SELLERS schedule plans		1
6.4.3.d.(2)	1	Status Report		Monthly
6.4.3.e.(1)	1	On-Site Service		
6.4.3.e.(2)	1	Additional On-Site Service		
6.4.3.e.(3)	1	Warranty		

GLOSSARY

This glossary defines basic terminology used in telecommunications at a semi-technical level. * Detailed definitions of some terms are contained within the main text where required for complete understanding of the text material.

ASCII

The American Standard Code for Information Interchange (ASCII) is an 8-level code accepted as a communication standard in North America to achieve compatability between data services. ASCII uses 7 binary bits for information and the 8th bit for parity purposes.

address

(1) In communication: the coded representation of the destination of a message.

(2) In computing: the coded representation of the location of a set of data in storage.

adjacent channel

The channel next to or in close proximity either physically or electrically to the channel being used.

algorithm

A prescribed set of well-defined rules or processes for arriving at a solution to a problem.

amplitude modulation (AM)

The process of modifying the amplitude of a carrier wave with a signal.

asynchronous transmission

Transmission in which the intervals between transmitted characters may be of unequal length. Transmission is controlled by start and stop elements at the beginning and end of each character. Also referred to as start-stop transmission.

attenuation

The difference (loss) between transmitted and received power due to transmission loss through equipment, lines or other communication devices.

*This glossary has been excerpted, with minor changes, from "Computer Communications and Telecommunications Terminology", April, 1977; The Computer Communications Group, Ottowa, Canada.

band

A range of frequencies between two defined limits; e.g., the voiceband in telephony is about 300 to 3,000 Hz.

bandwidth

The difference between the upper and lower limits of a band; e.g., bandwidth of a voice channel is 3,000-300 equals 2,700 Hz.

baseband

The frequency band occupied by information bearing signals before they are combined with a carrier in the modulation process.

baud

A unit of signalling speed. It can be defined in two ways: (1) The number of signal elements per second where all such elements are of equal length and represent one or more information bits. (2) The reciprocal of the time duration of the shortest signal element being transmitted; e.g., if the shortest signal element is .02 seconds, the signalling speed would be 50 baud.

binary

A numbering system in which there are only two states, conditions or numbers. The binary system is represented by the numbers 0 and 1.

bit

A contraction of the term binary digit. A bit can be either 0 or 1 and is the smallest possible unit of information.

bit rate

The rate at which bits (binary digits) are transmitted over a communications path. Normally expressed in bits per second (bps). The bit rate is not to be confused with the data signalling rate which measures the rate of signal elements being transmitted.

block

A set of associated words or characters handled as a unit. Data is normally organized into blocks on continuous recording media such as magnetic or paper tape, or for transmission purposes.

bridge, bridging

Equipment and techniques used to match circuits to each other ensuring minimum transmission impairment. Bridging is normally required on multipoint data channels where several local loops or channels are interconnected.

broadband

Refers to transmission facilities whose bandwidth (range of frequencies they will handle) is greater than that available on voice grade facilities. Also called wideband.

buffer

A temporary storage device for data which cannot be used immediately. Buffers may be used on a network for error checking, for store and forward or to compensate for a difference in the rate of flow of data when transmitting from one device to another.

burst, error

A series of consecutive errors in data transmission. Refers to the phenomenon that errors are highly prone to occurring in groups or clusters.

bus

A common medium for transmitting energy or data from one or more sources to one or more receivers.

byte

A sequence of normally 8 bits operated on as a unit. A byte can represent either one alphanumeric character or two numerics.

CCITT

(Comité Consultatif International Télégraphique et Téléphonique.) The International Telegraph and Telephone Consultative Committee: an international organization concerned with devising and proposing recommendations for international telecommunications.

cable

An assembly of one or more insulated wires in a common protective sheath.

cable, coaxial

A cable consisting of one or more tubes each of which has a wire contained within and insulated from a surrounding conductor.

carrier wave

A single frequency signal of constant amplitude which may be modulated or modified with respect to frequency, amplitude or phase for transportation over a wire, cable, or radio facility.

central office

The location of telephone switching equipment where customers' lines are terminated and interconnected. Also called switching center.

central processing unit (CPU)

The heart of a digital computer where data is manipulated and calculations are performed. The CPU contains a control unit to interpret and execute the program and an arithmetic-logic unit.

channel

An electrical transmission path between two or more stations. Channels may be furnished by wire, radio, or a combination of both.

channel capacity

The maximum information rate which can be accommodated by a given channel. Channel capacity is normally measured in baud but may be stated in bits per second when specific terminating equipment is mentioned.

channel, four-wire

A two-way circuit where the signals may simultaneously follow separate and distinct paths in opposite directions in the transmission medium.

channel, full-duplex

A channel providing simultaneous transmissions in both directions.

channel, half-duplex

A channel in which signals can be transmitted in either direction but not simultaneously.

channel, voiceband or voice grade

A channel which permits transmission of frequencies normally in the passband between 300 and 3,000 Hz.

character

The actual or coded representation of a digit, letter, or special symbol. The character is a convenient unit of measurement of data volume as its definition is consistent throughout the data processing and communications disciplines.

clear-to-send delay

Time required by a data set to inform a terminal device that it is ready to send or reply to information just received. Also called modem turnaround.

clock

A timing device used to indicate the passage of or intervals of time. A clock circuit may be used in computers and data sets to synchronize and coordinate the manipulation and transmission of data.

code

A set of symbols and rules for use in representing information; e.g., the ASCII code is an eight-level system used for information interchange amoung data processing systems, communications systems, and assoicated equipment.

conditioning

The addition of electronic equipment such as loading coils to improve the transmission characteristics with regard to delay distortion and attenuation loss.

continuity check

A check made of the information bearer channel or channels in a connection to verify that an information path exists.

data

Any representations, such as digital characters or analog quantities, to which meaning might be assigned. Any information which can be transmitted electronically.

data set

A device which converts on-off voltage signals that are suitable for transmission over communications facilities at one end and back to signals at the other. It may also perform other related control and supervisory functions. See also modem.

DC signalling

Transmission of data and/or control signals using direct current pusles at signalling speeds below 150 baud. DC signaling is usable only on channels having wires with direct current continuity.

decibel

A unit for measuring the relative strength of a signal parameter such as power or voltage. Normally used in measuring the loss or gain of power in a device or channel.

delay distortion

A distortion which occurs on communication channels due to the different propagation speeds of signals at different frequencies. Some frequencies travel slower than other in a given transmission medium and therefore arrive at the destination at slightly different times. Delay distortion is measured in microseconds of delay relative to the delay at 1,700 Hz. This type of distortion does not affect voice but can have a serious effect on some data transmission.

demodulator

A component of a data set or modem which is responsible for recovering data from received signals and converting to a form suitable for the receiving digital equipment. See also modem.

digital

Pertaining to digits or to the representation of data or physical quantities by digits.

direct current (DC)

An electrical signal which flows in one direction at a constant amplitude. Direct current cannot be transmitted on the telephone network except when metallic circuitry is specifically provided.

distortion

The unwanted modification or change of signals from their true form by some characteristic of the channel or equipment being used for transmission, e.g., delay distortion, amplitude distortion.

drop

That portion of outside telephone plant which extends from the telephone distribution cable to the subscriber's premises or to a roadside cabinet.

EIA

Electronic Industries Association: a consultative group of manufacturers recognized as the standards writing agency in the United States for electronic equipment; e.g., one EIA interface is a voltage-operated interface approved for use under the EIA RS-232-C Standard.

error detection and correction

Techniques used in data communications systems to identify the occurrence of transmission or device errors and initiate some corrective action. Some systems only detect errors while others will order retransmission as a means of error correction or use complicated forward acting error correction.

exchange

A defined area for the provision and administration of telephone service. This area may consists of one or more central offices and normally includes a city or town and its environs.

fiber optics transmission system

A transmission system utilizing small diameter glass fibers through which light is transmitted. Information is transferred by modulating the transmitted light. These modulated signals are detected by light-sensitive semiconductor devices (photodiode).

filter

Electronic circuitry which blocks some components of a signal while allowing other components to pass through uniformly. For example, a high-pass filter blocks all frequencies in a signal which are below a specified frequency called the "cut-off".

flag

Refers to a signal set up to indicate that a specific condition has occurred in a computer. The flag may be programmed or generated in the machine. For example, when a buffer is full, a flag may be set up to indicate this condition.

frequency division multiplexing (FDM)

A multiplex system in which the available transmission frequency range is divided into narrower bands, each used for a separate channel. Channels are derived by allocating or "splitting up" a wider bandwidth into several narrower bandwidths.

frequency modulation (FM)

The process of modifying the frequency of a carrier wave in step with the amplitude variations of the signal to be transmitted.

frequency shift keying (FSK)

A form of frequency modulation in which the carrier frequency is made to vary or change in frequency at the instant when there is a change in the state of the signal being transmitted; i.e., the carrier frequency on the line during a "one" or marking condition would be shifted to another predetermined frequency during a "zero" or spacing condition.

full-duplex

See channel, full-duplex.

gain

The degree to which the amplitude of a signal is increased. The amount of amplication realized when a signal passes through an amplifier, repeater, or antenna. Normally measured in decibels.

Gaussian noise

A noise whose amplitude is characterized by the Gaussian distribution, a well-known statistical distribution.

half-duplex

See channel, half-duplex.

Hertz

Internationally recognized unit of measure for electrical frequency. The number of cycles per second. Abbreviated Hz.

hit on the line

General term used to describe errors caused by external interferences such as impulse noise caused by lightning or man-made interference.

I/O

A short form for input-output.

impedance

The total opposition offered by a component or circuit to the flow of an alternating or varying current; a combination of resistance and reactance.

impulse noise

A type of interference on communication channels characterized by high amplitude and short duration. This type of interference may be caused by lightning, electrical sparking action common in power tools, or by the make-break action of switching devices, etc. Sometimes called impulsive noise.

insertion loss

The power which is absorbed by a circuit element or device when it is connected into a channel or electronic device. The loss in power on a communications channel when bridges, filters, equalizers, or other components are used.

instruction, program

A command instructing the computer to perform a specific operation. A set of characters which define the operation to be performed and the data or equipment to be used.

integrated circuit

An electronic circuit or array of components etched into a single chip of silcon material. Used in third generation computers and other equipment to reduce size and increase speed and reliability.

interface

A shared boundary. The connection point between two subsystems or devices. Typically, the connection between computer or controller and the data set, modem or communications channel.

interference

Refers to unwanted occurrences on communications channels which are a result of natural or man-made noises and signals, not properly a part of the signals being transmitted.

interrupt

To interrupt or stop temporarily the operation of a computer program to perform some predetermined operation, after which control may be resumed at the point of interruption. Interrupts may be of two types: (1) Programmed by the system designer at regular and specific intervals during a program. (2) Priority interrupt, a part of the hardware which automatically interrupts operations when specific conditions arise.

kilo

Greek word meaning 1000. Used as a prefix in the international system of measurements; e.g., kilohertz, kilowatts, etc.

LSI

Large scale integrated circuit (as in integrated circuit except "a large number of circuit elements").

leased circuit data transmission service

A service whereby a circuit (or circuits) of the public data network is made available to a user or group of users for his exclusive use. Where only two data circuit-terminating equipments are involved, it is known as a point-to-point facility and where more than two are involved, it is known as a multipoint facility.

leased line

A communication channel provided for the exclusive use of a customer by a common carrier at a fixed monthly rate.

light-emitting diode (LED)

Semiconductor device which emits light when energized by an applied voltage. Major use is in visual displays as in electronic calculators.

loading cable

Adding inductance (load coils) at specific intervals along a cable in order to reduce amplitude distortion and improve frequency response over the desired bandwidth. This compensates for the effect of distributed capacitance between conductors in a cable.

local loop

In telephony-a channel connecting a subscriber to his serving central office.

longitudinal redundancy check (LRC)

A system of parity checking for transmission errors. Data organized into blocks will have a block-check or LRC character following the block. The LRC character is developed by forming a parity check on all bits in the same bit position in the block.

mark

A pulse on a data circuit used to signify a "one" binary condition. Contrast with space.

medium, data transmission

The method or physical equipment through which data is transmitted; e.g., cable, coaxial cable, atmosphere.

mega

A greek word meaning one million. Used as a prefix in the international system of measurements; e.g., megabits, that is one million bits (10^6).

message format

Rules for the placement of such portions of the message as message heading, address, text, and end of the message.

metal oxide silicon (MOS)

Refers to the type of technology by which a class of field effect transistors are made.

micro

Greek word meaning one millionth of a unit. Used as a prefix in the international system of measurements; e.g., microsecond, that is 0.000001 of a second commonly expressed as 10^{-6}.

microprocessor

A single LSI chip or set of chips that performs the basic arithmetic and logical functions of a computer central processing unit. When equipped with memory and input/output control circuitry, the micropressor becomes a "microcomputer" which can offer capabilities quite similar to minicomputers.

milli

Greek word meaning one thousandth of a unit. Used as a prefix in the international system of measurements; e.g., millisecond, that is 0.001 of a second commonly expressed as 10^{-3}.

modem

Contraction of the term modulator-demodulator. A device to convert one form of signal to another form for facility compatibility. For example, a modem is used to convert a digital signal from a computer into an analog signal so that it may be transmitted over the network.

modulation

A process whereby a signal is transformed from its original form into a signal that is more suitable for transmission over the medium between the transmitter and the receiver. Also see amplitude modulation, frequency modulation, and phase modulation.

multidrop

Line or channel connecting more than one station.

multiplexing

Techniques to combine several communications channels into one facility or transmission path. See frequency division multiplexing and time division multiplexing.

multipoint

Line or channel connecting stations in at least three different exchanges. See also leased circuit data transmission service.

nano

Greek work meaning one billionth of a unit. Used as a prefix in the international system of measurements; e.g., nanosecond, that is 0.000000001 of a second. Commonly expressed as 10^{-9}.

narrowband

A channel whose bandwidth is less than that of a voice grade channel. Commonly used for communication at speeds of less than 300 bits per second.

network

A series of points interconnected by communications channels.

noise

An interference present on communications channels.

parallel transmission

Simultaneous transmission of all code elements or bits representing a character or word.

parity bit

A bit added to coding schemes so that the total of all "one" or "mark" bits in an array will always be either even (even parity) or odd (odd parity).

parity check

The process of checking received data to determine if the correct parity has been received. If the total of "one" or "mark" bits is not odd or even depending on the system being used, an error has occurred. See parity bit.

passband

A range of frequencies which carries acceptable transmission on a given channel, e.g., the passband on a voice grade channel is from 300 to 3,000 Hz.

phase modulation, phase-shift keying

The process of modifying the phase of a carrier signal with an information bearing signal.

polling

The process of "calling out" to remote stations from a central point on a sequential systematic basis. The polling operation may be to request, collect or distribute data.

private line

A channel or circuit for a subscriber's exclusive use.

RS-232-C

See EIA.

random distribution

A distribution of events where the probability of any event occurring at any given time is the same for it occurring at any other time.

ratio, signal-to-noise

A relative measurement of the amplitude of a signal to the amplitude of the noise on a communications channel. Usually expressed in decibels. Used in measuring channel quality and specifying channel or equipment characteristics.

redundancy

That portion of the total information contained in a message which can be eliminated without loss of essential information. Information added to a message which does not change the content other than to provide supervisory or checking capability. Parity bits are considered redundant information.

repeater

A bidirectional device used in channels to amplify or regenerate signals.

response, frequency

The relationship of the gain or loss of a channel or device to the frequency of the applied signal. See also attenuation distortion.

serial transmission

A method of information transfer in which bits composing a character are sent sequentially. Contrast with parallel transmission.

signal

A detectable impulse (voltage, current magnetic field or light impulse) by which information is communicated through electronic or optical means or over wire, cable, microwave, or laser beams.

signal, digital

A descrete or discontinuous electrical signal; one whose various states are distinctly separated.

signal element

The basic unit by which data is transmitted on communication channels, Each signal element is a state or condition on a channel which represents one or more bits of digital information. A signal element might be a DC pulse or an AC signal of some amplitude, frequency, or phase which the receiving equipment can recognize and translate into the original format. Signalling speed is the number of such signal elements occurring in one second and is measured in baud.

storage

A general term for any device capable of retaining information. Normally some type of electronic or magnetic memory device.

subroutine

A set of instructions in a computer program which performs some well-defined mathematical or logical operation. Control may be transferred to a subroutine when necessary and back to the main program when the subroutine's functions habe been performed; e.g., an error subroutine.

synchronization

The process of maintaining common timing and coordination between two or more operations, events or processes.

tariff

The published volume of rates, rules, and regulations concerning specific equipment and services provided by a communications common carrier.

thermal noise

Electromagnetic noise produced in conductors or in electronic circuitry which is proportional to temperature. Also see Gaussian noise.

throughput

A productivity rating used to describe computing systems. Generally, the amount of data which can be input, processed and in turn output in a given unit of time.

time division multiplexing (TDM)

A technique for combining the information signals from several devices into one transmission path in which each signal is allotted a specific position in the signal stream.

transceiver

A device capable of transmitting and receiving, not necessarily simultaneously.

voiceband or voice grade channel

See channel, voiceband or voice grade.

wideband

Synonymous with broadband.

word

An ordered set of bits which is the normal unit in which information may be stored, transmitted, or operated upon within a computer. Word length is specified by the machine designer.

☆U.S. GOVERNMENT PRINTING OFFICE: 1979 628-619/2117 1-3

#35959

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

FHWA
R&D