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A COMMUNICATIONS TRADE-OFF STUDY FOR COMPUTERIZED TRAFFIC CONTROL

Vol. 2. Appendixes

November 1978

Final Report

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.

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Charles F. Scheffey

Charles F. Scheffey
Director, Office of Research

NOTICE

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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.

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METRIC CONVERSION FACTORS

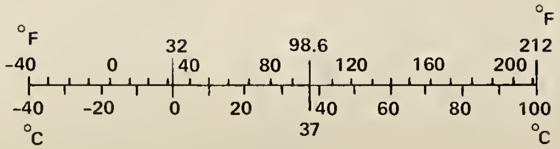
Approximate Conversions to Metric Measures

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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CONTENTS (Cont.)

FIGURES

FIGURES (Cont.)

FIGURES (Cont.)

TABLES

TABLES (Cont.)

APPENDIX A

VEHICLE DETECTOR DATA COMMUNICATIONS

A.1 INTRODUCTION

The purpose of this part of the study is to assess the performance capabilities of existing systems for communicating traffic surveillance data, to develop certain performance trade-offs for these systems and to explore related techniques for more efficient communication.

Current computer traffic control systems use TDM or FDM techniques for detector data transmission. The FDM approach usually utilizes general purpose telemetry equipment with a bandwidth of 120 Hz per channel. A number of such channels are multiplexed onto voice grade lines. This technique essentially replicates the vehicle pulse at the central computer. Computer interrogation (sampling) rates of 30 or 32 times per second are common.

The TDM technique interrogates the detector at the intersection and stores a limited amount of data. Most existing systems then transmit this data frequently to the central computer which accumulates it for a period and then processes it. The TDM approach has been selected for analysis in this report because the inherent design flexibility of this technique offers a greater potential opportunity to implement the results of this analysis.

A.2 ANALYSIS OF TYPICAL TDM SYSTEM TYPE

A.2.1 Block Diagram of Overall System

Figure A-1 shows a functional block diagram of a typical TDM communications system coupled to a central computer. In this analysis our attention will be focused on the occupancy variable because in a properly designed system it is only this variable (and its algorithmic derivatives) which are subject to sampling and quantization error.

The figure shows that the detectors are sampled each T seconds by field equipment, that these samples are stored in an occupancy counter of n bits and that this data is transmitted to the control center each T_1 seconds. The data is accumulated by the control center computer for a period T_2. It is then filtered by a suitable algorithm.

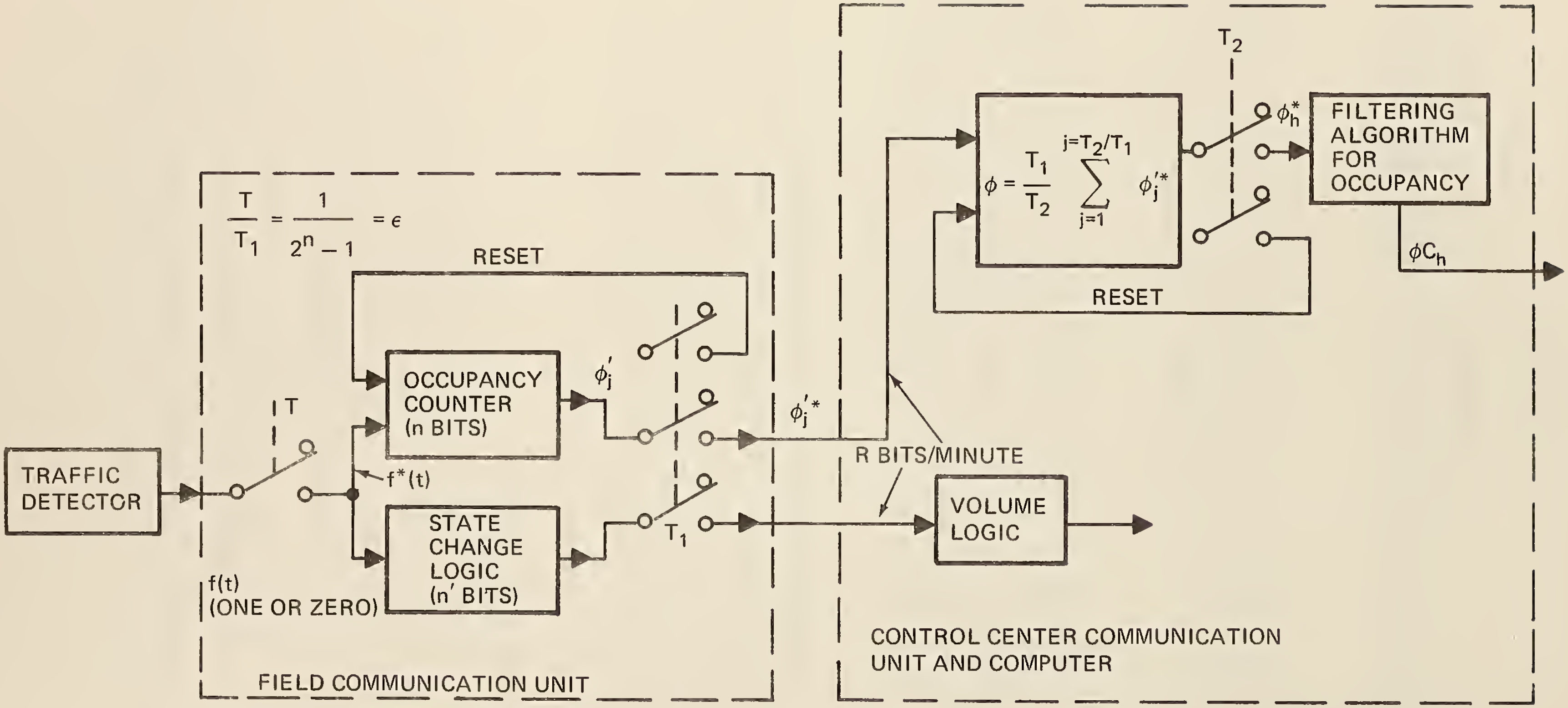


FIGURE A-1. SYSTEM FUNCTIONAL DIAGRAM

In one common embodiment of this design, the sampling time T_1 is one second, n equals 4, and T_2 equals the cycle length. In this case the state change logic for the volume computation can be implemented with one bit, and thus $n' = 1$.

A.2.2 Analysis of Sampling and Quantizing Error

Representative time sequences in certain portions of the field communication unit are shown in Figure A-2. Figure A-2(a) shows the sampling instants for the T samples, Figure A-2(b) shows the waveshape at the detector output, and Figure A-2(c) shows the sampled values. The waveform of Figure A-2(d) does not actually exist in the system but it serves to show an equivalent time replication of the output ϕ_j'. This output is actually physically present only as $\phi_J'{}^*$ which is analytically given by,

$$\phi_j'{}^* = \frac{1}{2^n - 1} \sum_{a=1}^{2^n - 1} f_a^*(aT) \; . \tag{A-1}$$

Figure A-2(e) shows the replicated error (given by subtracting Figure A-2(d) from Figure A-2(b).

Figure A-2 shows that error in the $\phi_j'{}^*$ is generated only when the detector changes state, where e_1 denotes the replicated error caused in going from the zero to the one state and e_2 denotes the replicated error caused in going from the one to the zero state.

For practical purposes, it may be assumed that vehicle passage occurs independent of the sampling instants. With this assumption, the leading and trailing edges of f(t) (considered separately) have a constant probability of lying at any given position within the sampling instant. This generates the error probability functions shown in Figure A-3, and leads to the following mean and variance relationships:

$$\text{Mean of } e_1\text{:} \quad E_{1M} = -\frac{\epsilon}{2} \; , \tag{A-2}$$

$$\text{Variance of } e_1\text{:} \quad E_{1V} = \frac{\epsilon^2}{12} \; . \tag{A-3}$$

Similarly,

$$E_{2M} = \frac{\epsilon}{2} \; , \tag{A-4}$$

$$E_{2V} = \frac{\epsilon^2}{12} \; . \tag{A-5}$$

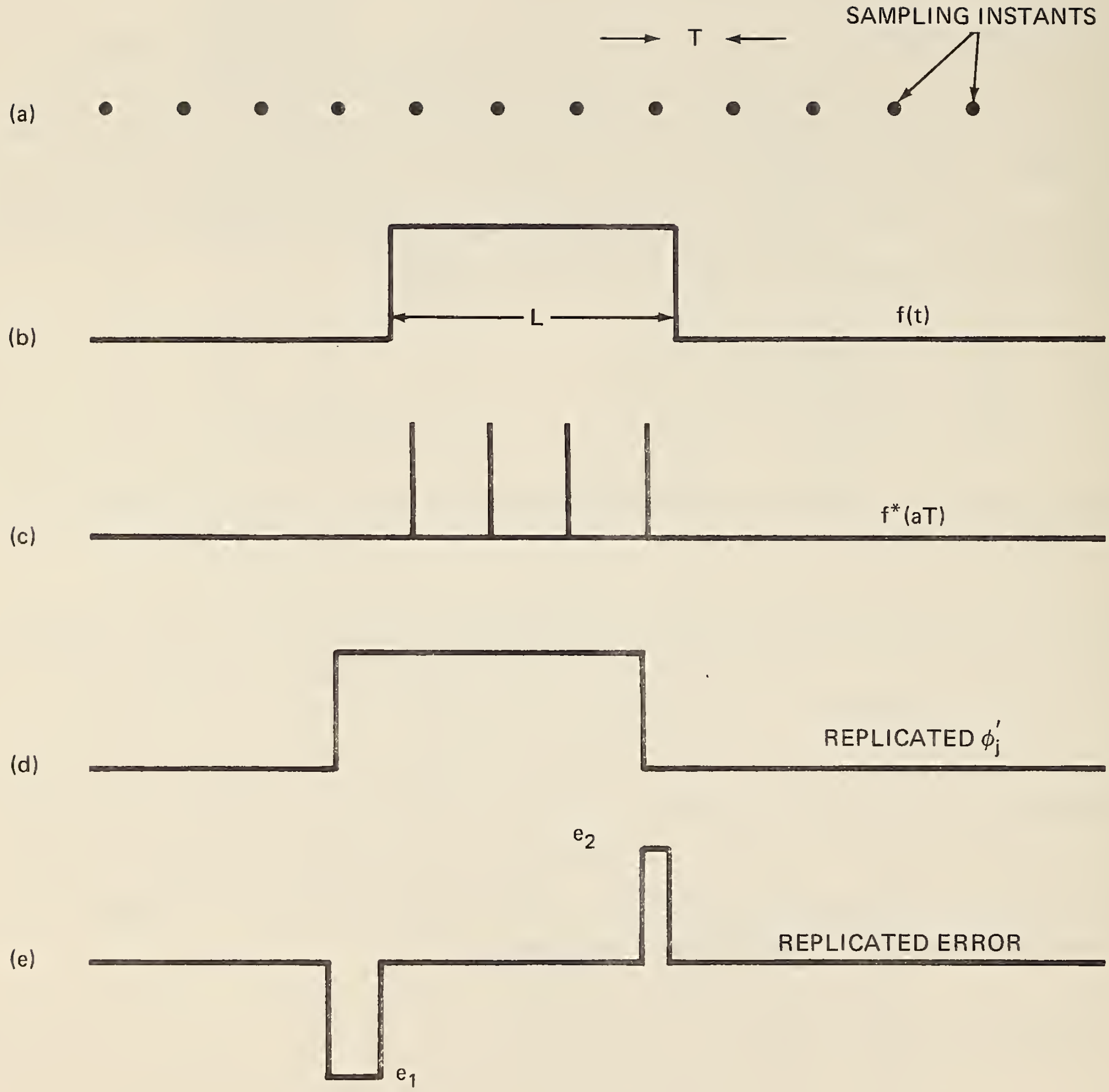
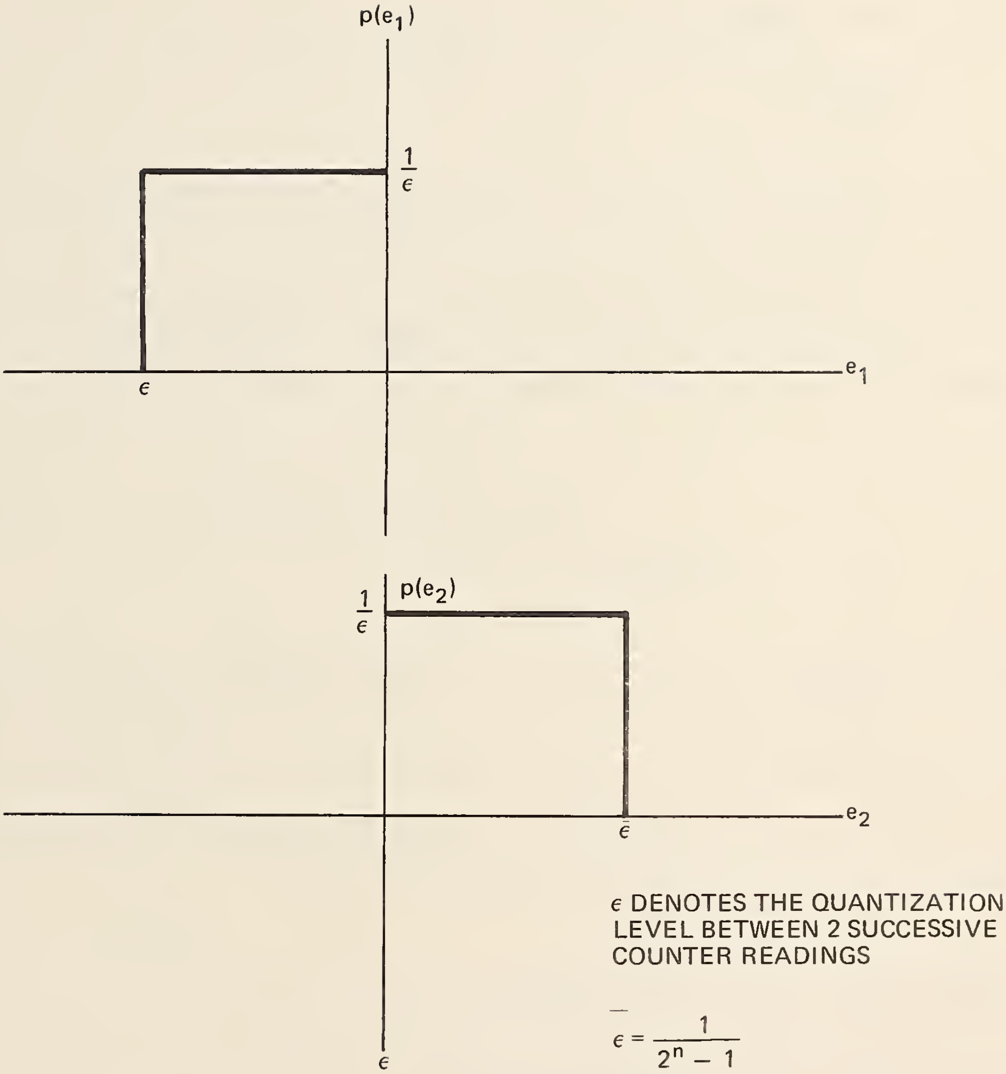


FIGURE A-2. TIME PROFILES OF SIGNALS



ε DENOTES THE QUANTIZATION LEVEL BETWEEN 2 SUCCESSIVE COUNTER READINGS

$$\bar{\epsilon} = \frac{1}{2^n - 1}$$

FIGURE A-3. PROBABILITY DISTRIBUTION OF QUANTIZATION ERROR

Referring to Figure A-2, it is seen that if the vehicle pulse length L is considerably longer than T, there will, from an engineering viewpoint, be little correlation between the error introduced by the leading and trailing vehicle pulse edges and the total variance for the error during the accumulation period T_1 may be obtained by

$$\begin{aligned} E_{TV} &= sE_{1V} + wE_{2V} \\ &= \frac{s + w}{12} \epsilon^2 , \end{aligned} \tag{A-6}$$

where s and w represent the number of appearances of the leading and trailing edge in the T_1 interval. Note that s and w cannot differ by more than ±1. In the case where L is sufficiently short to lie wholely within the sample period, the interval T must be sufficiently short to allow not more than one state change within a sampling interval. A maximum interval of approximately 0.2 seconds (or 3 bits when T_1 equals one second) will generally suffice.

The total mean error at the counter output at T_1 is given by

$$E_{TM} = -\frac{s\epsilon}{2} + \frac{w\epsilon}{2} = \frac{(w - s)}{2} \epsilon . \tag{A-7}$$

In the representation of Figure A-1, $\phi_j'*$ is scaled to unity. That is, if the sensor were to indicate a vehicle during the entire T_1 period, $\phi_j'*$ would indicate a unity output.

Now consider the effect of the summation process between the T_1 and T_2 samplers on the variance of $\phi_j'*$ given by equation (A-6). Because each $\phi_j'*$ is assumed to be statistically independent, the scaled value of the variance is given by

$$D_{TV}^2 = \frac{T_1^2}{T_2^2} \sum_{j=1}^{j=T_2/T_1} \left(\frac{s_j + w_j}{12} \right) \epsilon^2 . \tag{A-8}$$

For the sample constant volume core, where

$$s_j = w_j = q , \tag{A-9}$$

the variance is:

$$D_{TV}^2 = \frac{T_1 q \epsilon^2}{6T_2} = \frac{T_1 q}{6T_2 (2^n - 1)^2} . \tag{A-10}$$

In this equation, q represents volume (in vehicles per T_1 interval).

The mean error is given by

$$D_{TM} = \frac{T_1}{T_2} \sum_{j=1}^{j=T_2/T_1} \frac{(w_j - s_j)}{2} \epsilon . \tag{A-11}$$

Since in any interval T_2 the number of leading and trailing edges must differ by no more than one, the mean error during this period may assume the values

$$\text{zero} + \frac{T_1}{2T_2} \epsilon ,$$

$$\text{zero} - \frac{T_1}{2T_2} \epsilon . \tag{A-12}$$

It is shown in Attachment 1 that the error caused by this source is considerably less than the random error effect and may be disregarded.

A.2.3 Projection of Error Through Occupancy Filter

The UTCS first generation occupancy algorithm is given by

$$\phi C(h) = \phi C(h - 1) + K[\phi h - \phi C(h - 1)] , \tag{A-13}$$

where h represents the T_2 sampling period.

Using z transform notation,

$$\phi C(z) = z^{-1}\phi C(z) + K\phi(z) - z^{-1}K\phi C(z) \tag{A-14}$$

$$\frac{\phi C(z)}{\phi(z)} = \frac{Kz}{z - (1 - K)} . \tag{A-15}$$

In most cases the value of the smoothing constant K has been selected in the field based on the traffic engineer's or consultant's perceived estimate of an appropriate trade-off between responsivity and smoothed output. Note that although D_{TV} is a random input source to the filter, an even larger random input source is developed as a result of the normal variation in traffic flow. Assuming Poisson distributions for the counts accumulated during T_2, representative values of the standard deviation for volumes of 1,000 VPH and 500 VPH are respectively 24 percent and 35 percent of the volume when T_2 is taken as 60 seconds. The point of this discussion is that the random effect of traffic is usually much larger than the D_{TV} value of equation (A-10). Thus, the value of K cannot be specified based on considerations which minimize quantization effects relative to a systematic traffic input, and the analysis which follows assumes that the value of K is externally selected and is simply a parameter of the analysis.

The general formula for computing the power spectral density at the output of a filter given the input power spectral density is in general given by[1]

$$S_A(z) = H(z^{-1})\,H(z)\,S_{AR}(z) \ , \tag{A-16}$$

where $S_{AR}(z)$ is the input sampled power spectral density; $H(z)$ is the z transfer function; $H(z^{-1})$ is the $H(z)$ function with each z replaced by z^{-1}.

Since the values of the random portion of the error at each sampling instant have been assumed to be uncorrelated, the expression for the power spectral density of this component at the occupancy filter's input is directly given by equation (A-10). Substituting into equations (A-15) and (A-16) yields

$$S_A(z) = \left(\frac{K(z^{-1})}{z^{-1} - (1 - K)}\right)\left(\frac{Kz}{z - (1 - K)}\right) D_{TV}^2 \ , \tag{A-17}$$

$$S_A(z) = \frac{K^2 z D_{TV}^2}{[1 - (1 - K)z]\,[z - (1 - K)]} \ . \tag{A-18}$$

The variance of $S_A(z)$ can be obtained[2] by evaluating

$$S_A(0) = \frac{1}{2\pi j} \int_{\Gamma} S_A(z)\, z^{-1}\, dz \tag{A-19}$$

over the path of integration Γ, the unit circle.

This integral can be evaluated by the method of residues. Applying the formulation of equation (A-19) to equation (A-18) yields

$$J^2 = S_A(0) = \frac{1}{2\pi j} \int_{\Gamma} \frac{K^2 D_{TV}^2\, dz}{[1 - (1 - K)z]\,[z - (1 - K)]} \ . \tag{A-20}$$

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[1] J. Ragazzini and G. Franklin, "Sampled Data Control Systems", McGraw-Hill Book Co. Inc. 1958, page 264.

[2] Op Cit, page 258.

Evaluating equation (A-20) by the method of residues requires taking the residue of the expression in brackets in equation (A-20) at each pole which is located inside the unit circle[3] (in equation (A-20) at $z = 1 - K$). Performing this operation yields

$$J^2 = \frac{KD_{TV}^2}{2 - K} \,. \tag{A-21}$$

Substituting equation (A-10) into equation (A-21) yields

$$J^2 = \frac{T_1 K q \epsilon^2}{6T_2(2 - K)} = \frac{T_1 K q}{6T_2(2 - K)\,(2^n - 1)^2} \,. \tag{A-22}$$

This expression is the variance of the random error portion of the filter output. The standard deviation of the occupancy error is given by

$$J = \sqrt{\frac{T_1 K q}{6T_2(2 - K)}} \left(\frac{1}{2^n - 1}\right) . \tag{A-23}$$

Recall that equation (A-23) is scaled such that the units of q are in vehicles per T_1 interval. In the subsequent analysis, T_1 has been scaled in seconds.

Letting

$$q = q' T_1 \,, \tag{A-24}$$

where q' is the flow in veh/sec. Then,

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

Depending on the processing algorithm used, occupancy values may or may not be compensated for the apparent loop length. The following analysis assumes that this compensation has been made. Thus, the value of occupancy is given by

$$\phi = \frac{lq'}{u} \,, \tag{A-26}$$

where l is the average vehicle length (in feet); u is the average vehicle speed (in ft/sec); q' is the vehicle volume per second.

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[3] Op Cit. page 78, 79.

Thus, the standard deviation of occupancy error as a percent of occupancy is

$$\frac{J}{\phi} = \frac{uT_1}{l(2^n - 1)} \quad \frac{K}{6T_2(2 - K)q'} . \qquad \text{(A-27)}$$

One significant performance requirement for occupancy error is that in UTCS first generation software, threshold values of volume and occupancy are established from a number of available timing patterns. This selection should not be significantly affected by the communication system error contribution.

Another significant requirement for the accuracy of this variable is in the calculation of measures of effectiveness (MOE). Link speed is a commonly computed MOE. The percentage error in computed speed is highly correlated to the percentage error in computed occupancy.

Consider first the value of the occupancy error which may be tolerated by control strategies which use this information. For the case of the first generation UTCS strategy, it appears that indicated occupancy values whose errors are less than one percent of full scale (i.e., 0.01) may be tolerated. Equation (A-25) is plotted in Figure A-4 for the representative case of $T_1 = 1$ second and $T_2 = 60$ seconds. The values of $K = 0.1$ and $K = 0.5$ represent the approximate range of smoothing constant values for which such systems have been operated. The figure is plotted for a rather wide range of traffic volumes which may be encountered on surface streets.

Figure A-5 shows the percent occupancy error for various conditions and bit lengths as computed from equation (A-27). In general, a resolution of 3 bits for the occupancy variable is satisfactory for traffic control purposes. Taken together with the state change bit (volume) this results in a requirement of 4 data bits per second for the transmission of data from each field detector using this technique.

A.3 POSSIBLE VARIATIONS IN COMMUNICATION SCHEME

The preceding section described the errors which are developed as a function of varying the traffic conditions and changing the sampling interval T (and with it the occupancy word length n). In this section we consider the situation where the occupancy quantization error is kept constant (and with it by implication the sampling interval T). We allow the modem interrogation interval T_1 to vary, and with it the length of the occupancy counter n and the volume counter n'.

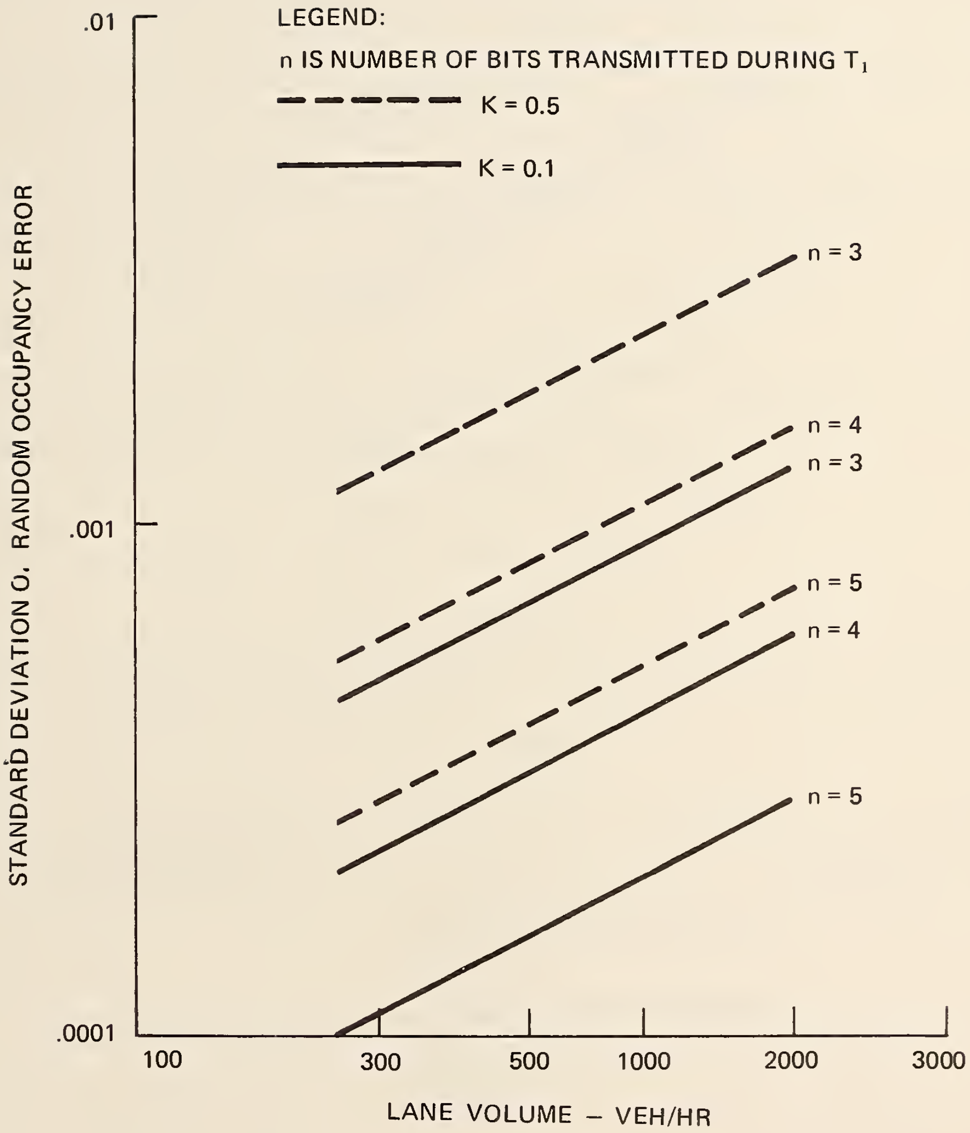

FIGURE A-4. OCCUPANCY ERROR

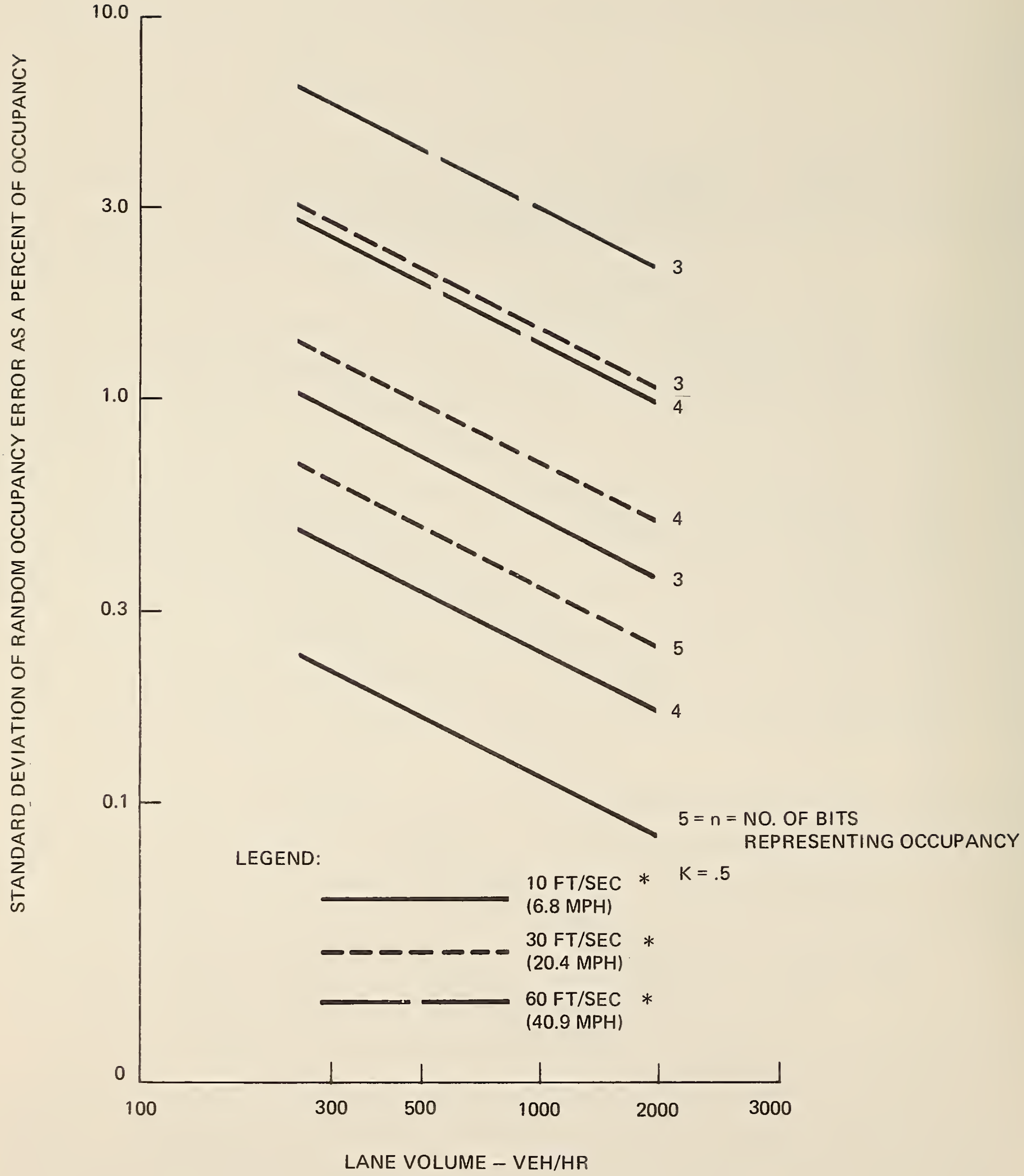

FIGURE A-5. PERCENTAGE ERROR IN OCCUPANCY

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*1 ft = 0.3048 m

The number of occupancy intervals sampled in the period T_2 is

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

Using the parameters of the previous example (T_2 = 60 seconds, T = 1 second, n = 4) the value of S is computed to be 900.

If n is varied in equation (A-28), appropriate values of T_1 can be computed to maintain the same system error, while T_2 and S are held constant.

The value of n' (the number of bits required in the volume register) can be obtained by solving the expression:

$$T_1 \times q_M \leq 2^{n'} - 1 , \tag{A-29}$$

where q_M is the maximum lane volume (say 2,500 VPH) which may be experienced.

The rate of data transmission per T_2 period is, then.

$$R = (n + n') \frac{T_2}{T_1} . \tag{A-30}$$

Figure A-6 plots the pertinent parameters for the sample case. As shown, distributed microprocessor systems using T_1 periods in excess of 30 seconds require considerably less communication capability for detector data.

An opportunity would appear to exist to reduce the communication requirements for centrally organized systems by providing greater internal modem storage capacity. The traffic functions which may be impacted by this approach (if, in fact they are system requirements) are:

a. The ability of the central computer to provide rapid local control responses such as critical intersection control, actuated control, and bus priority control*. T_1 may not be increased if these functions are to be performed by a central computer.

b. The ability of the central computer to implement cycle-free strategies such as UTCS third generation which may make considerable use of intra-cycle data. Thus, systems which want to retain the capability of later inclusion of these strategies can only increase T_1 to a modest extent.

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*Although a different type of detector is often used for bus priority, there is usually a strong desire to design a system with a single design approach for the communications system and adapt it as necessary to special requirements of this nature.

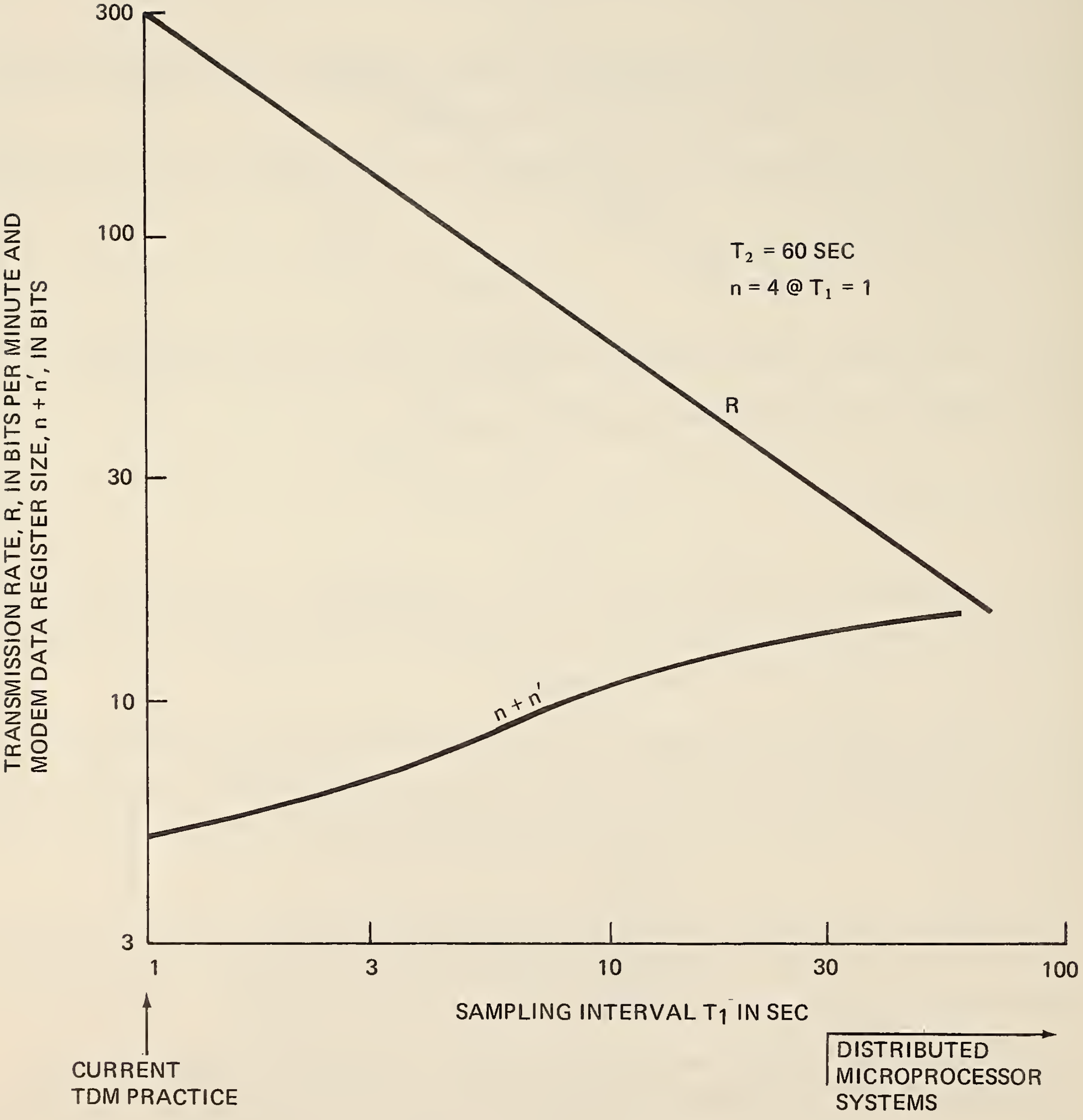

FIGURE A-6. DATA TRANSMISSION RATE AND REGISTER SIZE VS. T_1 FOR CONSTANT OCCUPANCY ERROR

A.4 CONCLUSIONS

This report has essentially developed the mathematical framework about which the system designer can interpret his requirements.

In centrally organized systems opportunities may exist for reducing communication data rates. These opportunities will cause some limitation (specifics were cited in previous sections) in system capability. The system designer should weigh these penalties against the potential cost savings resulting from data rate reduction.

APPENDIX A - ATTACHMENT 1

EFFECT OF MEAN ERROR ON SYSTEM RESPONSE

Equations (A-11) and (A-12) indicate that during sampling period T_2 an error is developed which represents the fact that the difference between the number of leading and trailing pulse edges might be ± 1. If this is the case and constant volume flow is assumed, the worst error situation is given by the case of a continually reversing error at each T_2 interval. This is representative by the pulse train

$$b(h) = \frac{T_1}{2T_2}\left(\frac{1}{2^n - 1}\right)(-1)^h , \tag{A-31}$$

where h represents the T_2 sample intervals.

The z transform of equation (A-1) is

$$B(z) = \left(\frac{T_1}{2T_2(2^n - 1)}\right)\left(\frac{z}{z + 1}\right) , \tag{A-32}$$

$$= \frac{Mz}{z + 1} . \tag{A-32a}$$

Substituting equation (A-32a) into equation (A-15) and neglecting initial conditions yields the z transform of the occupancy filter output

$$N(z) = \frac{KzB(z)}{z - (1 - K)} = \frac{Kz^2M}{[z - (1 - K)](z + 1)} . \tag{A-33}$$

The inverse transform may be obtained by the method of partial fractions, i.e.,

$$N(z) = \frac{KMz^2}{[z - (1 - K)](z + 1)} = \frac{C_1}{z + 1} + \frac{C_2}{z - (1 - K)} . \tag{A-34}$$

At the pole z = - 1

$$C_1 = \left.\frac{KMz^2}{z - (1 - K)}\right|_{-1} = \frac{KM}{-2 + K} . \tag{A-35}$$

At the pole $z = (1 - K)$

$$C_2 = \left. \frac{KMz^2}{z + 1} \right|_{1 - K} = \frac{KM(1 - K)^2}{2 - K} . \tag{A-36}$$

Thus,

$$N(z) = \frac{- KM}{(2 - K)(z + 1)} + \frac{KM(1 - K)^2}{(2 - K)[z - (1 - K)]} . \tag{A-37}$$

The inverse transform is

$$N(h) = \left(\frac{- KM}{2 - K} \right) (- 1)^h + \frac{KM(1 - K)^2}{2 - K} (1 - K)^h . \tag{A-38}$$

The first term is a periodic term while the second term, which is of lesser magnitude decays exponentially. The magnitude of the periodic term is

$$N_p = \frac{T_1 K}{2T_2(2^n - 1)(2 - K)} . \tag{A-39}$$

For the illustrative example of $T_1 = 1$ second, $T_2 = 60$ seconds, $n = 4$ and $K = 0.5$

$$N_p = .000185. \tag{A-40}$$

This error is seen to be considerably lower than the standard deviation of the random error for the same example (Figure A-4). Thus it does not significantly affect system performance.

APPENDIX B

MULTIPLEXING AND MODULATION

B.1 GENERAL

Two basic types of multiplexing are used to transmit two-state (binary) data from several sources using a single communication medium. These are frequency division multiplexing (FDM) and time division multiplexing (TDM). Frequency division multiplexing is a technique in which the available frequency band of the medium is divided into narrow bands, each of which is used for a separate two-state source. Time division multiplexing is a technique in which each two-state source is allotted a discrete time period within a basic time frame, with a theoretical occupancy of the entire available frequency band for its allotted time. FDM may be thought of as a parallel system, data from several sources simultaneously being transmitted over the same medium, while TDM can be thought of as a serial system, data from several sources being multiplexed into a serial format.

For transmitting data, a carrier frequency (or several, as in the case of FDM) is provided as the reference. This carrier is then modulated by any one of three techniques to represent the two states of the data. They are: amplitude modulation (AM), where the amplitude of the carrier is changed; frequency modulation (FM) where the carrier's frequency is changed; and phase modulation (PM) where the phase of the carrier is changed.

B.2 FREQUENCY DIVISION MULTIPLEXING

Frequency division multiplexing systems utilize either FM or AM as the modulation method. In such a system, each two-state source is assigned a unique tone or center frequency; the spacing between adjacent channels being a function of maximum data rates and the filter characteristics of the receiving devices. With AM, the tone is keyed on to represent the binary "one" state, and remains off for the "zero" state. At the receiver, two detection methods are used - coherent (or synchronous) and envelope (or nonsynchronous). The coherent techniques require the receiver to contain a local oscillator synchronized with the received carrier. The envelope system does not require a synchronized carrier and is easier and less costly to implement. Most FDM equipment utilizing AM employs the envelope technique. The synchronous method has, however, a superior noise immunity as illustrated in Figure B-1*, which shows the probability of error as a function of the carrier signal-to-noise ratio. In the envelope case, the threshold (percentage of peak amplitude in which an "on" state is considered to exist) for minimum error approaches 50 percent for high signal-to-noise ratio. In the coherent case, the optimum threshold is at 50 percent for all signal-to-noise ratios.

With frequency modulation, the tone is shifted in frequency when keyed. This technique, called frequency shift keying (FSK), utilizes two state (2 FS) and three state (3 FS) schemes. In a 2 FS (mark, space) scheme, the carrier remains in its quiescent state, normally space (lower frequency), until it is keyed, then shifting to its mark (higher frequency) to represent "zeros" and "ones", respectively. In a 3 FS system, data for two mutually exclusive two-state functions can be transmitted over the same channel; the carrier frequency being keyed either higher or lower then a neutral (center) frequency to represent the "one" states of the two functions, respectively. The channel can be keyed at approximately two-thirds the rate of a 2 FS system for a given total frequency shift.

FSK systems require guard bands between adjacent channels to prevent interchannel interference. This guard band is normally equal to the peak-to-peak frequency shift. For example, in a voiceband (wire medium) FDM system, one of the standard channels uses 930 Hz and 870 Hz to represent mark and space, respectively, while the adjacent higher channel uses 1,050 and 990 Hz, and the adjacent lower channel uses 810 and 750 Hz.

Coherent detection for FSK, as in AM systems, results in a slight improvement in noise performance. Noncoherent envelope detection is again simpler and less costly to implement and is usually used in traffic control applications. FSK, as illustrated in Figure B-1, offers a significant improvement over AM in a Gaussian noise environment.

For wire transmission, manufacturers offer several groups of standard frequencies conforming to recommendations of the CCITT, A.T.&T., and other organizations. One of the more common groups is the "CCITT and Control Spacing" group in which each channel is spaced 120 Hz from the adjacent one with the lowest frequency being 420 Hz and channel 23 (3,060 Hz) being the highest. Both AM and FSK equipment is available with the FSK equipment employing a ± 30 Hz tone shift (i.e., 60 Hz mark to space). This equipment has a 600-ohm terminal impedance, and is compatible with user-owned wire and unconditioned Bell 3002 voiceband channel networks.

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*Curves derived from references 1 and 2.

1. Panter, P.F., "Modulation Noise and Spectral Analysis", McGraw Hill, 1965.
2. Taub and Schilling, "Principles of Communication Systems", McGraw Hill, 1971.

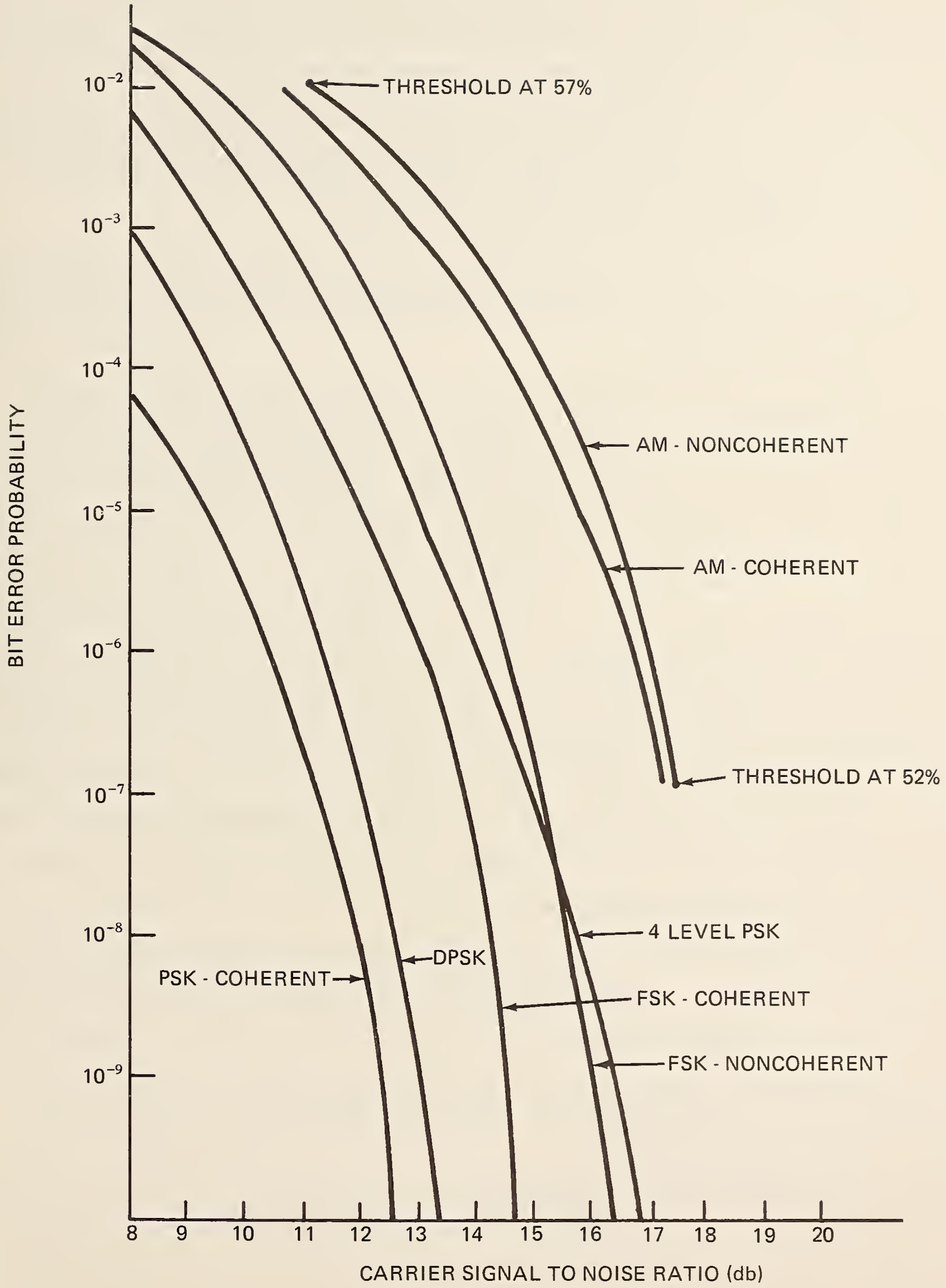

FIGURE B-1. BIT ERROR PROBABILITY FOR AM, FSK & PSK SYSTEMS

The transmission range of an FDM system is a function of the maximum frequency used and the wire attenuation. Transmitter amplitude levels are limited by receiver and amplifier characteristics to a composite value (all transmitters on) of about 0 dbm and receiver sensitivity levels are limited by signal-to-noise ratio considerations to about - 40 dbm.

The channels carrying the command data from central to the field should be assigned a separate pair from those carrying the monitor and surveillance data from the field to central to avoid the possibility of overloading at the receiver.

Following is a general example for assigning frequencies and for setting transmitter levels. Variations in equipment precludes an exact procedure, for which the equipment manufacturer should be consulted.

a. Assign the frequencies in inverse order to the length of the transmission path (lower frequencies to longer paths; higher frequencies to shorter paths). A maximum of 15 channels per cable pair is assumed in this example (maximum frequency 2,250 Hz).

b. Calculate the attenuation in each channel's signal level. In this example, 22 AWG wire is assumed, the 420 Hz channel's transmission distance is assumed to be 5 miles**, resulting in an attenuation of 6.5 db (1.3 db/mile** from Appendix F, Figure F-2); and the 2,250 Hz channel's transmission distance is assumed to be 3 miles, resulting in an attenuation of 8.1 db (2.7 db/mile** from Figure F-2). This computation would be repeated for all other channels. The resulting values should exceed the minimum desired receiver signal level = maximum transmitter level minus minimum desired receiver level; typically, - 40 dbm*. If the result is less than this value, the channel assignments of Step a. should be changed. This may require the use of additional cable pairs or larger diameter wire to permit the use of more low-frequency channels.

c. Determine maximum level of the signal at the receiver or line amplifier to limit the maximum composite level. In this example, the maximum composite level is assumed to be 0 dbm. Thus, the maximum signal level is - 11.8 dbm (Appendix G, Table G-2).

d. Compute the desired transmission level (W_T) = maximum signal level plus attenuation. For the 420 Hz channel:

$$W_T = -11.8 \text{ dbm} + 6.5 \text{ db} = -5.3 \text{ dbm}. \qquad \text{(B-1)}$$

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*The - 40 dbm minimum signal level is based on a typical wire-channel noise level of - 50 dbm and assignment of a minimum signal-to-noise ratio setting of 10 db.

**1 mi = 1.6093 km

For the 2250 Hz channel:

$$W_T = -\ 11.8\text{ dbm} + 8.1\text{ db} = -\ 3.7\text{ dbm.} \qquad \text{(B-2)}$$

e. Set the transmitter to this level or its maximum level, whichever is lower.

The range may be increased by the use of line amplifiers which may be placed in strategic locations in the network to maintain the signal at acceptable levels. These amplifiers provide essentially equal gain for all frequencies in the voiceband (300 to 3,000 Hz).

In a leased facility, the telephone company guarantees a minimum signal level of - 16 dbm, with the stipulation that the composite signal level does not exceed 0 dbm at any point in the telephone network. The user should thus set his transmitting levels per Appendix G, Table G-2.

Frequency division multiplexing at the radio frequency level is used in communications systems employing coaxial cable to provide two-way communication and to permit maximum use of the cable's inherent broadband characteristics. This technique permits multiple TV channels as well as two-way communication and camera control channels to share the same cable.

B.3 TIME DIVISION MULTIPLEXING

Time division multiplexing systems utilize FM, PM or a combination of AM and PM. In this type of system, known as polled or supervisory, the available time is shared among several data points with each point allotted a specific frame of time in which to transmit.

The polled system transmits messages between a central and several remote sites. Each remote site, or drop, is assigned a unique address and all messages to that site are prefaced with that address. Using communication systems employing wire pairs (either user-owned or leased-lines), an almost unlimited number of remote locations can be placed on a signal data bus, the basic limitations being:

- The communications timing, that is, how frequently each site is to be interrogated.
- Reliability - the more locations on one line the greater the number of locations to which communications will be lost in the event of the failure of that line.
- Noise - the greater the number of devices attached to one cable pair the more noise introduced by the additional leads and circuitry.

For leased-line multipoint systems, the telephone company recommends a maximum of twenty locations on each data line. For user-owned wire pair systems, the methods of determining the maximum number of locations are discussed in Appendix F. Communication systems employing coaxial cable or fiber optics are not subjected to such limitations.

The message transmitted by the master unit at central, besides carrying the address, typically contains command and control data and check bits utilized for error detection. The return message from the remote site contains controller and detector status as well as error detection bits.

Each remote site is polled (interrogated) in sequence, the duration of the polling cycle, which is the time required to poll all of the remote units on a line, is a function of the hardware and number of drops on the line, with the maximum permissible duration being a function of the processing algorithm and data encoding technique utilized. Since, in TDM, events are not transmitted in real time, as in FDM, it is necessary to encode the occurrence of events such as the passage of a vehicle over two detectors. One method of accomplishing this is by providing accumulators to record the numbers of vehicles which have passed since the last interrogation and the duration of the period that vehicles were over the loop (presence period). In distributed processing systems, the parameters necessary to control traffic are calculated at the remote site and then transmitted to central, thus reducing the required interrogation rate. These parameters may include volume, occupancy and speed averages over several minutes.

Various manufacturers utilize different synchronizing techniques, data formats and error detection schemes. Some utilize one single long word containing all the data while others transmit a message containing several short words. Examples of short and long word schemes are shown in Figure B-2. In each of these cases, the message is prefixed by a synchronizing bit (or bits) to allow the receiving equipment to synchronize with the transmitting site. The single long word format has the advantage of more efficient utilization of the channel, not requiring the additional start, stop and space bits of the multiple word message. The latter technique does, however, have greater flexibility, the number of words in the message being tailored to the data requirements. Thus, if an intersection contains only one detector, generating eight bits of data, a message format utilizing eight-bit words is more suitable than one using 32-bit words. Note that in the examples shown, the message returned from the remote site is prefixed with its address so the master knows that the proper site received and understood the message. Such address acknowledgement is a form of error detection used in some, but not all, TDM communication methods.

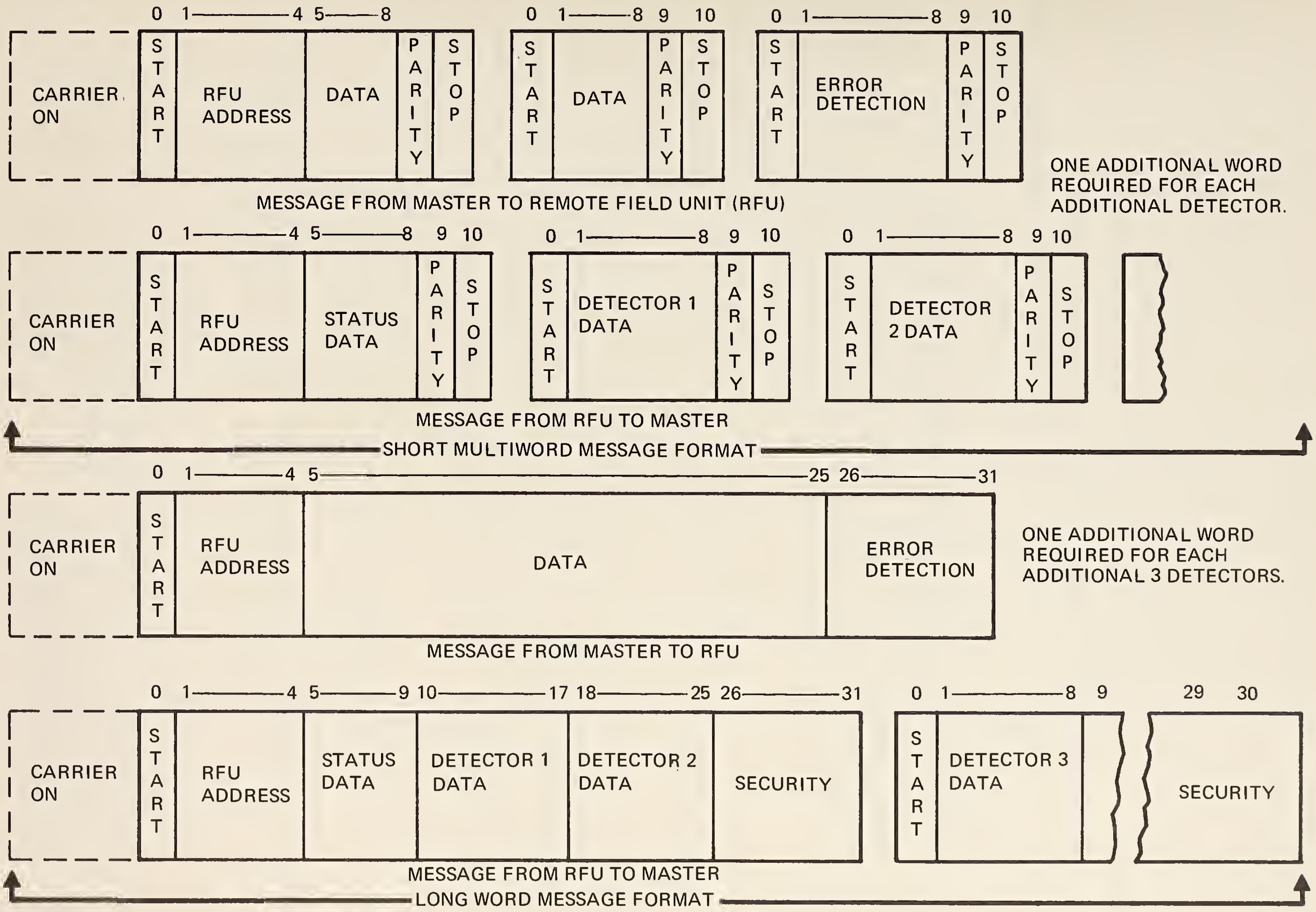

FIGURE B-2. TYPICAL TDM MESSAGE FORMATS

For those systems utilizing FSK, the frequency shift in Hz is from one half to three quarters of the maximum bit rate and the bandwidth required is equal to about twice the maximum bit rate. The relationship between maximum allowable bit rate and the frequency shift for a practical system is complex, and depends upon the signal-to-noise ratio and the filter characteristics of the receiver and transmitter. In an idealized system, the ratio of maximum allowable bit rate can be shown to be equal to twice the frequency shift.[2,3] This ratio is usually lower for commercially available equipment. For example, modems for transmitting serial data in TDM applications typically transmit data at 1,800 bits per second using a mark/space frequency shift of 2,200 to 1,200 Hz, giving a ratio of 1,800/1,000 or 1.8. FDM equipment of the "CCITT and Control Spacing" class employs a 60 Hz shift and is capable of transmitting at 75 bits per second, giving a ratio of 75/60 = 1.25.

Higher rates and more efficient utilization of the bandwidth in wire pair systems can be obtained by utilizing phase shift keying (PSK) or differential phase shift keying (DPSK). With this technique, the change in phase conveys the information.[3] Typical DPSK systems utilize phase shifts of ± 45° and ± 135° allowing for the transmission of two data bits per symbol period (baud); other systems utilize eight possible phase changes and are thus capable of transmitting three binary coded bits of data per symbol, or effectively 4,800 bits per second at 1,600 baud. Detection is either by coherent means, in which a local oscillator is maintained in phase lock with the received signal, or by differential means in which the phase of two successive symbols are compared. The latter method has the lower noise immunity; an error in one symbol resulting in an error in the following symbol. Both methods have, however, greater noise immunity than FSK (Figure B-1). Data rates up to 9,600 bps can be obtained by amplitude modulating each phase change of an 8-phase system; thus, each symbol represents four bits of data. The modems utilizing PSK are more sophisticated and costly than the FSK modems. They are also sensitive to phase hits (sudden changes in phase) which occur in the leased private line service.

An error detection capability is required in TDM systems due to the high vulnerability to noise bursts. Many traffic systems utilizing TDM operate at 1,200 bits per second or more, so that each data bit lasts for less than one millisecond.* Several schemes are

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[2] Ibid.

[3] Davey, J.R., "Modems, Computer Communications", IEEE Press, 1975.

* With FDM the communication signal replicates the source, so that the signals never change more often than every 100 milliseconds. This permits longer time constants and narrower bandwidths than TDM systems, with a concomitant improvement in noise immunity and no need for error detection.

utilized for security, including framing, where the received word is checked for the proper start and stop format and the use of error detecting codes (discussed in Appendix C).

The TDM data formatting and decoding can be implemented in either hardware or software. The software approach can result in a cost saving if microprocessors are to be utilized at the intersections. In this scheme, a modem is provided to transmit and receive the data and a UART (universal asychronous receiver transmitter) or similar type of device is used to convert the serial data transmitted over the medium to parallel form suitable for use by the processor.

B.4 MODEMS

The Modem (Modulator-Demodulator) modulates and demodulates the carrier utilizing FSK or PSK at rates up to 9,600 bps. Most, however, operate at 1,800 bps or less, utilizing unconditioned type 3002 lines or user-owned wire pairs. Higher rates require either conditioned lines or the use of modems with automatic equalization, where the equalization compensates for the poor frequency response of the network.

To understand modems, several terms need to be defined:

Request to Send (RTS) is an electrical signal applied to the modem by the data source (terminal or computer) notifying the modem that data is ready to be transmitted.

Clear to Send (CTS) is an indication by the modem to the data source that it is prepared to transmit. The clear to send delay is the elapsed time since the request to send signal was generated. The terminal or computer can start transmitting data to the modem when the clear to send signal is present. The length of this delay is programmed into the modem, allowing the receiving modem time to detect and lock to the transmitting modem's carrier before data transmission commences.

Carrier Detect Turn On time is the time it takes for a receiving modem to turn on its signal detector after it detects a carrier from a transmitting modem.

Carrier Detect Turn Off time is the time it takes for the receiving modem to turn off its signal detector after detecting loss of carrier or soft carrier.

Soft Carrier is the transmission of a specific frequency, below the mark and space frequencies, at the end of a transmission to avoid spurious signals caused by the sharp transition that would otherwise occur if the carrier was turned off. The receiving modem turns off its signal detector upon detecting this signal (Carrier Detect Turn Off time).

Turnaround Time is the time required to reverse the direction on a half-duplex line.

Modem designs vary and include different combinations of half-duplex, full-duplex, two-wire and four-wire operation. In four-wire operation, a channel is established in each direction on two pairs of wire. This scheme has the advantage of allowing the master to operate in the continuous carrier mode, thus eliminating the several millisecond clear-to-send delay, and eliminating the time it takes the remote unit to recognize the carrier and to turn around the channel (turn off the master) for its reply. In a two-wire system (one pair), the master would first transmit several milliseconds of carrier before it commences transmission of the message to allow the remote units to detect the carrier, and the remote unit would require an additional several milliseconds to switch from its receiving to its transmitting mode. Full-duplex operation (simultaneous transmission in both directions) is not normally used in traffic applications because of the need to re-transmit messages in which an error is detected.

In selecting a speed for transmission, several factors need to be considered. They include:

Data Rate - The data rate requirements of the system are a function of number of drops on each pair and the requirements for control and surveillance.

Message Format - All multipoint networks have fixed delays as a result of the time required for the master to detect the carrier of the responding intersection remote field unit (RFU). These delays are in the order of one to ten milliseconds, assuming the system uses four-wires, with the master in the continuous carrier mode. The effective data rate as a function of message length, data rate and clear-to-send (CTS) delay is given by the following expression, assuming that the RFU responds as soon as a message is received and that the master interrogates the next RFU as soon as it received the response from the previous RFU:

$$\text{Effective rate} = \text{modem speed} \times \left(\frac{\text{length of messages both ways}}{\text{length of messages both ways} + \text{CTS delay}}\right).$$

Assuming an RFU clear-to-send delay of 8 ms, and equal lengths of messages in both directions, Figure B-3 shows the effective data rate for various message lengths. Figure B-4 shows the modem efficiency as a percentage of the modem speed and message length. This figure shows that for short messages, a high speed modem is inefficient and that additional cost would not be justified.

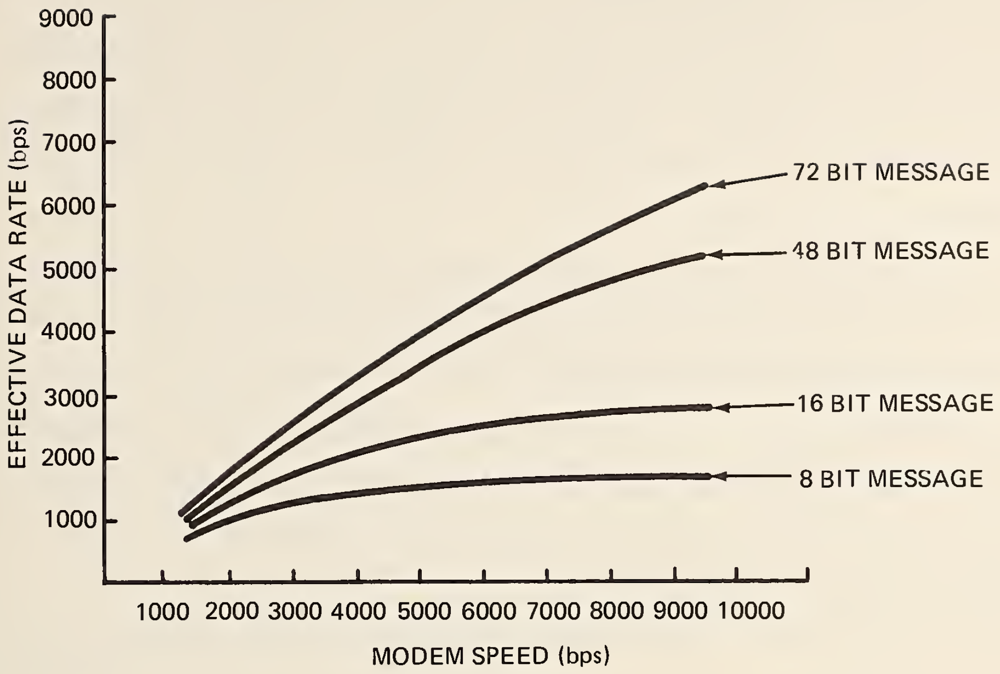

FIGURE B-3. EFFECTIVE DATA RATE AS A FUNCTION OF MODEM SPEED AND MESSAGE LENGTH

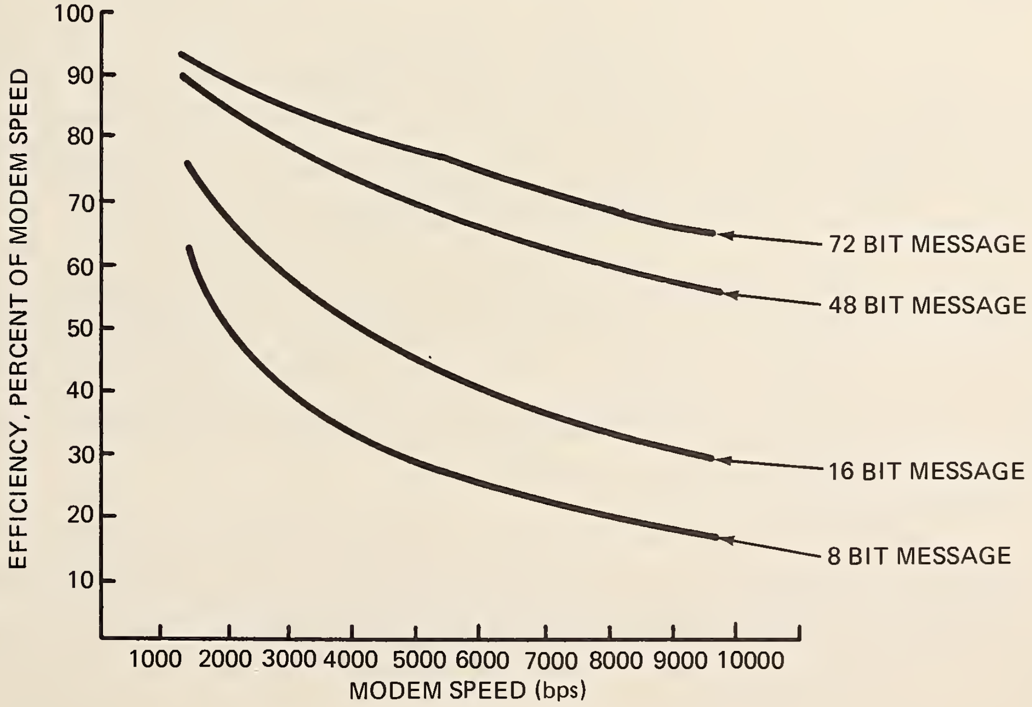

FIGURE B-4. MODEM EFFICIENCY AS A FUNCTION OF MODEM SPEED AND MESSAGE LENGTH

Cost - The higher speed modems not only require highly sophisticated circuitry but also either conditioned lines or equalization networks, all of which increase hardware and medium costs. As an example, modems similar to Bell type 202C, a commonly used asychronous FSK modem operating at speeds up to 1,800 bps, costs about $400 while modems equivalent to the Bell 208A, a PSK, 8-phase synchronous modem operating at 4,800 bps, costs about $3,500.

Many modems are provided with diagnostic capabilities to aid the user in isolating a fault. These include a test pattern generator to allow the modem to test itself, and loop-back equipment to test the terminal, modem line and remote device.

To insure compatibility between the modems and their terminal, standard interfaces have been defined. These standards, such as RS 232C and RS 449, specify the signal level and timing requirements for the data and control signals. Thus, it is only necessary to invoke the suitable standard in specifying the terminal-to-modem interface.

Several vendors manufacture complete TDM systems whereby all remote site formatting and decoding is done in hardware. This type of system is suitable when the traffic signal controller does not have a formatting capability. With this type of system, the computer at the traffic control center is utilized for encoding and decoding the messages transmitted and received.

Modems are available that directly transmit serial data for time division multiplexing by switching DC voltage instead of modulating a carrier. (They are sometimes classified as short-haul, or limited-distance, modems.) This method does not require the complex circuitry of the conventional modem and thus has potentially greater reliability.

These modems are available with many of the features of conventional modems, including error detection capability, various data rates, asynchronous and synchronous operation, and capability for use in multipoint networks. The major limitation of short-haul modems is the need for a continuous electrically conductive path, which precludes the use of leased-lines in most locations at the time of this writing.

The maximum transmission range depends upon transmission level, data range and cable size. The following table shows the transmission range for this type of modem as a function of data rate and cable size for a 0 dbm transmission level in a point-to-point configuration.

Data rate (bps)	Cable length (miles)		
	19 AWG	22 AWG	24 AWG
2400	23	15	12
4800	17	12	8
7200	15	9	6
9600	14	8	6
	Note: 1 mile = 1.6 Km		

Comparison of FDM and TDM

Table B-1 is a comparison of FDM and TDM systems. The cost for the FDM system is on a narrowband channel basis. A typical simple intersection requires at least three such channels for the controller (advance, hold and A-phase green monitor) and one channel per detector. The TDM cost is on an intersection basis with an assumed capability of 16 data bits available for control and monitoring.

TABLE B-1. COMPARISON OF FDM AND TDM

Parameter	FDM	TDM
Cost	AM $400 per channel FSK $500 per channel	$1000 per intersection
Multiplexing capability	18 data points per pair	16 intersections per two pair; 16 data points per intersection
Packaging	One module in central per data point	One module in central per two pair
Expansion capability (assuming spare capacity on existing pairs)	One module at central plus one in field per point	Restrapping at central + one module in field for additional intersection, or restrapping for expansion of existing intersection
Single module failure	Disables one data point	Can disable single intersection or all intersections on that pair
Failure rate	Low(a)	May be higher than FDM since more complex (a)
Noise immunity	Excellent - utilizes narrow bandwidth, long time-constant filter	Subject to Telco "hits" and noise bursts - requires error detection techniques
Modulation techniques	AM, FSK	FSK, PSK

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[a] See Appendix D - Reliability.

TABLE B-1. COMPARISON OF FDM AND TDM (Cont.)

Parameter	FDM	TDM
Ease of maintenance	Easy to check single channel and isolate problem	Somewhat more complex test equipment required
Spare equipment requirements	Requires unique transmitter and receiver for each channel frequency	All channels utilize common components; field units strapped for assigned address

The system is assumed to be four-wire half duplex with a capability of 16 drops per pair. The number of drops permissible is affected by distance, modem speed and data requirements, as explained in Appendices F and G.

APPENDIX C

ERROR DETECTION AND CORRECTION

C.1 ERROR SOURCES

Impulse noise is the primary cause of errors in data transmission for most communication media. A TDM system is more sensitive to such noise than an FDM system, since an FDM channel requires less bandwidth and transmits at a lower data rate. That is, most of the high-frequency components of the noise power in a short burst are filtered out by the narrowband FDM receiver, and, at the lower data rates, the amount of information that would be altered by a noise burst of fixed duration is small.

When discussing error rates, it is useful to differentiate two types: bit error rate and block error rate. Bit error rate is the probability that an error occurs in a given bit. Block error rate is the probability that an error occurs in a block of bits. Since a block contains several bits, its error rate is higher than the bit error rates.

Figure C-1[1] shows the probability of having m or more errors in a message of size n. This empirical data is based upon a study of the switched telephone network by A.T. & T. in 1969-1970, utilizing Bell 202 data sets, and is referred to here only to illustrate the probability of multiple errors occurring in various size blocks. Figure C-2[2] shows the probability of an error occurring in the next n bits after an error has occurred. The significance of multiple errors will become apparent in the discussion of error correcting techniques.

C.2 ERROR CORRECTION TECHNIQUES

Two fundamental methods have been developed to overcome the problem of errors in communication systems; they are automatic-repeat-request (ARQ) and forward error control (FEC) techniques.[3] In an ARQ system, a block consisting of data, control,

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1. Balovic, Klancer, Klare, McGruther, 1969-70 Connection Survey: High Speed Voiceband Data Transmission Performance on the Switched Telecommunications Network, The Bell System Telephone Journal, American Telephone and Telegraph Company, Vol. 50, No. 4, April 1971.
2. Martin, James, Telecommunications and the Computer, 2nd edition, Prentice Hall, 1979.
3. Burton and Sullivan, Errors and Error Control, Proceedings of IEEE, Vol. 60, No. 11, November 1972.

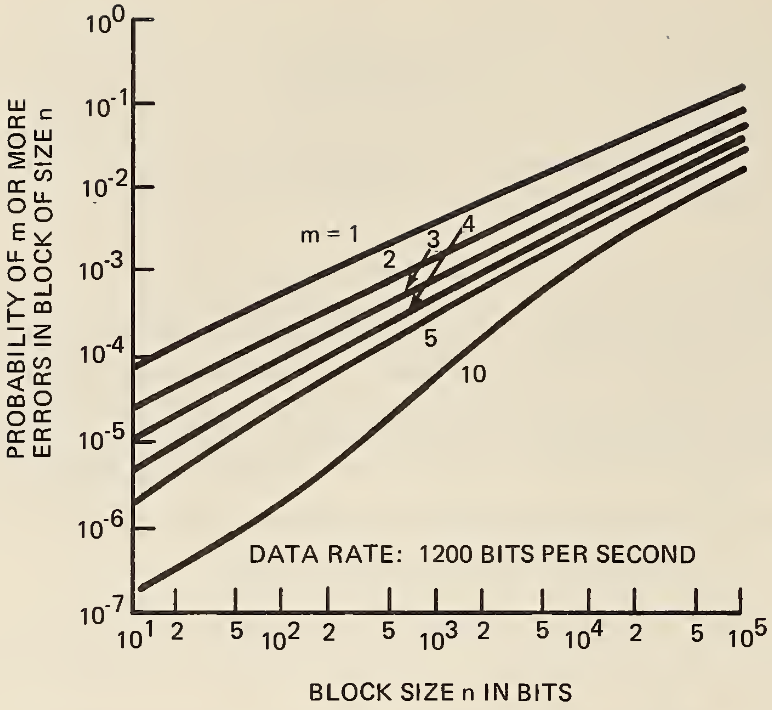

FIGURE C-1. PROBABILITY OF m OR MORE ERRORS IN A BLOCK OF SIZE n

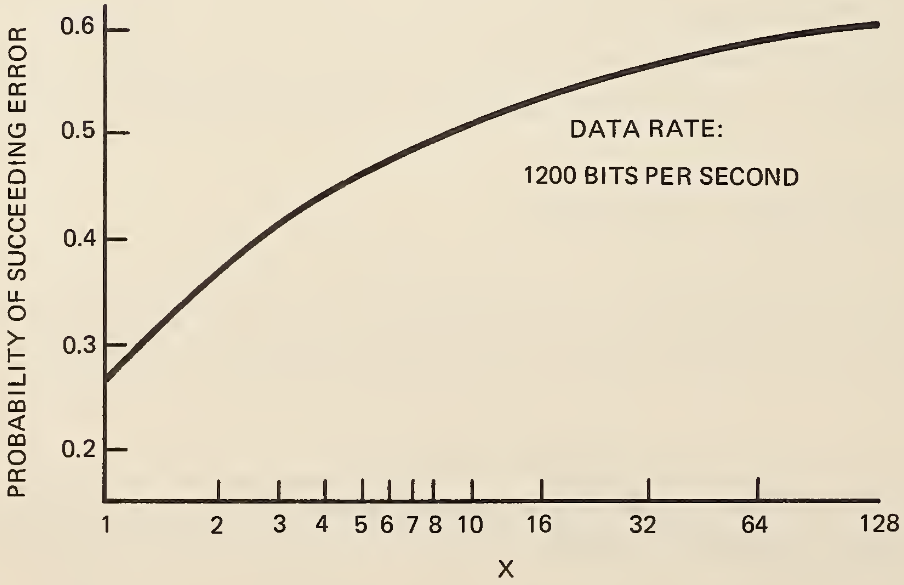

FIGURE C-2. PROBABILITY THAT AFTER AN ERROR BIT THERE WILL BE ANOTHER ERROR WITHIN THE FOLLOWING X BITS synchronization and parity bits is transmitted. The receiver computes the expected parity bits and compares them with the received parity bits. If there are no errors, the data is accepted; if not, the transmitter is notified and requested to retransmit that data block. Thus, erroneous data is only accepted by the receiving terminal when the receiver fails to detect the error. This method requires a return transmission channel. In an FEC system, the receiving terminal attempts to detect the presence of an error and also to correct it. This system requires a priori knowledge of the type of errors that may occur and employs sophisticated codes. Even with these codes, it is impossible to correct bursts of errors. Messages are accepted as valid when the receiving terminal cannot determine the exact location of the error. These systems do not, however, require the return path needed by the ARQ system. Their application is primarily in systems where the message cannot be repeated or where only a simplex (one-way) channel exists, such as certain satellite communication systems.

The ARQ type system is more suitable than FEC systems for traffic control, requiring less complex equipment, and better utilizing the bandwidth required for its two-way data transmission.

The primary method used to reduce the probability of an error being undetected is by redundancy. This may be accomplished either by appending check bits to the message or by repeating the message several times.

The repeat technique, called double scan when the message is repeated once and triple scan when it is repeated twice, requires that the receiving equipment simply compare the data word to its redundant transmission. When a discrepancy is detected, the data is rejected. The redundancy can be accomplished by either transmitting each data bit followed by its repeat or by transmitting each complete word or message before it is repeated. The latter method requires a large buffer to store the first transmission until the second word is received and compared. In a burst noise environment, it has superior error detection characteristics since the longer the interval between the data and its check character the smaller the probability that both will be in error, nullifing the check. A variation of this technique is the "repeat back" technique in which the receiving equipment transmits back to the original source either the entire message or some predetermined portion of the message. The equipment at the original source then compares the two messages. The repeating of the data, in all cases, reduces the efficiency of the channel to less than fifty percent.

The most popular error check codes are the parity codes[4] which encompass a broad variety of codes including simple parity, hamming and cyclic. Of these, the simplest and most familiar is vertical parity. In this scheme, a single non-data bit is added to each word. The bit is such that the total number of logical ones occurring in the word is caused to be either odd or even. The effectiveness of this code can be determined by utilizing the following data from Figure C-1 for a 10-bit word:

$$P_{1(\text{error})} = 8 \times 10^{-5} , \tag{C-1}$$

$$P_{2(\text{error})} = 3 \times 10^{-5} , \tag{C-2}$$

$$P_{3(\text{error})} = 1 \times 10^{-5} , \tag{C-3}$$

$$P_{4(\text{error})} = 6 \times 10^{-6} , \tag{C-4}$$

where $P_{n(\text{error})}$ is the probability that n bits are in error in a 10-bit word.

Vertical parity detects an odd number of errors but does not detect an even number of errors. Therefore, neglecting the sixth and larger numbers of bit errors, the following results are obtained using this method:

$$\text{Percent of errors missed} = \frac{\text{Number of even errors}}{\text{Total number of errors}} \times 100\% , \tag{C-5a}$$

$$= \frac{(3.0 + .6) \times 10^{-5}}{(8 + 3 + 1 + .6) \times 10^{-5}} \times 100\% = 27\% . \tag{C-5b}$$

Thus, for the above case, 27 percent of the errors are undetected.

A variation of this technique is the addition of longitudinal parity. This scheme, used in conjunction with vertical parity, affords a high degree of error detection in the presence of noise bursts. It requires the message to contain two or more data words and one check sum word generated by summing, module 2, the corresponding data bits of each word. Since these bits are spaced one word apart, the probability is small that a noise burst will affect more than one bit. As can be seen from Figure C-2, the longer the interval since the last erroneous bit, the lower the probability of another bit also being in error. For an error to be undetected, an even number of corresponding bits would have to be in error without any other detected errors in that message. The probability of this occurring is

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[4] Franco and Wall, Coding for Error Control, Electronics, December 27, 1965.

very low, as derived in Attachment 1. The efficiency of this scheme is also low. For the case analyzed in Attachment 1, consisting of two eight-bit data words each with a start, stop and parity bit, a check sum word, and a one-bit spacing between words, the efficiency is:

$$\frac{\text{16 data bits}}{3(\text{1 start + 1 stop + 1 parity + 8 bits}) + \text{2 space bits}} = 46\%. \qquad \text{(C-6)}$$

C.3 ERROR DETECTION CODES

A class of codes known as polynomial or cyclic redundancy codes provide good protection and greater efficiency. These codes are based on polynomial manipulation using module 2 arithmetic. The size of the check word resulting from this manipulation depends on the size of the data block and the degree of protection desired. An r-bit cyclically-generated check word (where r is 2 or more) gives the following protection:[5]

Single bit errors: 100% protection
Two bit errors: 100% protection
Error burst of length less than r + 1 bits: 100%
Error burst of length r + 1 bits: $1 - (1/2)^{(r - 1)}$ probability of detection
Error burst of length greater than r + 1 bits: $1 - (1/2)^r$ probability of detection.

A rigorous explanation of the theory of these codes is quite involved, and can be found in Peterson and Weldon.[6] The basic theory behind these codes is that all messages can be represented by a polynomial of the form $A_m X^m + A_{m-1} X^{m-1} + A_0 X_0$ where the coefficients A are either 1 or 0, depending upon the value of that bit. Another polynomial, known as the generating polynomial, such that its degree is less than m but greater than 0 and whose X_0 coefficient is non-zero is specified. More than one such polynomial can be selected and several standard polynomials have been developed. The message polynomial is multiplied by X^r (r being the degree of the generating polynomial) and divided by the generating polynomial. The remainder is r bits or less and is added to the message polynomial (the lower r bits being vacant since the polynomial was multiplied by X^r). The coefficients of the resulting polynomial are used to form the check code to be transmitted. At the receiver, if no errors have occurred in the transmission, dividing the received polynomial by the same generating polynomial would result in a zero remainder; otherwise, error(s) have occurred in transmission.[7]

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5. Peterson and Brown, Cyclical Codes for Error Detection, Proceedings of the IEEE, January 1961.
6. Peterson and Weldon, Error Correcting Codes, Second Edition, 1972.
7. Rallapalli, K., Cyclic Checks for Error Detection, Progress, Fairchild, Feb. 1974.

One of the common cyclical codes is the Bose-Chaudhuri-Hocquenghem (BCH) which is a powerful random error-correcting code.[8] While this correcting characteristic is not useful for traffic system purposes, its ease of implementation in either hardware or software makes its error detection property attractive for such applications. Some communication equipment manufacturers incorporate this type of code in their message format.

The length of a check code is usually expressed as "n - k" where n is the length of each block and k is the number of data bits.

Table C-1 is a summary of error correcting codes and their characteristics. All of the codes with the exception of the convolution code are block codes; that is, they are of a fixed length. The convolution code has no fixed block structure and is useful for forward error correction.

TABLE C-1. TYPES OF ERROR DETECTING CODES[4, 5]

Type	Description (see Note)	Comment
Constant Ratio	Number of "0"s and "1"s constant	Detects all odd errors; requires higher redundancy than parity for comparable protection
Simple (vertical) parity	Sum module 2	Detects all odd errors
Geometric code	Two dimensional parity check (longitudinal and vertical)	Efficient, easy to implement for error detection
Hamming	$2^{n-k} \geq n + 1$, to detect double errors or correct single errors	Corrects single errors; detects double errors
Cyclic codes (polynomial)	Utilized shift registers of length k; detects all errors of length $< n - k + 1$	Easy to implement using shift registers of length k
BCH	Prob det $= 1 - (1/2)^{n - k - 1}$ error length $= n - k + 1$	Designed to correct random errors
Fire	Prob det $= 1 - (1/2)^{n - k}$ errors of length $> n - k + 1$	Burst correction code efficient when duration and frequency of burst are precisely defined
Convolution code	Nonblock code	Checks data in other data blocks as well, useful for FEC
Note in above descriptions: n = total number of bits k = number of information bits		

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[4] Op Cit., page C-4.
[5] Op Cit., page C-5.
[8] Lucky, Salz and Weldon, Principles of Data Communication, McGraw Hill, 1968.

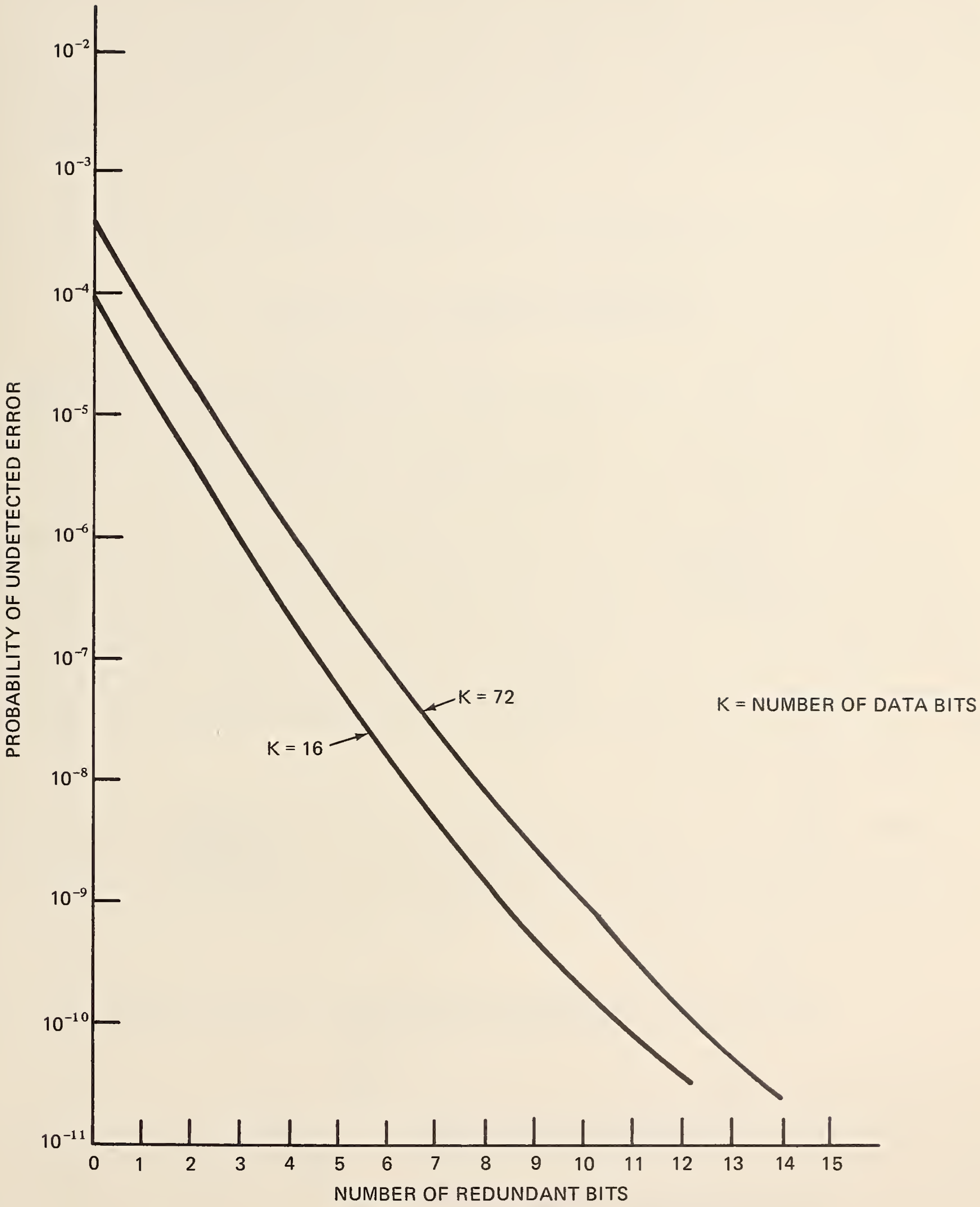

FIGURE C-3. UNDETECTED ERROR PROBABILITY AS A FUNCTION OF NUMBER OR REDUNDANT BITS FOR CYCLIC CODES

The curves in Figure C-3 shows the probability of an undetected error occurring as a function of the number of redundant bits when a cyclic code is used for 16-bit and 72-bit messages. The error statistics utilized to calculate the undetected error rate are from the aforementioned 1969-70 survey. To appreciate how low this rate is, one should consider that transmitting at 1,200 bps, 10^9 32-bit messages can be sent in one year of continuous transmission.

The above does not indicate the relative efficiency of the code. This is shown in Figure C-4 where the efficiency is defined as:

$$\frac{\text{number of data bits}}{\text{number of data bits + check bits + 1 start bit + 1 stop bit}} . \qquad \text{(C-7)}$$

The 16-bit and 72 data bit cases using a cyclic code is shown along with the check sum case discussed in Attachment 1. The relative efficiency for a given undetected error probability is seen to be greater for the longer data message. The check sum format is seen to be about 90 percent as efficient as a cyclic format for the 16-bit data message.

Of course, before a correction scheme is developed, the question of how many undetected errors can be tolerated must be addressed. The answer depends upon the impact an undetected error would have on system performance. In a traffic system, an undetected error in traffic volume could be tolerated while a long-term erroneous traffic signal timing sequence, with its severe impact on system performance and safety, cannot be accepted. This topic is discussed further in the sections on alternative configurations in Volume 1.

C.4 MESSAGE THROUGH-PUT

Another measure of communication system performance is through-put. Through-put (TP) can be defined as the amount of useable data that is transmitted over the communications system in a given time period. It can be expressed by the following formula:

$$P = \text{Data rate (bits/sec)}$$

$$\times \frac{\text{(total data bits)/(time period) - (Repeated data bits)/(time period)}}{\text{(Total bits)/(time period)}} . \qquad \text{(C-8)}$$

The above formula can be factored into the following form:

$$TP = B/S \times \frac{\text{Total data bits per time period}}{\text{Total bits per time period}}$$

$$- \frac{\text{Repeated data bits per time period}}{\text{Total bits per time period}} . \qquad \text{(C-9)}$$

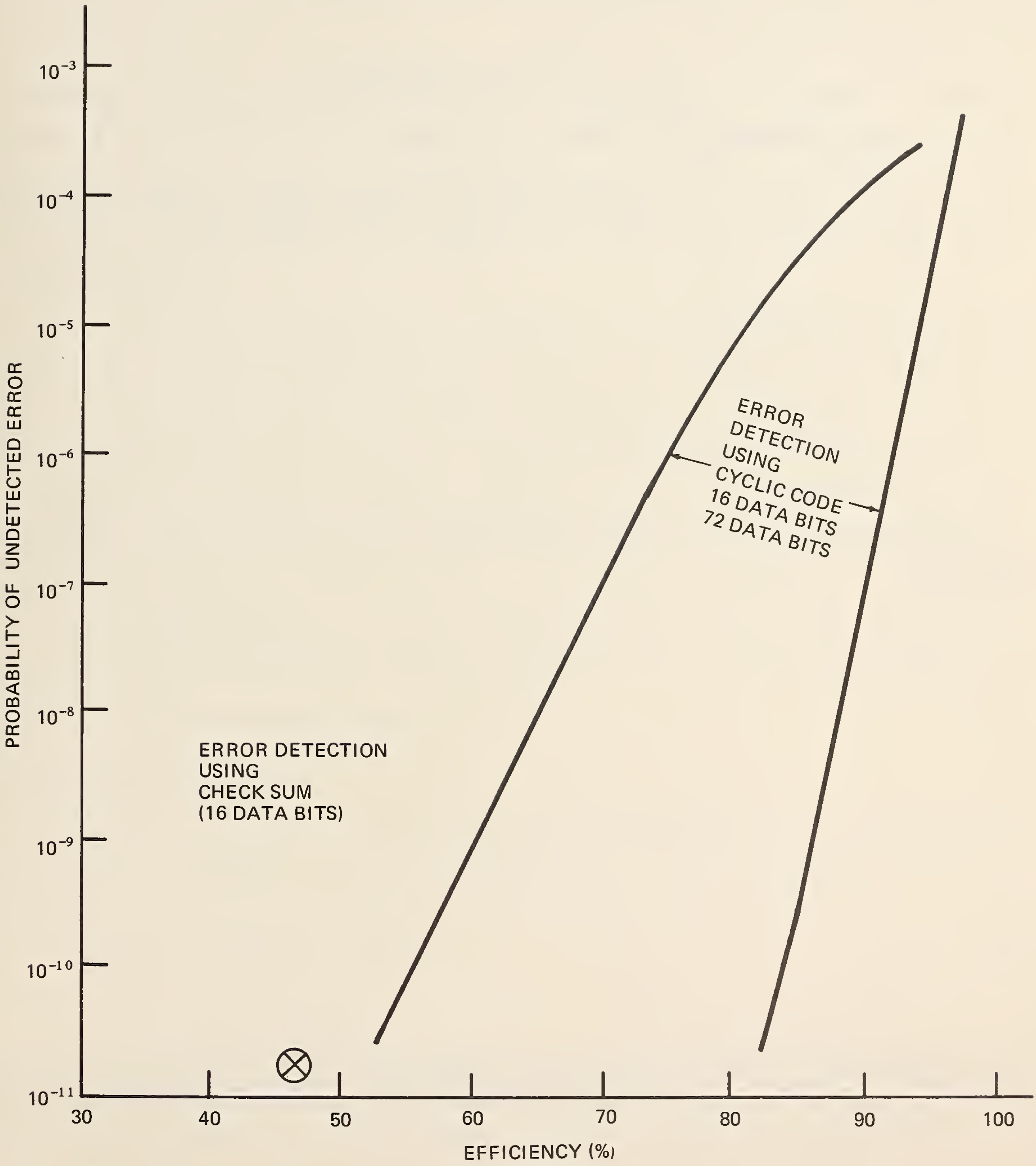

FIGURE C-4. UNDETECTED ERROR RATE AS A FUNCTION OF CODE EFFICIENCY

The first term: Total data bits per time period/Total bits per time period is the message efficiency as defined previously. The second term: Repeated data bits per time period/Total bits per time period is the detected error rate, which is very close to the total error rate, since the undetected error rate is low.

Thus, through-put can be expressed by the following formula:

$$TP = (B/S)\left(\frac{\text{Message efficiency }\%}{100}\right) - \text{Error rate} . \qquad (C\text{-}10)$$

As an example, using a combination of longitudinal and vertical parity, the results are:

Data rate (B/S) = 1,200

Message efficiency = 46%

Error rate = 1.3×10^{-4}

$TP = 1{,}200 \text{ bps} \times (.46 - 1.3 \times 10^{-4})$

TP = 552 bits/sec.

This example illustrates that the message efficiency term dominates in determining the through-put.

APPENDIX C - ATTACHMENT 1

COMMUNICATION CHANNEL ANALYSIS

INTRODUCTION

Several existing computerized traffic control systems utilize a combination of simple (vertical) parity and a longitudinal check word. Each message consists of two data words and a check word (Figure C-5). Each word contains one start, one stop, 8-data or check bits, and a simple parity bit. A one-bit interval separates each word. The message is not accepted if a simple parity error is detected in any of the three words or if a check word error is detected.

Data is transmitted over either private telephone lines or owned lines at 1,200 bits per second. These lines are subject to random noise and impulse noise. Impulse noise occurs in bursts lasting up to several milliseconds and results in a clustering of errors. Since complex mathematics is required to analyze a channel subject to burst noise, this analysis makes simplifying assumptions, yielding bounds rather than exact results. The non-burst or Gaussian noise case is also analyzed. In the latter case, the probability of any bit being in error is independent of time. Error rate statistics from the 1969-1970 telephone company survey of the switched network are used as the basis for this analysis. The results of this analysis are conservative because the switched system is subject to more severe impulse noise than either private lines or owned lines due to switching transients and coupling through its power system.

Error Detection Scheme

In this approach, vertical parity is used to detect an odd number of errors in each of the three words. In addition, a check word is generated by "Exclusive ORing" the corresponding bits of word 1 and word 2, and placing the results in word 3. That is:

$$wd_3 \text{ bit } n = wd_1 \text{ bit } n \otimes wd_2 \text{ bit } n \; . \qquad \text{(C-11)}$$

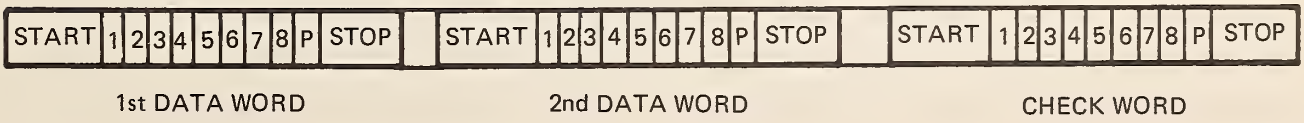

FIGURE C-5. EXAMPLE MESSAGE FORMAT

An error in the received message is undetected by the check word if an error occurs for the same bit in two, and only two, of the three words and a check-sum-detected error also does not occur in that message.

Thus, an undetected error can only occur if an even number of errors, four or greater, i.e.: 4, 6, 8, ..., has occurred in the message. Odd errors are detected by vertical parity and even errors are detected by either vertical parity or the longitudinal check word.

Computation of Undetected Error Rate for Burst Noise

In computing expected error rates for the three-word format, the probability of a random error consisting of one or more altered bits is assumed to be one in 100,000 bits transmitted.[2] The Bell 1969-1970 Survey Data[1] is also used. This data (Figure C-1) shows the probability of having m or more errors in a block of n bits.

The following nomenclature is used in the analysis:

Pu: probability of undetected error

Pe_{Bn}: probability of error in bit n

$Pe_{B(n+r)}$: probability of error in bit n + r

Pe: probability of first error in any bit

$Pe_{BK/e}$: probability of an error in a bit if an error occurred in the "K" previous bit.

The minimum number of errors that can result in an undetected error is four. In this case, the only error pattern for nondetection is two errors in one word and two errors in bits of a second word. This may occur in three ways:

Case 1: 2 errors in word 1; 2 errors in word 2; 0 errors in word 3.

Case 2: 2 errors in word 1; 0 errors in word 2; 2 errors in word 3.

Case 3: 0 errors in word 1; 2 errors in word 2; 2 errors in word 3.

The probability of the first error occurring in any one bit is assumed to be 10^{-5} as stated above, and the probability of this occurring for any one of the 9 bits in a word is assumed equally likely. However, the location of the second and all subsequent errors is dependent upon the location of the first error. (Note: The assumption has been made that

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[2] Op Cit. page C-1.
[1] Op Cit. page C-1.

the noise burst started during the message. This is a conservative approach for if the burst started prior to the message, the probability of subsequent bits in the message being in error is reduced.) A weighted average is utilized to calculate the expected location of the second error (see Supplement 1). This second error is calculated to occur 2 bits after the first error.

The undetected error probability is:

$$Pu = Pu_{\text{case 1}} + Pu_{\text{case 2}} + Pu_{\text{case 3}} , \tag{C-12}$$

$$Pu_{\text{case 1}} = Pe(Pe_{B(n+2)/e}) \cdot Pe_{B(n+12)/e} \cdot Pe_{B(n+14)e} . \tag{C-13}$$

The last two terms are the probability of errors occurring in the corresponding bits of the second word; thus, they are the probability of errors occurring in the 12th and 14th bits after the first bit of the first word. These are calculated in Supplement 2.

$$Pu_{\text{case 1}} = 10^{-5}(.1)(4 \times 10^{-3})(4 \times 10^{-3}) = 1.6 \times 10^{-11} , \tag{C-14}$$

$$Pu_{\text{case 2}} = Pe(Pe_{B(n+2)/e}) \cdot (Pe_{B(n+24)/e}) \cdot (Pe_{B(n+26)/e}) , \tag{C-15}$$

$$Pu_{\text{case 2}} = 10^{-5}(.1)(2 \times 10^{-3})(2 \times 10^{-3}) , \tag{C-16a}$$

$$= 4 \times 10^{-12} . \tag{C-16b}$$

$Pu_{\text{case 3}}$ is similar to case 1, i.e., the error occurring in adjacent words:

$$Pu_{\text{case 3}} = Pu_{\text{case 1}} = 1.6 \times 10^{-11} , \tag{C-17}$$

$$Pu = 1.6 \times 10^{-11} + .4 \times 10^{-11} + 1.6 \times 10^{-11} = 3.6 \times 10^{-11} . \tag{C-18}$$

The probability of having six undetected errors is next analyzed. The only error pattern resulting in nondetection is two errors in each word, being distributed over three bit locations in the three words. This may occur in two ways:

Case 1: Errors in word 1 bits i and j
Errors in word 2 bits i and k
Errors in word 3 bits j and k

Case 2: Errors in word 1 bits i and j
Errors in word 2 bits j and k
Errors in word 3 bits i and k.

The undetected error probability is:

$$Pu = Pu_{\text{case 1}} + Pu_{\text{case 2}} \,, \tag{C-19}$$

$$\begin{aligned} Pu_{\text{case 1}} = {} & Pe(Pe_{B(n+2)/e}) \times (Pe_{B(n+12)/e}) \times (\overline{Pe_{B(n+14)/e}}) \\ & \times (P_{17} - P_8 - Pe_{B(n+12)/e} - Pe_{B(n+14)/e}) \times (Pe_{B(n+20)/e}) \\ & \times (Pe_{B(n+26)/e}) \,. \end{aligned} \tag{C-20}$$

The expression:

$$(Pe_{B(n+12)/e})(\overline{Pe_{B(n+14)/4}})(P_{17} - P_8 - Pe_{B(n+12)/e} - Pe_{B(n+14)/e}) \,, \tag{C-21}$$

is the probability of having an error in the second word in the same bit location (n + 12) as the first error in the first word and another error in any bit location other than the same location as the first word's second error bit. The term $(P_{17} - P_8 - Pe_{B(n+12)/e} - Pe_{B(n+14)/e})$ is the probability of having a second error in word 2 in any bit other than bit n + 12 or n + 14 (bit n + 12 is assumed to be in error and bit n + 14 cannot contain an error for this case). $P_{17} - P_8$ assumes that the expected location of the first error is in bit 5 of the first word (there being an equal likelihood of the first error occurring for any bit, and thus bits 1 through 9 of the second word are the 8th through 17th bits after the expected location of the first error). The term $Pe_{B(n+26)/e}$ is the probability of having an error in the third word in the same bit location as the second error in the first word. The term $Pe_{B(n+20)/e}$ is the approximate probability of having an error in the third word in the same location as the error in the second word, and not occurring in the same location as the first word. To calculate the actual probability, the expected position of this error in the second word has to be computed, but since the error in the third word occurs 20 or more bits after the first error in the burst (n + 20), and for $Pe_{B(n+20)/e}$ through $Pe_{B(n+28)/e}$, which are the possible locations of the error in word 3, the probability is constant (see Supplement 2), the actual position need not be calculated.

Substituting the following values into the formula for Case 1

$$Pe = 10^{-5} \,, \tag{C-22}$$

$$Pe_{B(n+2)/e} = .1 \text{ (Supplement 2)} \,, \tag{C-23}$$

$$Pe_{B(n+12)/e} = .004 \text{ (Supplement 2)} \,, \tag{C-24}$$

$$Pe_{B(n+14)/e} = .004 \text{ (Supplement 2)} , \tag{C-25}$$

$$\overline{Pe_{B(n+14)/e}} = 1 - Pe_{B(n+14)/e} = 1 - .004 = .996 , \tag{C-26}$$

$$Pe_{B(n+20)/e} = .002 \text{ (Supplement 2)} , \tag{C-27}$$

$$Pe_{B(n+26)/e} = .002 \text{ (Supplement 2)} , \tag{C-28}$$

$$P_{17} = .54 \text{ (from Figure C-2)} , \tag{C-29}$$

$$P_8 = .49 \text{ (from Figure C-2)} , \tag{C-30}$$

$$Pu_{\text{case 1}} = (10^{-5})(.1)(.004)(.996)(.54 - .49 - .004 - .004)(.002)(.002) , \tag{C-31}$$

$$Pu_{\text{case 1}} = 6.7 \times 10^{-16} . \tag{C-32}$$

Utilizing the same reasoning as for case 1:

$$\begin{aligned} Pu_{\text{case 2}} = {} & Pe(Pe_{B(n+2)/e}) \times (Pe_{B(n+14)/e}) \times \overline{(Pe_{B(n+12)/e})} \\ & \times (P_{17} - P_8 - Pe_{B(n+14)/e} - Pe_{B(n+12)/e}) \times (Pe_{B(n+20)/e}) \\ & \times (Pe_{B(n+24)/e}) \times (Pe_{B(n+20)/e}) . \end{aligned} \tag{C-33}$$

This formula is identical to $Pu_{\text{case 1}}$ when values are substituted. Thus,

$$Pu = 2Pu_{\text{case 1}} = 2(6.7 \times 10^{-16}) , \tag{C-34}$$

$$Pu = 1.34 \times 10^{-15} . \tag{C-35}$$

Note that the probability of having six undetected errors in a message is significantly lower than for four errors. The probability of having eight or more errors is even lower and, thus, the probability of having an undetected error is approximately equal to the four error case = 3.6×10^{-11}.

Computation of Error Rate for Gaussian Noise

For the Gaussian noise model, the probability of any bit being in error is independent of any previous bit being in error.

As previously discussed, all odd errors and all cases having two errors in the message are detected; thus the minimum number of errors that can result in nondetection is four. Assuming n bits per word and 3 words per message, we have for the "four" error case:

$$Pu_{4 \text{ error case}} = \binom{3}{2}(P_A)(P_B)(P_C) , \tag{C-36}$$

where $P_A = (n/2)(P_e)^2(1 - Pe)^{n - 2}$ is the probability of having two errors in a word; $P_B = (Pe)^2 (1 - Pe)^{n - 2}$ is the probability of having two specific bits in a word in error (the same two as were in error in the word for which P_A was computed); $P_C = (1 - Pe)^n$ is the probability of having an error-free word; and (3/2) is the possible permutations of the three words with the aforementioned error sequence.

For n = 9 and Pe, the probability of error in 1 bit, = 10^{-5};

$$\begin{aligned} Pu_{4 \text{ error case}} &= \binom{3}{2}\binom{9}{2}(10^{-5})^2(1 - 10^{-5})^7(10^{-5})^2(1 - 10^{-5})^7(1 - 10^{-5})^9 \\ &= 10^{-18} . \end{aligned} \tag{C-37}$$

The next case analyzed is for six errors:

$$Pu_{6 \text{ error case}} = (P_A)(P_D)(P_E) ,$$

where

$$P_D = (2Pe)(1 - Pe)(n - 2/1)(Pe)(1 - Pe)^{n - 3} . \tag{C-38}$$

The first term, Pe, represents the probability of having an error in the same bit position as one of the two errors in the first word; (1 - Pe) is the probability of not having an error in the other error bit position. The bracketed term represents the probability of having 1 and only 1 error in the remaining n - 2 bits of the message. The term $P_E = (Pe^2)(1 - Pe)^{n - 2}$ represents the probability of having two specific bits and no others in error. These bits are the two bits in the other words which did not have corresponding errors.

For n = 9 and Pe = 10^{-5}, we have:

$$Pu_{6\text{ error case}} = \binom{9}{2}(10^{-5})^2(1 - 10^{-5})^7(2)(10^{-5})(1 - 10^{-5})\binom{7}{1}(10^{-5})(1 - 10^{-5})^6$$

$$\times\ (10^{-5})^3(1 - 10^{-5})^n \qquad \text{(C-39a)}$$

$$= 5 \times 10^{-28}\ . \qquad \text{(C-39b)}$$

Note that $Pu_{6\text{ error case}}$ is several orders of magnitude less than $Pu_{4\text{ error case}}$ and thus the over-all probability of undetected error is the same as the form error case, namely, 10^{-18}.

Conclusion: Assuming that traffic systems using either leased or owned lines will be subjected to burst noise no worse than the telephone switched network noise, the number of undetected errors is seen to be less than one in 3 x 10^{-11} messages. This rate results in fewer than one undetected error per year, assuming a continuous transmission rate of 1,200 bits (10^9 messages per year). The through-put will also be relatively unaffected by retransmission of messages having detected errors, since less than one retransmission in 3,000 will be required for error correction.

If random noise conditions are assumed, the number of undetected errors is seen to be a negligible one in 10^{18} messages.

APPENDIX C - SUPPLEMENT 1

CALCULATION OF EXPECTED LOCATION OF SECOND ERROR IN WORD WITH RESPECT TO FIRST ERROR

A weighted average approach will be used:

$$\text{Expected Location} = \frac{\displaystyle\sum_{n=1}^{8} \left(\frac{\displaystyle\sum_{i=1}^{9-n} i Pe_{B(n+i)}}{\displaystyle\sum_{i=1}^{9-n} Pe_{B(n+i)}} \right)}{8} \quad . \tag{C-40}$$

The term in parenthesis represents the expected location of the second error assuming that the first error has occurred at bit location "n".

This term is computed for each of the eight possible locations for the first error bit (bits 1 through 8) and then averaged to yield the expected location of the second error.

The following probabilities are derived in Supplement 2.

$$Pe_{n+1/e} = .27 \ , \tag{C-41}$$

$$Pe_{B(n+2)/e} = .1 \ , \tag{C-42}$$

$$Pe_{B(n+3)/e} = .04 \ , \tag{C-43}$$

$$Pe_{B(n+4)/e} = .017 \ , \tag{C-44}$$

$$Pe_{B(n+5)/e} = .017 \ , \tag{C-45}$$

$$Pe_{B(n+6)/e} = .017 \ , \tag{C-46}$$

$$Pe_{B(n+7)/e} = .013 \ , \tag{C-47}$$

$$Pe_{B(n+8)/e} = .013 \ . \tag{C-48}$$

Utilizing the above equation, we obtain 1.75. Rounding off to the nearest integer, we assume that the second error occurs two bits after the first error.

APPENDIX C - SUPPLEMENT 2

THE PROBABILITY OF ERROR IN ANY GIVEN BIT

The probability of the next error occurring in the kth bit if an error occurred in the first bit is derived from Figure C-2.

$$Pe_{B(n+1)/e} = P_1 = .27 , \tag{C-49}$$

$$Pe_{B(n+2)/e} = (P_2 - P_1)^* = .37 - .27 = .1 , \tag{C-50}$$

$$Pe_{B(n+3)/e} = P_3 - P_2 = .41 - .37 = .04 . \tag{C-51}$$

The next 5 errors are obtained by interpolation:

$$P_6 = .46 , \tag{C-52}$$

$$P_3 = .41 , \tag{C-53}$$

$$\text{Diff} = .05 , \tag{C-54}$$

$$Pe_{B(n+4)/e} = .05/3 = .017 , \tag{C-55}$$

$$Pe_{B(n+5)/e} = .05/3 = .017 , \tag{C-56}$$

$$Pe_{B(n+6)/e} = .05/3 = .017 . \tag{C-57}$$

Interpolating for $Pe_{B(n+1)/e}$ and $Pe_{B(n+8)/e}$:

$$P_{10} = .51 , \tag{C-58}$$

$$P_6 = .46 , \tag{C-59}$$

$$\text{Diff} = .05 , \tag{C-60}$$

$$Pe_{B(n+1)/e} = .05/4 = .013 , \tag{C-61}$$

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*This expression indicates that the probability of the second error in the word occurring in the second bit after the first error in that word is the probability of that error occurring within the first 2 bits (P_2) minus the probability of that error occurring in the first bit (P_1).

$$Pe_{B(n+8)/e} = .05/4 = .013 \,, \tag{C-62}$$

$$Pe_{B(n+12)/e} = Pe_{11} - Pe_{12} \,. \tag{C-63}$$

Interpolating between values shown in Figure C-2:

$$Pe_{16} = .535 \,, \tag{C-64}$$

$$Pe_{10} = .51 \,, \tag{C-65}$$

$$\text{Diff} = .025 \,, \tag{C-66}$$

$$Pe_{B(n+12)/e} = Pe_{B(n+14)/e} = .025/6 = .004 \,, \tag{C-67}$$

$$Pe_{B(n+24)/e} = (Pe_{24}) - (Pe_{25}) \,. \tag{C-68}$$

Interpolating:

$$Pe_{32} = .565 \,, \tag{C-69}$$

$$Pe_{16} = .535 \,, \tag{C-70}$$

$$\text{Diff} = .03 \,, \tag{C-71}$$

$$Pe_{B(n+24)/e} = Pe_{B(n+26)/e} = .03/16 = .002 \,. \tag{C-72}$$

Note Figure C-2 was interpreted conservatively in assuming that only 1 error has occurred between the first error bit and x. If additional errors have occurred, they would result in detection of an error condition for that message and hence reduce the undetected error rate.

The following table summarizes the above computations.

i	$Pe_{B(n+i)/e}$	i	$Pe_{B(n+i)/e}$	i	$Pe_{B(n+i)/e}$	i	$Pe_{B(n+i)/e}$
1	.27	8	.013	15	.004	22	.002
2	.1	9	.011	16	.004	23	.002
3	.04	10	.009	17	.003	24	.002
4	.017	11	.00	18	.003	25	.002
5	.017	12	.004	19	.003	26	.002
6	.015	13	.004	20	.002	27	.002
7	.013	14	.004	21	.002	28	.002

APPENDIX D

RELIABILITY & AVAILABILITY

D.1 BACKGROUND FOR SELECTION OF INTERSECTION AVAILABILITY AS A MEASURE OF EFFECTIVENESS

The candidate systems have generally been configured to allow for the implementation of first generation traffic responsive UTCS software. Thus, in essence, and within the physical constraints of the design, the candidate systems are assumed to implement the same traffic responsive control strategies (area traffic responsive control, critical intersection control, actuated control) and thus to provide the same timing controls in the principal modes of operation.

In this context, the major issues which relate to the reliability of the communications candidates are: the level of service or service interruption of the signal system as perceived by the motorist at the intersection; and, the cost of maintenance to the traffic engineer.

The first issue, that of level of service, can be quantified by a system availability model.

The second issue is a component of system cost and is treated along with all other costs.

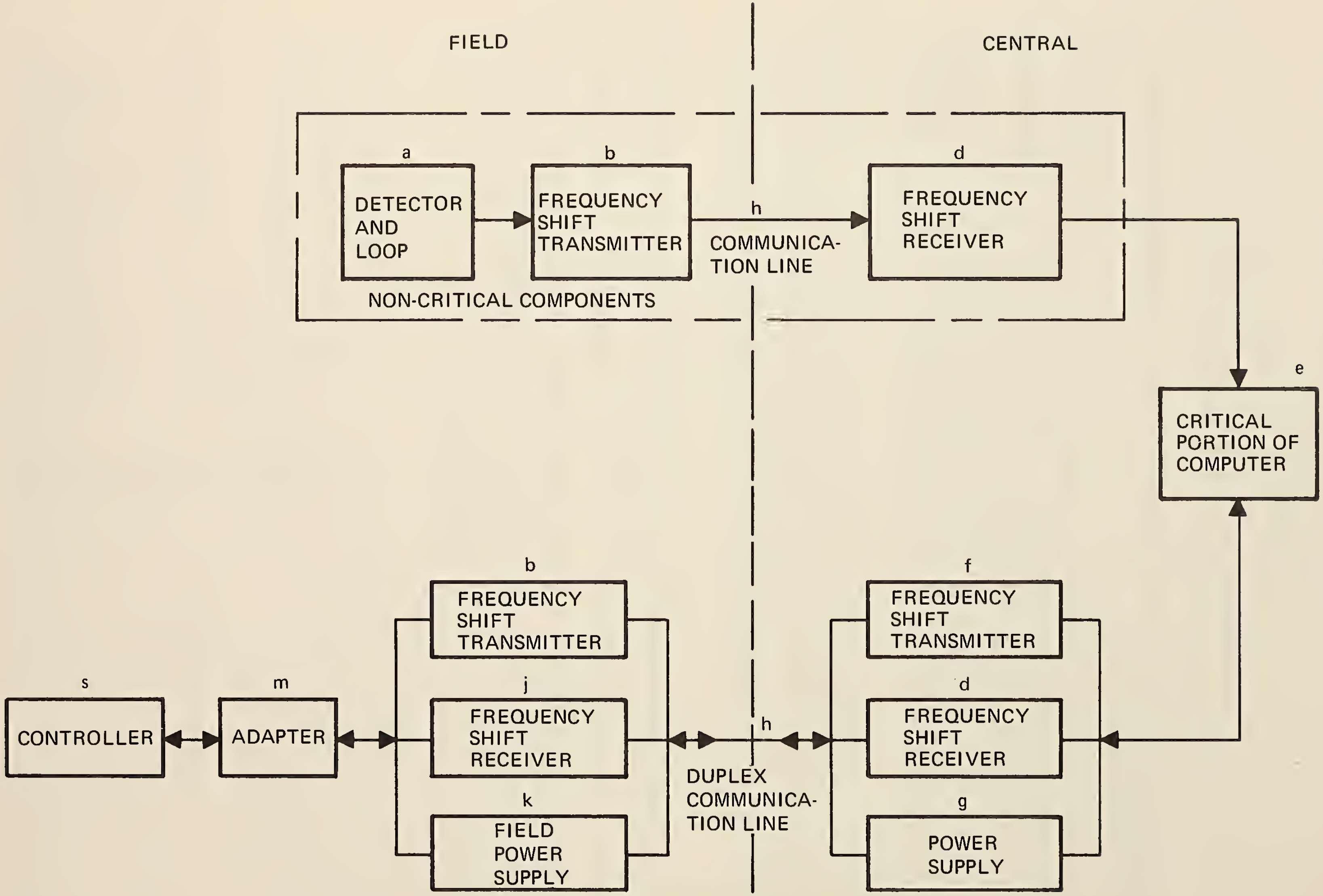
In the simplified form used in this anlysis, the "availability" of an intersection is defined (for all candidates and architectures) as the percentage of the time (based on component failure rates and equipment repair times) that an intersection is able to operate utilizing the UTCS 1st generation area-wide control strategy.

This type of model is useful because it:

- Describes reliability in terms perceived by the system user, i.e., the motorist.
- Normalizes the system as to size; for example, a twenty-five intersection system can be easily compared to a two-hundred intersection system.
- Allows systems with different communications technologies to be easily compared.

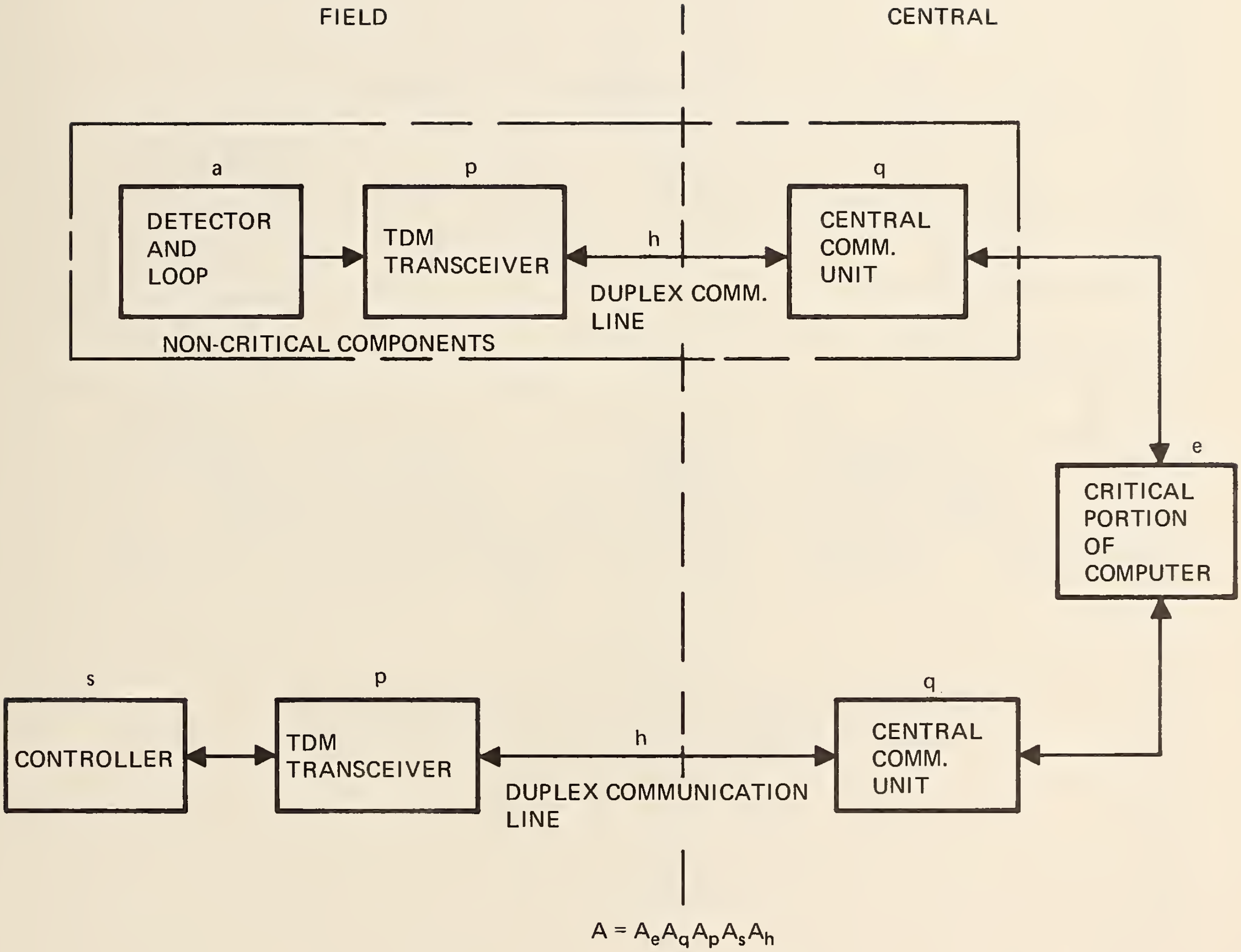
D.2 DESCRIPTION OF RELIABILITY AND AVAILABILITY ANALYSIS

The availability models for the area traffic responsive mode (principal mode) of the centralized system architecture are shown in Figures D-1 through D-4 for the candidate communication technologies. Availability for each component is provided by the formula



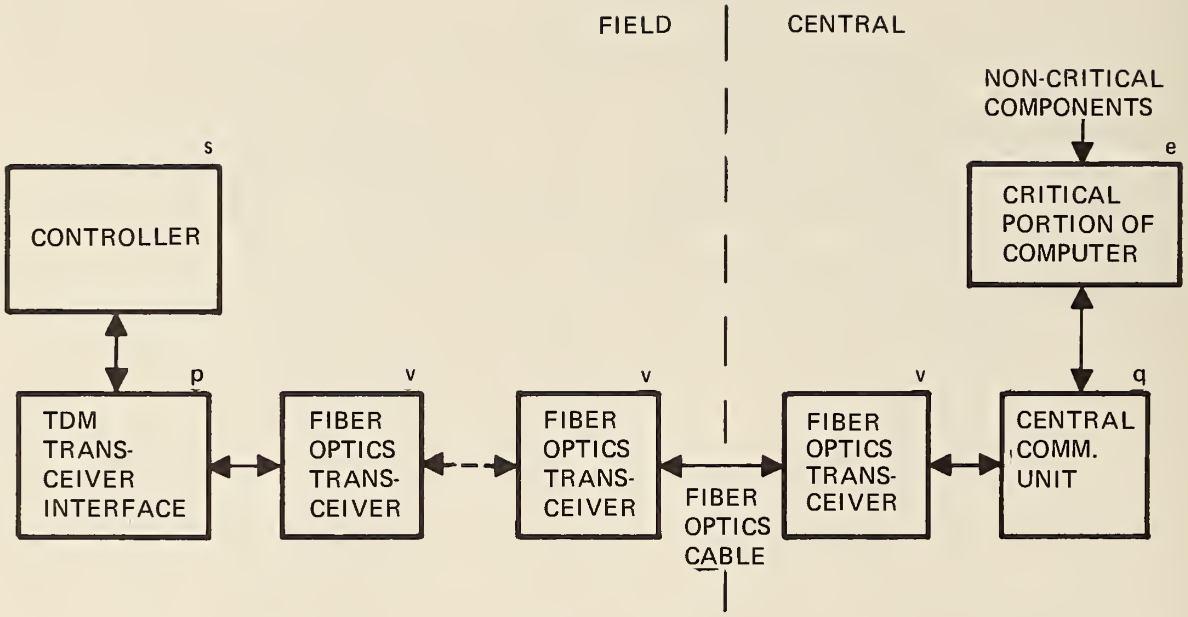
$$A = A_e A_f A_d A_g A_h A_b A_j A_k A_m A_s$$

FIGURE D-1. AVAILABILITY OF PRINCIPAL MODE FOR FDM WIRE BASED CENTRAL SYSTEM



$A = A_e A_q A_p A_s A_h$

FIGURE D-2. AVAILABILITY OF PRINCIPAL MODE FOR TDM WIRE BASED CENTRAL SYSTEM

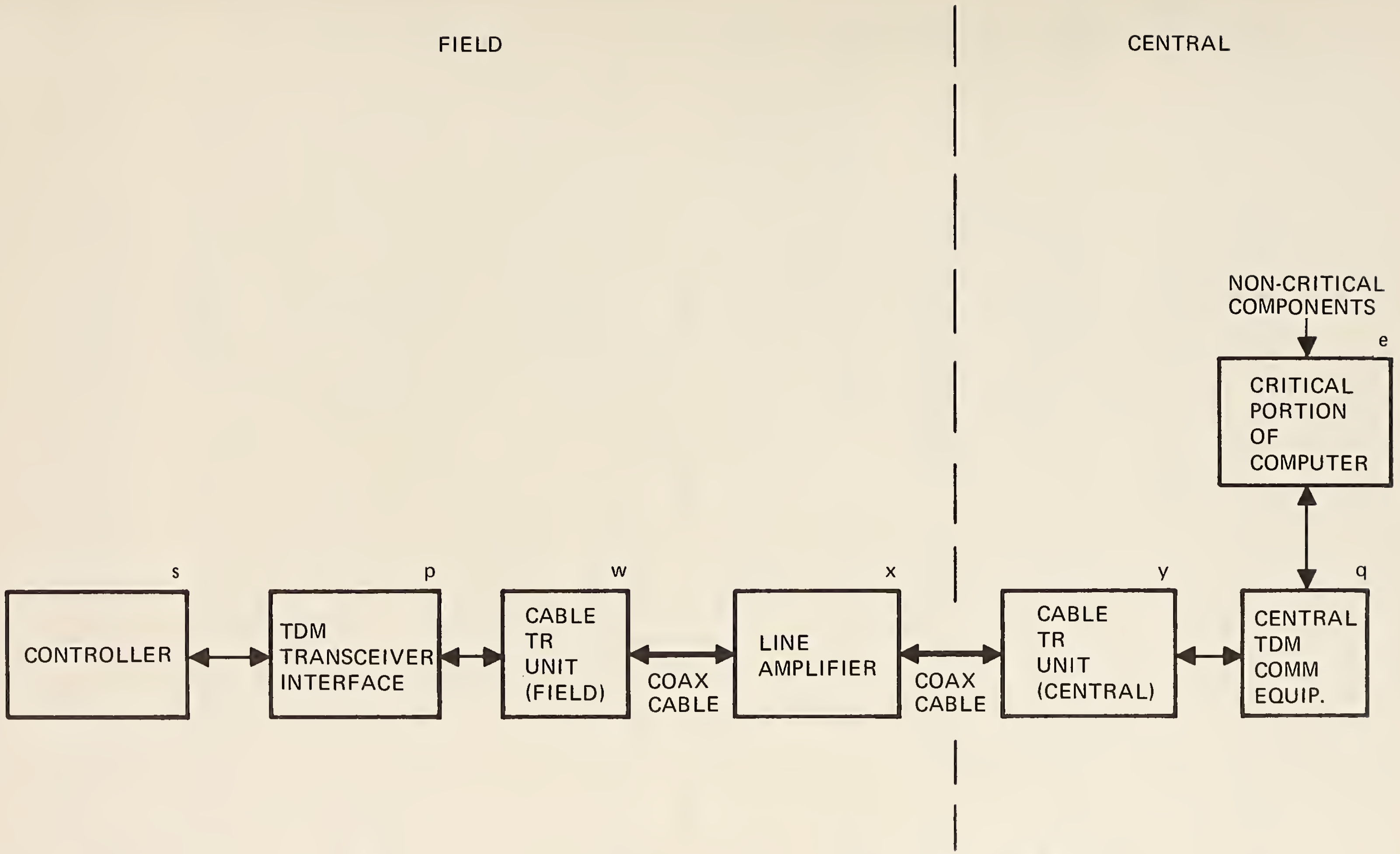


$$A_k = A_e A_q A_p A_s A_v^z$$

WHERE z IS THE NUMBER OF TRANSCEIVERS AND CABLE LINKS BETWEEN INTERSECTION K AND THE CENTRAL COMPUTER

$$A_{AV} = \frac{A_e A_q A_p A_s}{n} \sum_{K=1}^{n} A_v^z$$

FIGURE D-3. PRINCIPAL MODE AVAILABILITY DIAGRAM AND RELATIONSHIPS FOR FIBER OPTICS WITH CENTRAL SYSTEM



$$A_k = A_e A_p A_q A_s A_w A_y A_x^z$$

WHERE z IS THE NUMBER OF LINE AMPLIFIERS BETWEEN INTERSECTION K AND CENTRAL

$$A_{AV} = \frac{A_e A_p A_q A_s A_w}{n} \sum_{K=1}^{n} A_x^z$$

FIGURE D-4. PRINCIPAL MODE AVAILABILITY DIAGRAM AND RELATIONSHIPS FOR COAXIAL CABLE COMMUNICATIONS WITH CENTRAL SYSTEM

$A = MTBF/(MTBF + MTTR)$, where MTBF is the mean time between failures and MTTR is the mean time to repair. Table D-1 describes a representative value for the MTBF of each component. Field experience generally indicates wide variations in the component values because of the basic differences in workmanship and quality in the manufacturing and installation process; and, because of different methods of reporting reliability. Because the basic purpose of this reliability/availability study is to compare different communication candidates within an architecture (in contrast to obtaining a single "absolute" value), these factors were considered to be the same for each of the candidates.

Thus the values in Table D-1 are, for each component, generally (with a few exceptions) based on those field experiences which reflect the best performance reports. In a few instances, because of the absence of useful field information, it was necessary to make estimates based on the complexity of the equipment relative to equipment in a similar environment. The specific source of each MTBF value is listed in Table D-1.

For certain communication techniques, the number of electronic units which the signal must pass through varies with distance or with the number of signalized intersections serially connected between the critical computer and the intersection for which the availability is being computed. In these cases, (Figures D-3, D-4, D-6), the symbol A_{AV} is used to represent the average availability of all of the intersections.

The availability during the principal mode of operation for the communications candidates used with the central system architecture are shown in Table D-2 along with the "downtime" per year of this mode as seen at each intersection (based on twelve-hours-per-day six-days-per-week operation). Included in this table are the availabilities of: The "critical computer", i.e., that portion of the computer which must function for this mode to be operative; and, the combination of the critical computer and the communication lines. From the data it is concluded that the central computer dominates the reliability picture for this architecture and that differences between basically highly reliable communication systems even of radically different designs have little effect on system availability or performance as perceived at the intersection. Differences in maintenance cost among such systems using technologies which have comparable repair times are similarly small and do not constitute a basis for system selection.

Similar results would be obtained for the hierarchical system, since this system also utilizes a central minicomputer to provide the on-line pattern selection feature of the UTCS first generation strategy.

TABLE D-1. COMPONENT RELIABILITIES FOR CENTRAL SYSTEM ARCHITECTURE

Identifier for (figures D-1 to D-6)	Equipment	MTBF (hrs)	MTTR (hrs)	Availability	Traffic control system source of MTBF data
a	Detector and loop	1.65×10^5	1.5	.9999909	Washington UTCS
b	Freq. shift trans. (field)	2.83×10^5	1.5	.9999964	Washington UTCS
d	Freq. shift rec. (central)	4.87×10^5	1.0	.9999964	Washington UTCS
e	Critical portion of computer	2×10^3	5.0	.9975062	Washington UTCS, Miami, New Orleans
f	Freq. shift transmitter (central)	3.75×10^5	1.0	.9999973	Washington UTCS
g	Power supply	2.67×10^4	1.0	.9999625	Washington UTCS
h	Duplex comm. line	2.27×10^4	2.0	.9999119	Washington UTCS
j	Freq. shift rec. (field)	4.00×10^5	1.5	.9999962	Washington UTCS
k	Field power supply	12.9×10^5	1.5	.9999988	Washington UTCS
m	Controller adapter	1.99×10^5	1.5	.9999925	Washington UTCS
o	Electromech. controller	1.72×10^5	1.5	.9999913	Washington UTCS
p	TDM field transceiver	effective combination $= 2.66 \times 10^4$	1.5	.9999436	Miami and South Bay data
q	Central office TDM comm. unit				
v	Fiber optics transceiver	2×10^4	1.5	.9999250	estimate
w	Cable TR unit (field)	3.125×10^3	1.5	.999520	Columbus-estimate probably conservative
y	Cable TR unit (central)	4.6×10^3	1.0	.999782	Columbus-estimate probably conservative
x	Line amplifier	2.5×10^4	1.5	.999940	Columbus

TABLE D-2. AVAILABILITY AND DOWNTIME FOR CENTRAL SYSTEMS CANDIDATES

System failure mode	Intersection availability	Intersection downtime[a] per year (hrs)
A. Critical computer	.997506	21.7
B. Critical computer plus communication lines	.997418	22.5
C. Entire system with FDM (wire)	.997349	23.1
D. Entire system with TDM (wire)	.997353	23.0
E. Entire system with fiber optics	.996689	28.9
F. Entire system with coax cable	.996564	29.9

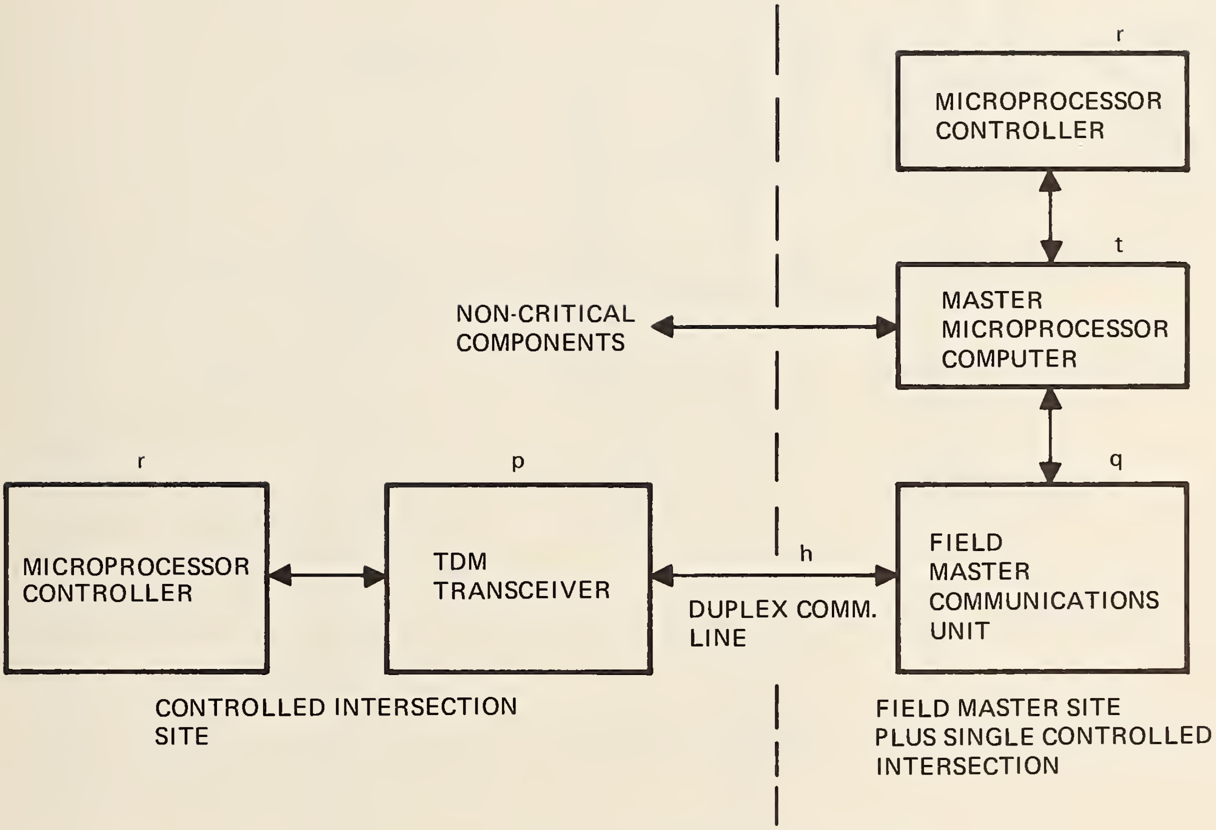
[a] "Downtime" signifies that the UTCS first generation control strategy is unavailable. System failure modes provide for a lower level of performance for most failures.

Figures D-5 and D-6 show the availability diagrams and relationships for the wire-based and air path optics based candidates for the network architecture. Reliability estimates for the components which are unique to this architecture are provided in Table D-3.

Reliability data on both the microcomputer components (as used in traffic control applications) and air path optics components is limited. The microcomputer reliability estimate is a conservative estimate based on a combination of limited field data and piece part failure rate data.

In the air path optics communication concept, the signal is essentially received at each intersection and then retransmitted to a succeeding intersection. Thus, failure of the transceiver at any intersection will interrupt the data flow to all other intersections in the optical chain on the other side of the master.

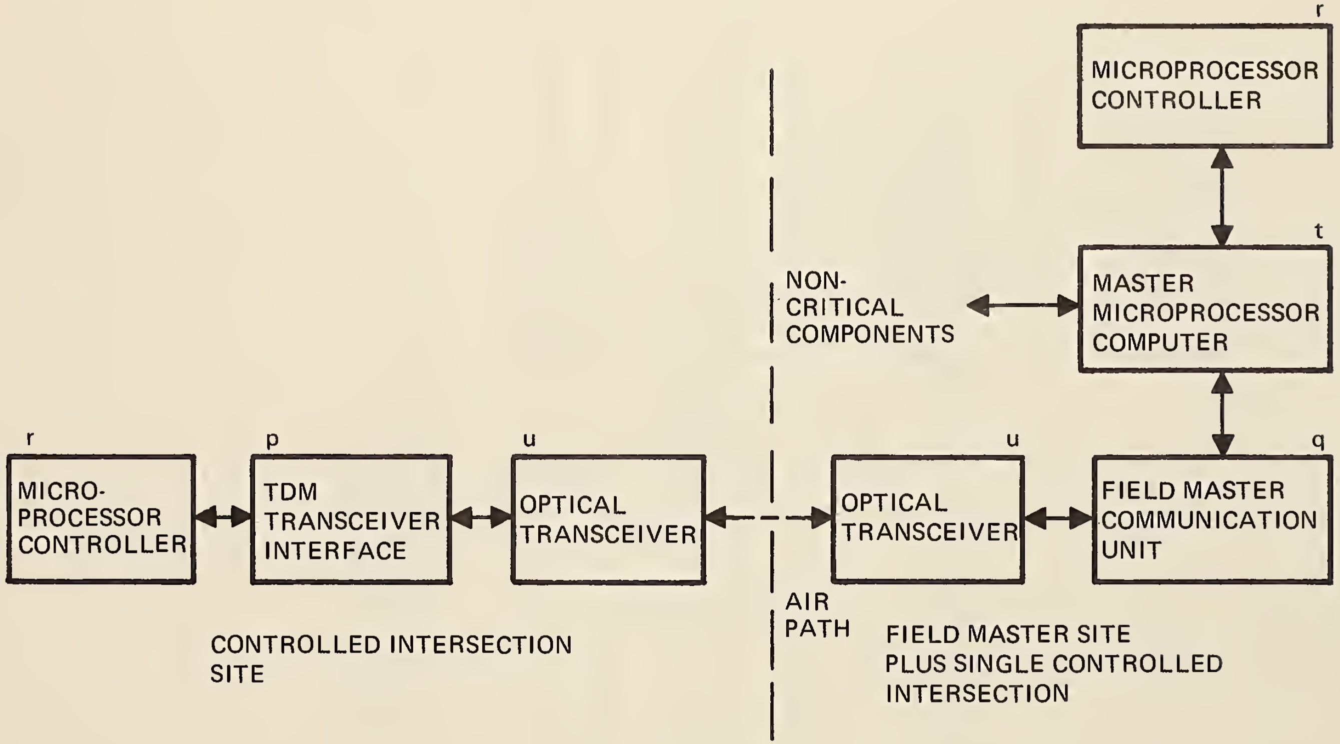
Table D-3 shows a reliability estimate for the air path optics communications system based on limited testing (2 failures in 21,836 equipment hours of on-going outdoor testing). This is probably a conservative number as the failures occurred on units which were relatively early in a product experience cycle.



$A_k = A_t A_q A_p A_h A_r$ FOR ALL INTERSECTIONS REMOTE FROM FIELD MASTER SITE

$A_o = A_t A_r$ FOR FIELD MASTER SITE

FIGURE D-5. PRINCIPAL MODE AVAILABILITY DIAGRAM AND RELATIONSHIPS FOR TDM AND WIRE MEDIUM WITH NETWORK SYSTEM



$A_k = A_t A_q A_u^z A_p A_r$ FOR $z > 1$

$A_0 = A_t A_r$ $z = 0$

WHERE z IS THE NUMBER OF OPTICAL TRANSCEIVERS BETWEEN INTERSECTION K AND THE FIELD MASTER SITE

$$A_{AV} = \frac{1}{m+1} \sum_{k=0}^{m} A_k$$

FIGURE D-6. PRINCIPAL MODE AVAILABILITY DIAGRAM AND RELATIONSHIPS FOR AIR PATH OPTICS WITH NETWORK SYSTEM

TABLE D-3. RELIABILITIES FOR ADDITIONAL COMPONENTS

Identifier for figures D-5 and D-6	Equipment	MTBF (hours)	MTTR (hours)	Availability
r	Microprocessor controller	20000	1.5	.9999250
t	Master microprocessor	20000	1.5	.9999250
u	Optical transceiver	11000	1.5	.9998636

When the reliability data in Table D-3 is applied to the network test case example the following availabilities and yearly unavailability times resulted:

Candidate	Availability	Yearly down time (hours)
TDM wire based communications	.999729	2.3
TDM air path optics based communications	.999439	4.9

These numbers indicate the basically high system reliability achievable with this architecture.

The relatively small difference in reliability among the communication candidates do not constitute a basis for decisions.

APPENDIX E

CHARACTERISTICS OF EXISTING COMPUTERIZED TRAFFIC CONTROL SYSTEMS

This Appendix summarizes the principal features and communication-related characteristics of fifteen in-place or under-contract computerized traffic control systems installed or designed by Sperry Systems Management. These systems date from the Washington, D.C. UTCS System - operational in 1970 - to the Seattle, Washington (SR-5) System currently being designed at the time of this writing. System size ranges from the 21-intersection Danville, Virginia System to the 250-intersection Birmingham, Alabama System.

This material is presented in Tables E-1, E-2 and E-3 located at the rear of the Appendix. The accompanying text defines the table headings.

Table E-1 summarizes the principal features and data sampling rates for the 15 traffic control systems. The items listed in this table are defined as follows:

- Number of intersections is the number of intersections either under computer control or scheduled for computer control. For example, in Bellevue, Washington, the system has been designed for 71 intersections. Presently, however, only 48 intersections have been implemented; and, of this number, 19 utilize microprocessors.
- Number/type of controller is the number of intersections utilizing pretimed (Pt.) and actuated (Act.) controllers.

  The SR 5 controllers (labeled local and master) consist of twenty-five microprocessor local controllers supervised by five master controllers.
- Number of detectors is the number installed for surveillance in the computerized system and does not include those used for controller actuation.
- Communications medium is the method used to connect the computer to the street equipment and over which command, status and surveillance data is transmitted. All of the representative systems, with the exception of Columbus, Ohio, utilize wire consisting of twisted pairs bundled in a shielded cable which may be either buried or installed overhead. These cables may be leased from the telephone company or owned by the city. Columbus, Ohio utilizes a coaxial cable which carries closed circuit television as well as traffic system communications. The communication medium characteristics for each city is summarized in Table E-2.

- The items listed for Computer, Peripherals and Operator Controls reflect the size of the computer and features of the control center. They do not affect the surveillance and control communications except in a distributed processing system where certain system parameters are transmitted to central solely for display and logging.

- Special functions have a significant impact on the communications requirements. A bus priority (BPS) function, as in Washington, DC, required the transmission of a large volume of data from the field. The fire preemption (FP) systems installed in Memphis, Tenn.; Birmingham, Ala.; Winston-Salem, NC; SR 5 and Raleigh, NC require communication between central and each intersection with a premption capability. The Amarillo, Texas and Danville, Virginia fire preempt systems allow the operator to select a preprogrammed preemption pattern via a control panel which interfaces with the computer. In these cities, preemption commands are not transmitted to each intersection.

- Control software is the type of traffic control program used. The abbreviations UTCS ASSY and UTCS FORT refer to the assembly-language and FORTRAN versions of the UTCS program, and SRT refers to the Sperry Traffic Control program.

- Traffic control is the decision making process used to generate traffic-signal timing patterns. The major types covered are Time of Day (TOD), Traffic Responsive (TR) and Critical Intersection Control (CIC). In a computerized system, various algorithms are available to generate the patterns required for each method. The data transmission requirements of these types of control differ primarily in that TR and CIC require volume and occupancy data, while TOD does not.

- Data sampling rates vary for the surveillance, monitor and command functions. Maximum rates are listed for each traffic control system. CIC capability requires pattern update a maximum of once per traffic-signal cycle.

Table E-2 is a summary of the salient characteristics of the communications medium. The items listed in this table are defined as follows:

- Type: Fourteen of the cities use wire in the form of twisted pairs, size 19 to 24 AWG, in a shielded cable. The fifteenth city, Columbus, Ohio, uses a coaxial cable.

- Supplier is either the telephone company "Tel", in the case of a leased system, or "Own" when the city owns the medium. Several systems utilize both suppliers.

- Functional configuration describes the multiplex capability of the medium in each city. The multiplex capability is dependent not only upon the medium but the multiplex technique used.
- Transmission range is the maximum distance over which each city's data is transmitted.
- Operating frequencies is that portion of the available spectrum actually used for communications.
- Interface requirements defines the recommended impedance of the data terminal to optimize performance. A substantial mismatch in the terminating impedance may result in degrading of system performance.
- Conditioning requirements lists any auxiliary hardware required in the communication network between the transmitter and receiver. The Washington, DC, New Orleans and Birmingham systems are FDM and utilize line amplifiers at central. These amplifiers have a flat frequency response over the 300 Hz to 3,000 Hz band of operation and are used for isolation as well as amplification.

  The broadband communications system in Columbus required line amplifiers and couplers. These devices are distributed throughout the system.
- Available bandwidth is the inherent bandwidth of the medium available for communications. Leased line systems generally utilize voiceband channels. The telephone companies guarantee the quality of this transmission medium over the 300 Hz to 3,000 Hz band.

  The Raleigh DC system required the telephone company to provide lines with DC continuity and isolation from the telephone company office equipment - a nonstandard service.

  Owned systems utilize shielded twisted pairs with a bandwidth from DC to about 100 kHz. The 100 kHz upper limit is based upon a maximum 40 db signal attenuation over an eight-mile (12.9 Km) distance on 22 AWG cable. Higher frequencies could be utilized over shorter distances and/or larger cable. Using FDM, however, the highest frequency usually is 2,340 Hz; the FDM tone equipment being designed primarily for compatibility with voiceband telephone systems.

  The coaxial cable system used in Columbus has a bandwidth from 5 MHz to 300 MHz; although the cable has a bandwidth down to DC, line amplifiers have bandwidths no lower than 5 MHz. The Columbus system allocated the frequency bands 20-22 MHz and 45-54 MHz for traffic control communications. Other bands were allocated for video surveillance and voice communications.

- Channels in use is the number of channels actually used for traffic control surveillance and control. In FDM systems and in Columbus, this is the total number of tone channels used. In DC and TDM systems, this is the number of cable pairs in use. For Winston-Salem and Memphis, the number of cable pairs required had not yet been defined at the time of this writing.

- Installation costs for the medium include the cost of:

  - conduit furnished and installed
  - cable furnished and installed
  - splice and pull boxes furnished and installed
  - lightning protection furnished and installed
  - telephone company connection charges.

  The approximate costs were derived from purchase orders, correspondence with the city and/or the local telephone company, and bid lists. Caution should be used in drawing conclusions from this data since these systems were installed over a span of several years during which high inflation occurred and, in several cities, some or all of the interconnect system either previously existed or was installed by the municipality. Chicago and Atlanta are examples of systems where the communication network was not furnished as part of the traffic system contract. For Winston-Salem, Memphis and Birmingham, final cost figures were not available at the time of this writing.

- Annual operating cost has been obtained for several of the leased-line systems. This is the telephone leasing charge. Operating costs are not available for owned systems since most municipalities do not keep such records.

Table E-3 is a summary of the communications hardware used in the fifteen systems. The items listed in this table are defined as follows:

- Type is either frequency division multiplexing (FDM), time division multiplexing (TDM), direct current (DC), or a combination of FDM and TDM.

- Supplier is the manufacturer of the communications equipment.

  Bellevue, Washington uses RFL equipment in conjunction with the TRW type microprocessor controller and ADC equipment for the conventional controller communications.

  DC communication systems utilize relays, hence AMF, a relay manufacturer, is listed as the supplier in Raleigh and Amarillo. In Danville, Va., Interdata, the computer manufacturer, supplied the relays at central as part of its computer interface.

- Functional configuration summarizes the equipment used. FDM equipment can be either three frequency shift (3 FS) or two frequency shift (2 FS). Three frequency shift equipment is useful in two-function single-channel applications where the two events do not occur simultaneously.

- Multiplex capability is the largest number of data points multiplexed on one cable pair. This does not necessarily mean that each cable pair carries that amount of data - some carry less.

  In an FDM system, up to 17 channel tones can readily be carried on one cable pair. This is predicated upon a 120 Hz channel separation and utilization of the band from 420 Hz to 2,340 Hz. It is desirable to limit transmission to this portion of the 300 Hz to 3,000 Hz band to avoid the roll off in the bandpass curve. In Birmingham, the maximum of 16 channels per pair was written into the specification.

  In DC systems, two pairs are assigned for each controller (A-phase green, hold, advance and return) and one pair for each detector.

  TDM systems multiplex the data required for several intersections onto one pair, where each intersection's data includes controller status, detector data, controller commands, and special function status and command. Chicago and Seattle, however, utilize dedicated cable pairs for each intersection. Columbus's broadband system has a capacity of 16 channels, and each channel is assigned a unique frequency on which data for 64 intersections can be time multiplexed.

- Data format is applicable to TDM systems which require synchronization and address bits and, in some cases, parity bits. Addressing can be accomplished by dedicated address bits, the use of a preamble, or by substituting address bits for data bits.

- Data thruput is the number of data bits transmitted per second.

  For Columbus, the number represents the total capacity of the 16 data channels.

  For the TDM systems, the data rates were derived by removing the synchronizing, address, and parity bits.

- Input interface lists the type of hardware feeding the transmitter.

- Output interface lists the type of hardware the receiver must drive.

- Channels in use is the number of channels or cable pairs being utilized in the system. Though the 2 FS and 3 FS channels are listed separately for Washington, DC, they both have the same channel bandwidth and share the same cable pairs.

- Installation costs include the cost of furnishing and installing communication hardware and controller adapters.

  These numbers are derived from purchase orders, contractor bid sheets and discussions with individuals involved in the program. Caution should be exercised in using this data in that it covers a span of several years, round numbers are used, and estimates had to be made where the communications hardware is incorporated into either the traffic signal controller or the computer.

  The communication hardware installation costs had not yet been finalized for Memphis, Winston-Salem and Birmingham at the time of this writing.

- Synchronization (sync) is required for TDM systems. Either asynchronous (ASYNC) or synchronous (SYNC) methods are used. The FDM and DC communication systems do not require synchronization.

- Modulation coding is a result of the requirement for synchronization and error detection capability in TDM systems. Various formats, customized for the application, are currently being utilized to encode the data. FDM and DC traffic communication systems do not require encoding.

- Modulation type defines the method used to transmit the message over the communication medium.

  The FDM systems utilize frequency shift keying (FSK). In FSK, the carrier tone is shifted in frequency whenever it is keyed.

  DC systems utilize a contact closure to transmit data.

Most of the TDM systems utilize FSK as the modulation technique. The Chicago system and the ADC portion of the Bellevue system, however, use phase shift keying (PSK). In PSK, the phase rather than the frequency of the carrier is shifted.

- Error codes are required for TDM systems due to their relatively low noise immunity in comparison to DC or FDM systems. Various techniques are utilized, with the most prevalent being the generation and transmission of a parity bit for each word or byte. Other techniques include: double scan which is the retransmission and comparison of the two messages; form check to ascertain that the message has the correct format; and the transmission of a BCH (Bose-Chaudhuri-Hocquenhem) cyclic code with each word.

TABLE E-1. PRINCIPAL FEATURES AND DATA SAMPLING RATES OF 15 TRAFFIC CONTROL SYSTEMS

		Washington D.C.	Raleigh N.C.	Columbus Ohio	Atlanta Ga.	Chicago Ill.	Amarillo Tex.	Omaha Neb.	Bellevue Wash.	Danville Va.	New Orleans La.	Winston Salem N.C.	Memphis Tenn.	Birmingham Ala.	Lincoln Neb.	SR 5 (Seattle) Wash.
Number of intersections		200	153	94	49	73	133	128	71	21	203	203	145	250	208	25
Number/type of controller		192 Pt. 8 Act.	120 Pt. 33 Act.	78 Pt. 16 Act.	49 Act.	73 Pt.	120 Pt. 13 Act.	101 Pt. 27 Act.	71 Act	16 Pt. 5 Act.	189 Pt. 14 Act.	120 Pt. 83 Act.	60 Pt. 85 Act.	171 Pt. 79 Act.	170 Pt. 38 Act.	25 Local 5 Master
Number of detectors		520	110	253	70	450	162	110	680	17	278	525	118	350	252	191
Communications medium		Wire	Wire	Coax	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire
Computer	make	Xerox	Interdata 70	Interdata 70	Interdata 70	Interdata 7/32	Interdata 7/16	Interdata 7/32	Interdata 7/32	Interdata 7/16	Interdata 7/32	Interdata 7/32	Interdata 7/32	Interdata 7/32	Interdata 7/32	Interdata 7/32
	size	257 K	64 K	128 K	64 K	224 K	64 K	196 K	288 K	32 K	256 K	320 K	256 K	256 K	320 K	256 K
Peripherals		TTY, LP CR, CRT	TTY, LP CR	CRT	TTY, LP CR, CRT	TTY, LP CR, CRT	TTY, LP CR, CRT	TTY, LP CR, CRT	LP, TTY CR, CRT	TTY	TTY, LP CRT	TTY CRT	TTY CRT	TTY, CRT CR, LP	CRT LP	TTY, CRT LP
Operator controls		CP, MAP	MAP	CP, MAP	CP, MAP	CP, MAP	CP, MAP	CP, MAP	MAP	MAP	CP, MAP	CP, MAP	CP, MAP	CP, MAP	MAP	MAP
Special functions		BPS	FP	TV	Data Aca REV LANE	RRP	FP	None	None	FP	None	FP, RRP VMS	FP, RRP	FP	None	FP, RRP, REV LANE, LAMP OUT
Control software		UTCS-ASSY	SRT	UTCS-ASSY	SRT	ASCOT	SRT	SRT	UTCS-FORT	SRT	UTCS-FORT	UTCS-FORT	UTCS-FORT	UTCS-FORT	UTCS-FORT	Special
Traffic control		TOD, CIC TR	TOD, CIC TR	TOD, CIC TR	TOD, CIC TR	TOD, CIC TR GATING	TOD, TR	TOD, TR CIC	TOD, TR CIC	TOD, TR	TOD, TR CIC	TOD, TR	TOD, TR TR	TOD, TR CIC	TOD, TR CIC	TOD, TR
Operational status		Oper. 11/72, 7/75	Oper. 2/75	Oper. 10/75	Oper. 9/73	Oper. 12/75	Oper. 3/76	Oper. 5/77	Oper. 6/76	Oper. 1/77	Oper. 6/77	Install	Install	Install	Install	Design

TABLE E-1. PRINCIPAL FEATURES AND DATA SAMPLING RATES OF 15 TRAFFIC CONTROL SYSTEMS (Cont.)

	Washington D.C.	Raleigh N.C.	Columbus Ohio	Atlanta Ga.	Chicago Ill.	Amarillo Tex.	Omaha Neb.	Bellevue Wash.	Danville Va.	New Orleans La.	Winston Salem N.C.	Memphis Tenn.	Birmingham Ala.	Lincoln Neb.	SR 5 (Seattle) Wash.
Data sampling rates															
Surveillance	32/sec	32/sec	10/sec	32/sec	20/sec	32/sec	60/sec	30/sec	32/sec	32/sec	32/sec	32/sec	32/sec	14/sec	60/sec
Monitor	2/sec	1/sec	1/sec	1/sec	1/sec	1/sec	2/sec	1/sec	1/sec	1/sec	2/sec	1/sec	1/sec	1/sec	1/sec
Command	2/sec	1/cycle	1/cycle	1/cycle	1/sec	1/cycle	2/sec	1/sec	1/sec	1/cycle	2/sec	1/sec	1/cycle	1/sec	1/sec

N.A. - Not applicable

LEGEND

Pt. - Pretimed
Act. - Actuated
LP - Lineprinter
CR - Cardreader
CP - Control panel

FP - Fire preempt
RRP - Railroad preempt
VMS - Variable message sign
TOD - Time of day
TR - Traffic responsive

TABLE E-2. MEDIA FOR 15 TRAFFIC CONTROL SYSTEMS

	Washington D.C.	Raleigh N.C.	Columbus Ohio	Atlanta Ga.	Chicago Ill.	Amarillo Tex.	Omaha Neb.	Bellevue Wash.	Denville Va.	New Orleans La.	Winston Salem N.C.	Memphis Tenn.	Birmingham Ala.	Lincoln Neb.	SR 5 (Seattle) Wash.
Type	Wire	Wire	Coax	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire	Wire
Supplier	Tel	Tel	Own	Own	Tel	Own	Tel/ Own	Tel	Own	Tel/ Own	Tel/ Own	Own	Own	Own	Tel/ Own
Functional configuration	Varies	2 PR/ CONT 1 PR/ DET	TDM on 16 FDM Chan + 7 TV Chan	Varies	1 INT/PR	2 PR/ CONTR 1 PR/ DET	4 INT/ PR	3 INT/ PR	2 PR/ CONT 1 PR/ DET	Varies	8 INT/ 2 PR	8 INT/ 2 PR	Varies	8 INT/ PR	1 Local/ PR 1 Mast/ PR
Transmission range	(8 km) 5 Mi.	(5.6 km) 3.5 Mi.	(2.4 km) 1.5 Mi.	(12 km) 7.5 Mi.	(1.6 km) 1 Mi.	(6.4 km) 4 Mi.	(4.8 km) 3 Mi.	(6.4 km) 4 Mi.	(1 km) .6 Mi.	(4.8 km) 3 Mi.	5 Mi. (8 km)	5 Mi. (8 km)	2.5 Mi. (4 km)	2 Mi. (3.3 km)	20 Mi. (32 km)
Operating frequencies	420 Hz to 2340 Hz	DC	20.2 MHz 45-54 MHz	420 Hz to 2340 Hz	300 Hz to 2100 Hz	DC	1200/ 2200 Hz	1200/ 2200 Hz	DC	420 Hz to 2340 Hz	1200/ 2200 Hz	1200/ 2200 Hz	420 Hz to 2220 Hz	1200/ 2200 Hz	
Interface requirements	600 Ω	600 Ω	75 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω	600 Ω
Conditioning requirements	Line AMP At Central	None	Bi-directional coupler	None	None	None	None	None	None	Line AMP at Central	None	None	Line AMP at Central	None	None
Available bandwidth	300 Hz to 3000 Hz	DC to 3 KHz	5 MHz to 300 MHz	DC to 100 KHz	300 Hz to 3000 Hz	DC to 100 KHz	300 Hz to 3000 Hz	DC to 100 KHz	DC to 100 KHz	300 Hz to 3000 Hz	300 Hz to 3000 Hz	DC to 100 KHz	DC to 100 KHz	300 Hz to 3000 Hz	300 Hz to 3000 Hz
Channels in use	885	420 PR	4	274	73 PR	428 PR	128 PR	24 PR	59 PR	897	N.O.	N.O.	691	32 PR	30 PR
Installation cost ($)	20,000	5,500	287,000	N.O.	N.O.	205,000	180,000	7,000	232,000	410,000	N.O.	N.O.	N.O.	200,000	2,000
Annual operating cost ($)	6,000	42,000	N.O.	N.O.	N.O.	N.O.	3,300	5,800	N.O.	2,000	N.O.	N.O.	N.O.	N.O.	N.O.

N.O. - Not readily obtainable
N.A. - Not applicable

TABLE E-3. COMMUNICATIONS HARDWARE FOR 15 TRAFFIC CONTROL SYSTEMS

	Washington D.C.	Raleigh N.C.	Columbus Ohio	Atlanta Ga.	Chicago Ill.	Amarillo Tex.	Omaha Neb.	Bellevue Wash.	Danville Va.	New Orleans La.	Winston Salem N.C.	Memphis Tenn.	Birmingham Ala.	Lincoln Neb.	SR 5 (Seattle) Wash.
Type	FDM	DC	FDM/TDM	FDM	TDM	DC	TDM	TDM	DC	FDM	TDM	TDM	FDM	TDM	TDM
Supplier	RFL	AMF	TOCOM	RFL	TDS	AMF	Sonex	RFL, ADC	Interdata	Data Master	Sonex	Sonex	RFL	Eagle	Sonex
Functional configuration	2 FS-AφG, DET, 3 FS-HOLD, ADV, BPS	Relay	Full DPLX 16 CHAN.	2 FS	Half Duplex	Relay	Half Duplex	Full DPLX 4 Wire	Relay	2 FS	Half Duplex	Full DPLX 4 Wire	3 FS	Half Duplex	Half Duplex
Multiplex capability	17 CHAN/PR	2 PR/CONT; 1 PR/DET	16 CHAN 64 INT/CH	17 CHAN/PR	1 INT/PR	2 PR/CONT 1 PR/DET	4 INT/PAIR	3 INT/PAIR	2 PR/CONT 1 PR/DET	17 CHAN/PR	3 INT/2 PR	8 INT/2 PR	16 CHAN/PR	8 INT/PR	1 Local/PR 1 Loc-Mast/PR
Data format	N.A.	N.A.	2 SYNC 6 ADDR 10 COMM	N.A.	16 Data 16 SYNC	N.A.	8 Data 2 SYNC 1 Parity	8 Data 2 SYNC	N.A.	N.A.	8 Data 2 SYNC 1 Parity	8 Data 2 SYNC 1 Parity	N.A.	16 Data 4 SYNC	6 Data 2 SYNC 1 Parity
Data thruput	2 FS/3 FS 60/40 PPS	N.A.	7 TV CHAN, 400 KBS	60 bps	500 bps	N.A.	770 bps	790 bps	N.A.	60 PPS	770 bps	770 bps	40 PPS	600 bps	770 bps
Input interface	Relay and Transistor	Relay and Transistor	TTL	Relay and Transistor	TTL	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor
Output interface	Relay and Transistor	Relay and Transistor	TTL	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Relay and Transistor	Transistor
Channels in use	630-2 FS 255-3 FS	420 PR	4	274	73 PR	428 PR	128 PR	48 PR	59 PR	870	N.O.	N.O.	691	32	30
Installation cost ($)	360,000	25,000	260,000	100,000	10,000	20,000	88,000	100,000	8,200	570,000	N.O.	N.O.	N.O.	150,000	58,000
Sync	N.A.	N.A.	SYNC	N.A.	SYNC	N.A.	ASYNC	ASYNC	N.A.	N.A.	ASYNC	ASYNC	N.A.	ASYNC	ASYNC
Modulation code	N.A.	N.A.	Custom	N.A.	Custom	N.A.	Custom	Custom	N.A.	N.A.	Custom	Custom	N.A.	Custom	Custom

TABLE E-3. COMMUNICATIONS HARDWARE FOR 15 TRAFFIC CONTROL SYSTEMS (Cont.)

	Washington D.C.	Raleigh N.C.	Columbus Ohio	Atlanta Ga.	Chicago Ill.	Amarillo Tex.	Omaha Neb.	Bellevue Wash.	Danville Va.	New Orleans La.	Winston Salem N.C.	Memphis Tenn.	Birmingham Ala.	Lincoln Neb.	SR 5 (Seattle) Wash.
Modulation type	FSK	DC	FSK	FSK	PSK	DC	FSK	FSK/ PSK	FSK	FSK	FSK	FSK	FSK	FSK	FSK
Error code	None	None	Parity for Data	None	Word SYNC, Double Scan, Form Check	None	Parity	Parity + BCH	None	None	Parity	Parity	None	Double Scan	Parity

N.O. - Data not readily obtainable
N.A. - Not applicable
*ADC System uses 18 data + 5 BCH + 2 SYNC

APPENDIX F

USER OWNED WIRE PAIR COMMUNICATION

F.1 GENERAL

Wire pair cables suitable for transmitting traffic control systems data ("telephone-type" cable) consist of insulated solid copper conductors which are twisted into pairs to minimize cross talk, wrapped with a protective material, covered with a shield to reduce electrostatic interference, and then wrapped with a protective jacket. These cables are available in a variety of configurations covering different pair counts and gauges, and are manufactured to specifications promulgated by agencies such as the Rural Electrification Administration (REA) or International Municipal Signal Association Inc. (IMSA).

In selecting the configuration, consideration must be given to the number of pairs required, the distance of transmission, and the method of routing (direct-burial, aerial, and conduit). Standard wire gauge (AWG) numbers are used to represent wire diameter, with larger gauge numbers representing smaller diameter. The lower gauge wire offers lower attenuation per unit length than the higher gauge wire; however, the overall diameter of the cable is larger. This might present a problem if an existing conduit with limited space is to be utilized. In most applications, the AWG 19 or 22 sizes are specified.

The conductors are normally insulated with color-coded low density polyethylene (LDPE) or polyvinyl chloride (PVC)[1]. The polyethylene type offers low dielectric constant, low power factor, high dielectric strength and electrical stability over wide frequency and temperature ranges - desirable properties in a communication cable. The polyvinyl chloride type offers excellent flame resistance and good electrical stability over a wide frequency range.

F.2 CABLE CONSTRUCTION

A multiconductor cable is constructed by twisting the conductors into pairs and then binding them into groups. The bound groups are formed into a single cylindrical group or "core", which is covered with a nonhygroscopic dielectrical material to serve as a heat barrier that prevents damage during the jacketing operation. A single corrugated shield, usually of annealed solid copper or plastic-coated aluminum is applied over this cover. The term shield percentage, often encountered in the specification, refers to the area of

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[1] Pehrson and Rossi, Communications Cable Versus Environment, ICC '77 Chicago, Conference Record Volume 1, IEEE Catalog No. 77CH1209-6 CSCB.

coverage of the shield and not necessarily the shielding effectiveness. (Thus, an 80 percent shield of one material might be more effective than a 100 percent shield of another). The cable is jacketed by a black polyethylene compound. The standard number of pairs available in these cables are: 3, 6, 12, 18, 25, 50, 75, 100, 150, 200, 300, 400, 600, and 1200, and the wire sizes available include AWG 19, 22, 24, and 26.

For use in direct-burial installation or in conduit where dampness is expected, "filled" cable is often used. In a filled cable, a moisture-resistant compound is applied to the individual conductors and to the core before the outer jacket is applied. The compound is intended to fill the voids between the pairs and groups and to prevent moisture from penetrating in the event the insulation is damaged.

F.3 CABLE INSTALLATION

Before the cable requirements can be defined, the installation method, aerial, direct-burial or burial in conduit must be selected. This decision is constrained by local ordinances as well as the terrain. Table F-1 is a summary of the characteristics of the various techniques.

TABLE F-1. COMPARISON OF CABLE INSTALLATION TECHNIQUES

	Aerial	Conduit	Direct burial
Relative cost of installation	Low(a)	High	Moderate
Visual impact	High	Low	Low
Vulnerability to damage	High	Low	Moderate
Ease of repair	Good	Fair	Poor
Ease of installing additional pairs	Good	Fair	Poor

[a] Assuming poles exist, otherwise "moderate".

If existing utilities employ overhead right of way, the possibility of using the same poles should be considered as a cost saving measure. When the communication cable is sharing the same pole as a lamp cable or power cable, the communication cable, where possible, should be located below the power cable (to avoid the possibility of falling across and shorting the power cable) as stated in the National Electric Code. Systems using aerial cables are subject to the same interruptions experienced by power and telephone company cables caused by falling trees and other storm-induced damage.*

Cable may be buried directly or in conduit. Conduit affords the cable added protection and simplifies the replacement of cable or addition of cable. Certain localities place restrictions on the type of conduit to be used, the conduit usually being either rigid steel or polyvinyl chloride (PVC). PVC conduit is becoming more prevalent principally because it is less costly to install, and is not subject to corrosion, as steel is. This latter property makes its use attractive in corrosive soils. The use of conduit should be considered in an area where construction activity poses a risk to a directly buried cable. When a direct buried cable is laid, it should be below the frost line; and in a rocky terrain, should be in a bed of sand to minimize the hazard caused by jagged rocks. The direct burial cable is also available in a gopher-resistant jacket for installation in areas plagued by this problem.

The "National Electric Code" specifies that direct burial cable be buried a minimum of 24 inches (61 cm) below grade, rigid non-metallic conduit be 18 inches (46 cm) minimum below grade, and rigid metal conduit be 6 inches (15 cm) minimum below grade. These rules apply for cable operating between 0 to 600 volts.

Tests are currently being conducted[2] to determine if the burial of communication cable with a power cable is feasible. Until the results are complete, it is not recommended.

F.4 ENVIRONMENTAL EFFECTS

One of the primary environmental problems encountered by communication cable is moisture, which can increase attenuation, phase shift, and characteristic impedance by as much as 50 percent and increase leakage by a factor of 10. In addition, moisture can increase cross-talk and cable noise by introducing reflections and variable attenuation. These effects were measured in tests conducted on a 19 AWG, .08 uf cable.[3] The primary

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*Several municipalities have agreements with the utility companies whereby the utility will rehang any municipal cable dislodged with other utility cables by incidents such as falling trees or a damaged pole; the municipality is responsible, however, for the repair of damaged cables.

2. Harrison, R. L., Field Measurements of Inductive Interference on a Joint Random Buried Installation and on a Joint Conduit Installation, ICC '77 Chicago, Conference Record, Volume 1, IEEE Catalog No. 77CH1209-6 CSCB.
3. Eager, G.S., Jachimowicz, L., Kolodny, I., Robinson, D.E., Transmission Properties of Polyethylene-Insulated Telephone Cables at Voice and Carrier Frequencies, Communications and Electronics, American Institute of Electrical Engineers, November 1959.

source of moisture entry, found to be at splices,[1] can be eliminated by the use of splice enclosures and silicon-filled polyethylene sleeves developed to insulate conductor joints and effectively prevent moisture problems. Another source of moisture entry is imperfections in the cable jacketing, a problem which is encountered most often with PVC jacketing, less often with LDPE, and almost never with filled cable. The concomitant problem of the effect of low temperature on the cable properties has also been investigated,[1] with the resulting recommendation that communication cables be purchased to either an REA or similar specification which specifies type testing at low temperature.

F.5 TRANSIENT PROTECTION

All wire communication systems are subject to electrical transients either from natural phenomena, such as lightning, or man-made, such as those caused by maintenance activities. To prevent damage to the electronic devices connected to the medium, it is necessary to provide suitable protection.

The incidence of thunderstorms varies greatly with the United States as illustrated in Figure F-1. The probability of a cable being struck by lightning not only is a function of the storm incidence in the area but also of terrain and the type of cable installation; aerial cable routed in open terrain being more susceptible to hits than either buried cable or aerial cable in built-up areas. Several precautions should be taken to minimize damage. These include[4]:

- Use of cable with a high dielectric constant.
- Bonded shield grounded on both ends utilizing AWG 6 wire size, or larger.
- Grounding of supporting (messenger) cable in aerial installations.
- Use of protective devices on all working (used) pairs.
- Grounding of all non-used pairs.

The protective device most commonly used is a three-electrode gas-tube arrestor. This device provides a path to ground for the surge. It operates on the same principle as a neon tube but is capable of shunting tens of kiloamps to ground, the device being a virtual open circuit until the gas is ionized by the surge, at which time it conducts to ground. The three-electrode device placed across the pair with the third terminal connected to ground offers greater protection that would two two-terminal devices (one between each wire and

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1. Op Cit. page F-1.
4. Bodle, D., Electrical Protection Guide for Land-Based Radio Facilities, Joslyn Electronic System.

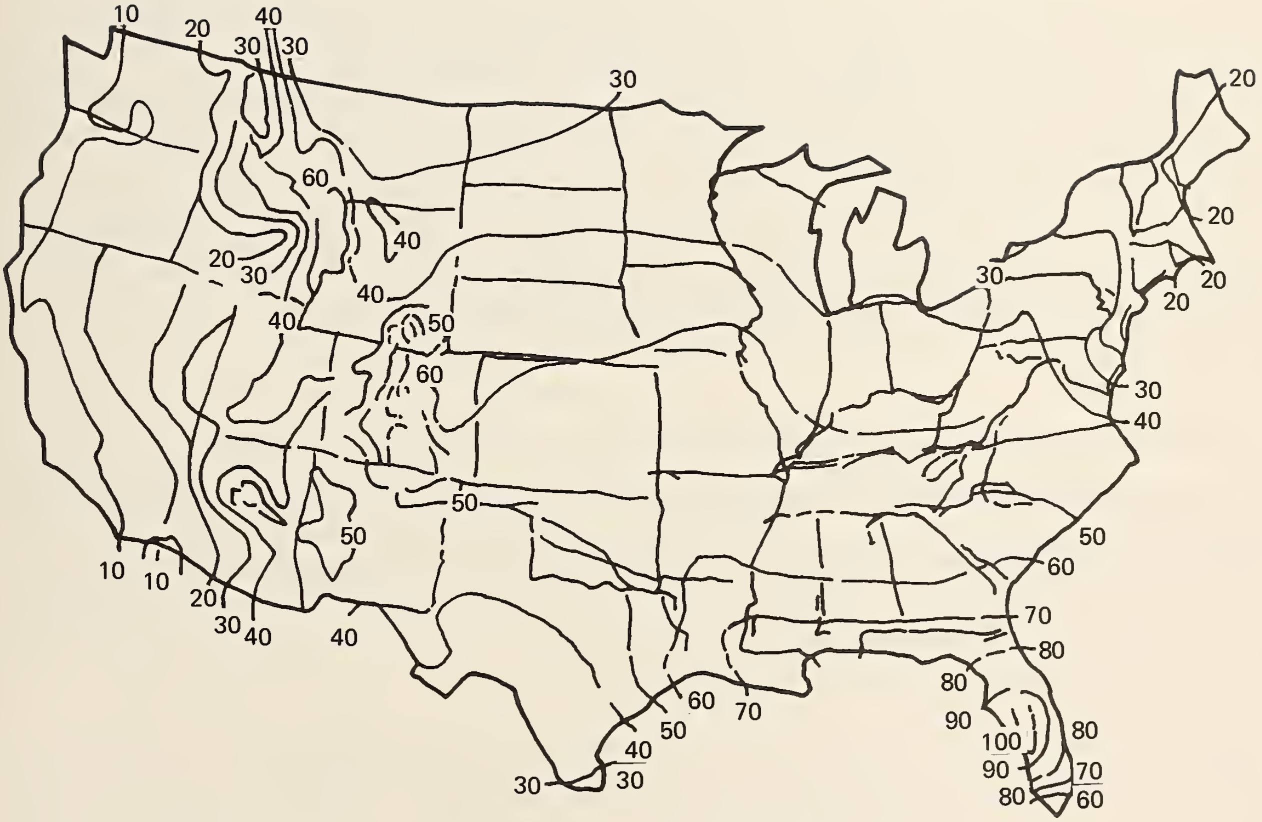

FIGURE F-1. MEAN ANNUAL NUMBER OF DAYS WITH THUNDERSTORMS IN THE UNITED STATES ground) by simultaneously shorting each pair.[5] The gas tube is a self-recovering device, returning to its off state when the disturbance has been removed. A device designed to fire at 150 volts is usually employed.

Solid state protectors, either zener diodes or varistors, are also utilized for protection.[6] These devices have greater current leakage and higher shunt capacitance than does the gas tube when in their quiescent state. They do offer lower and more precise triggering voltage and are often used to provide protection for solid state circuitry.

When communication cables are routed in the proximity of power cables, additional protection has to be provided to prevent damage from accidental contact. The recommended type of protector uses a fusable link in series and before the gas tube, opening when subject to a sustained current surge.

In all cases, the protective device should be placed on both ends of the communication cable where it enters either the building or the roadside cabinet. These devices are available in several mounting arrangements facilitating their installation.

F.6 CROSSTALK

Crosstalk is the unwanted transfer of energy from one circuit to another. In communication networks, two types of crosstalk exist - near end and far end. Near end crosstalk is caused by the coupling between a circuit transmitting in one direction and another circuit transmitting in the opposite direction. The energy is usually transferred in the region near the disturbing circuit's transmitter. Far end crosstalk is the coupling between two circuits whose signals are traveling in the same direction.

Modern communication systems reduce crosstalk by using balanced pairs in which the resistance, inductance and mutual capacitance of each pair are matched, and by twisting each pair together and varying the twist between adjacent pairs, thus effectively reversing the coupling along the cable to obtain crosstalk cancellation. Such measures may be nullified by improper soldering and poor connections which cause cable imbalances.

Crosstalk is expressed by the term "coupling loss" which refers to the amount of signal transferred from the disturbing to the disturbed pair. Crosstalk coupling loss (X coupling) is commonly expressed in db per mile. Thus, in a one mile cable with a 100 db per mile

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5. Tindale, S.A., Solid State Traffic System Battles Environment, Traffic Engineering, December 1975.
6. Bazarian, A.V., When Should You Use Discharge Protectors?, EDN, December 20, 1973.

coupling coefficient at the frequency of interest, a 0 dbm signal would induce a - 100 dbm signal. Coupling loss as a function of frequency for a 25 pair center unit of a 100 pair 22 AWG filled cable has been measured[3] and shown to decrease with increasing frequency and increase with greater pair separation. Note that lower coupling loss means greater crosstalk disturbance.

The following formula[7] is used to calculate the crosstalk over any distance and at any frequency.

$$X_{\text{coupling}} = K_f - 10 \log L/L_o - 20 \log \frac{f}{f_o} \qquad \text{(F-1)}$$

where X_{coupling} = crosstalk in db for length L; K_f = crosstalk in db at frequency f_o for length L_o (typical values are 71 db per mile for AWG 19 wire at a frequency of 150 KHz); L = length of cable; L_o = length for which K_f is given; f_o = frequency for which K_f is given; f = frequency of interest.

Studies[3] have shown that cable size does not have a significant effect on far end crosstalk. Near end crosstalk with AWG 19, 24, and 26 wire varies - 2.1, + 1.5, and + 3.3 db, respectively, compared to AWG 22 wire.

The crosstalk measurements given in these references were made under specific environmental and electrical conditions, and thus slight variations can be expected in practice.

The following example illustrates the use of the formula and reference 3 in calculating crosstalk:

- Cable: 19 AWG 50 pair filled cable.
- L = 5 miles (8 km).
- f = 3 KHz (maximum frequency of operation in this example).
- Maximum signal level = 0 dbm.
- Minimum signal level = - 40 dbm.

Far end crosstalk (F_{ext}) calculation

- f_o = 150 KHz.
- L_o = 1 mile (1.6 km).

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[3] Op Cit. page F-3.

[7] United States Department of Agriculture, Rural Electrification Administration, REA Bulletin 345-67 PE-39, December 1972.

For 19 AWG, 50-pair, filled cable[3]:

- $K_{f\ ext}$ = 71 db (using worst case rms value - layer to layer).

- $F_{ext} = Kf_{f\ ext} - 10 \log \frac{L}{L_o} - 20 \log \frac{f}{f_o}$ + signal level (db).

  $= 71 - 10 \log \frac{5}{1} - 20 \log \frac{3\text{ KHz}}{150\text{ KHz}} + 0$ dbm.

- F_{ext} = 98 db.

Near end cross talk (N_{ext}) calculation

- f_o = 772 KHz.

- L_o = 3,000 feet (914 m).

For 19 AWG, 50-pair, filled cable:

- $K_{f\ next}$ = 60 db (using worst case within - layer adjacent pairs).

- $F_{f\ next} = K_{f\ next} - \log \frac{L}{Lo} - 20 \log \frac{f}{f_o}$ + signal level (db),

  $= 60 - 10 \log \frac{5\text{ mi x }5280\text{ ft/mi}}{3000\text{ feet}} - 20 \log \frac{3\text{ KHz}}{772\text{ KHz}}$.

- F_{next} = 99 db.

Taking the worst case signal level situation, that is, the signals in the interfering pair are at the maximum level (0 dbm) and the signal being disturbed is of the minimum level (- 40 dbm), we have that the far end crosstalk signal is - 98 dbm and the near end crosstalk signal is - 99 dbm. These signals are thus 58 db and 59 db below the disturbed signal level. System operation would not be effected since most communication receivers are capable of rejecting an interfering signal 10 db below the received signal level.

F.7 DATA RATE LIMITS

The maximum theoretical data rate on a communication channel is a function of the channel bandwidth and signal-to-noise ratio. These parameters are related by Shannon's Law:

- $C = W \log_2 (1 + S/N)$,

- C = channel capacity in bits/second,

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[3] Op Cit. page F-3.

- W = channel bandwidth in Hz,
- S/N = signal-to-noise ratio,
- C is a theoretical limit that can be approached but not exceeded.

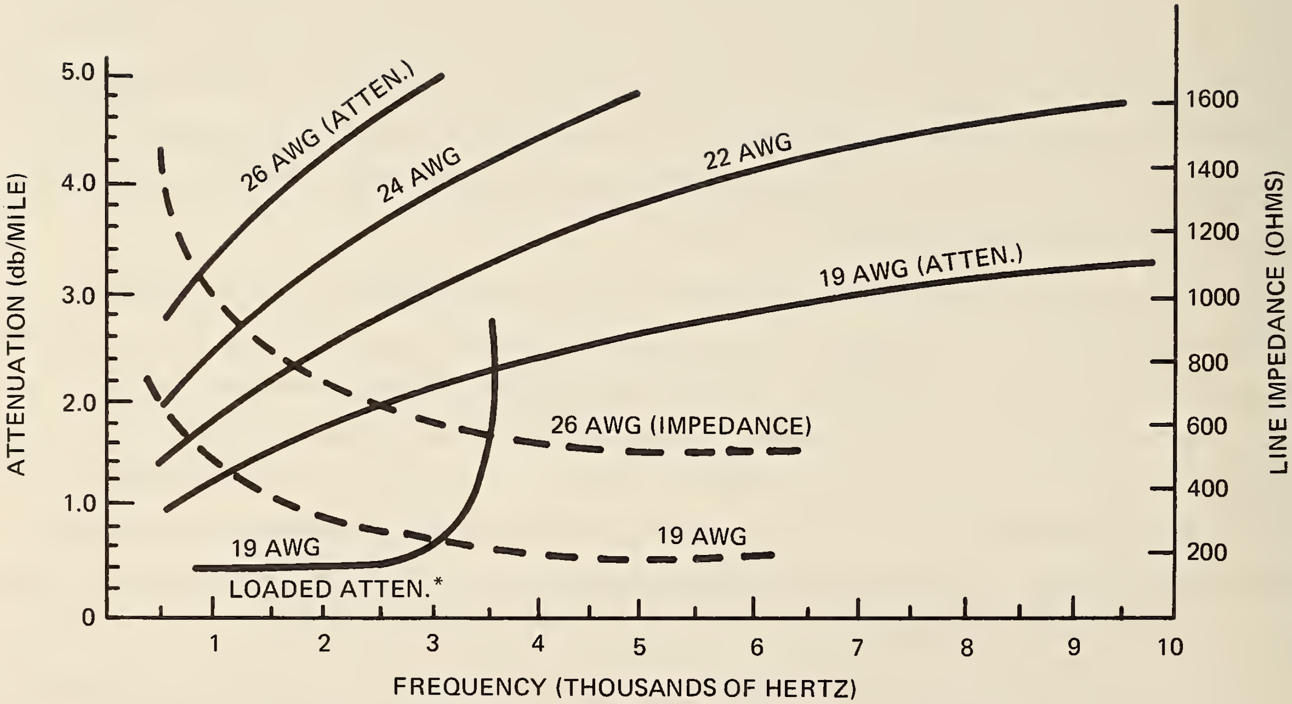
A signal-to-noise ratio of 24 db or better can normally be expected; this, of course, depends upon the environment through which the cable is routed, the signal level, and the quality of the installation. The use of high quality cable, and the following of good design practices as previously discussed should minimize noise. If the signal is to be transmitted over long distances, the use of repeaters should be considered. The location of the repeaters is critical in maximizing the signal-to-noise ratios since the repeaters amplify the noise as well as the signal. Thus, as a signal is allowed to be attenuated over a long distance before being amplified, the effective signal-to-noise ratio is reduced. The maximum signal level is usually limited by equipment design to 0 dbm. (If several channels of different frequencies are transmitted over the same pair, as with an FDM system, the transmitter level must be set so that the RMS sum does not exceed 0 dbm to avoid receiver saturation, as shown in Appendix G - (Table 6-2.)

The attenuation of the network is a function of wire cross-section and frequency, as shown in Figure F-2. The greater attenuation at the higher frequencies can be compensated for by the use of loading coils. The effects of such compensation is shown in Figure F-2 for the 19 AWG wire size, using standard 88 millihenry coils spaced at 6,000 feet (1,829 m) (designated H88 loading in the communication industry). This loading configuration produces a nominal cutoff frequency of about 3.4 KHz, while other standard loading configurations using different inductance values and different spacing provide nominal cutoff frequencies between 2.4 and 9.6 KHz.

To illustrate the effect of the above parameters on data rate, an example of the use of Shannon's Law follows:

Assume a signal-to-noise ratio (S/N) of 20 db, transmission distance of 10 miles (16 km) using 22 gauge cable with no conditioning, and a 30 db loss permitted on the line, or 3 db/mile (1.9 db/km). According to Figure F-2, the maximum frequency for a drop of 3 db/mile (1.9 db/km) is 3 KHz. Therefore,

$W = 3$ KHz,
$S/N = 20$ db $= 100$,
$C = 3 \text{ KHz} \log_2 (101) = 20$ Kbps.



*88 MH @ 6000 FEET (1830 m)

NOTE: 1 MILE = 1.6 km

FIGURE F-2. CABLE CHARACTERISTICS

Thus, it is theoretically possible to transmit data at 20,000 bits per second for 10 miles (16 km) over a 22 AWG line. However, even with the use of sophisticated transmitting and receiving equipment utilizing complex coding and modulation equipment, only half of this speed has ever been obtained, indicating that Shannon's Law establishes a theoretical maximum limit for a given bandwidth and signal-to-noise ratio, and not a realizable value. It serves to illustrate, however, the relationships among channel capacity, bandwidth, and signal-to-noise ratio.

A discussion on suitable data rate limits for a traffic control communication system is given in Appendix B.

F.8 EQUIPMENT INTERFACE

The communication equipment designed to operate over telephone company private lines is suitable for use with user-owned cable. Such equipment has an impedance of approximately 600 ohms at 1,000 Hz, closely matching the characteristic impedance of standard cables.

The number of data points that can be multiplexed onto one pair is a function of multiplexing technique and distance. When FDM is utilized, the limiting factor without repeaters is the maximum transmission distance. This distance can be optimized by assigning the lower frequency channels, which are subject to lower attenuation to the farther locations and the higher frequency channels (which are subject to greater attenuation), to the nearer locations. The connection of multiple FDM units across single pair of wires does not cause significant attenuation of the signals because each channel has a narrowband filter tuned to a unique frequency and thus appears as a high impedance at all the other frequencies.

The connection of TDM units does cause attenuation as a result of the effective parallel connection of full bandwidth equipment, thereby limiting the number of units that can be connected. The curves in Figure F-3 show the effect of wire size, distance, and number of units (drops) on a single pair of a TDM system. In generating the curves, the simplifying assumption was made that all loads are connected at the same distance from central. This assumption is conservative in that the attenuation would not be as great with the loads distributed as in an actual system. The assumed maximum limit is that combination of parameters that result in a 40 db attenuation - the effective signal range of most communication equipment. Of course, in a noisy environment, the - 40 dbm signal level, with the transmitter adjusted to its maximum level of 0 dbm, might result in an excessive error rate (as discussed in Appendix B). As shown in Figure F-3, the maximum transmission range of a pair can be increased by using a heavier wire, or by reducing the number of

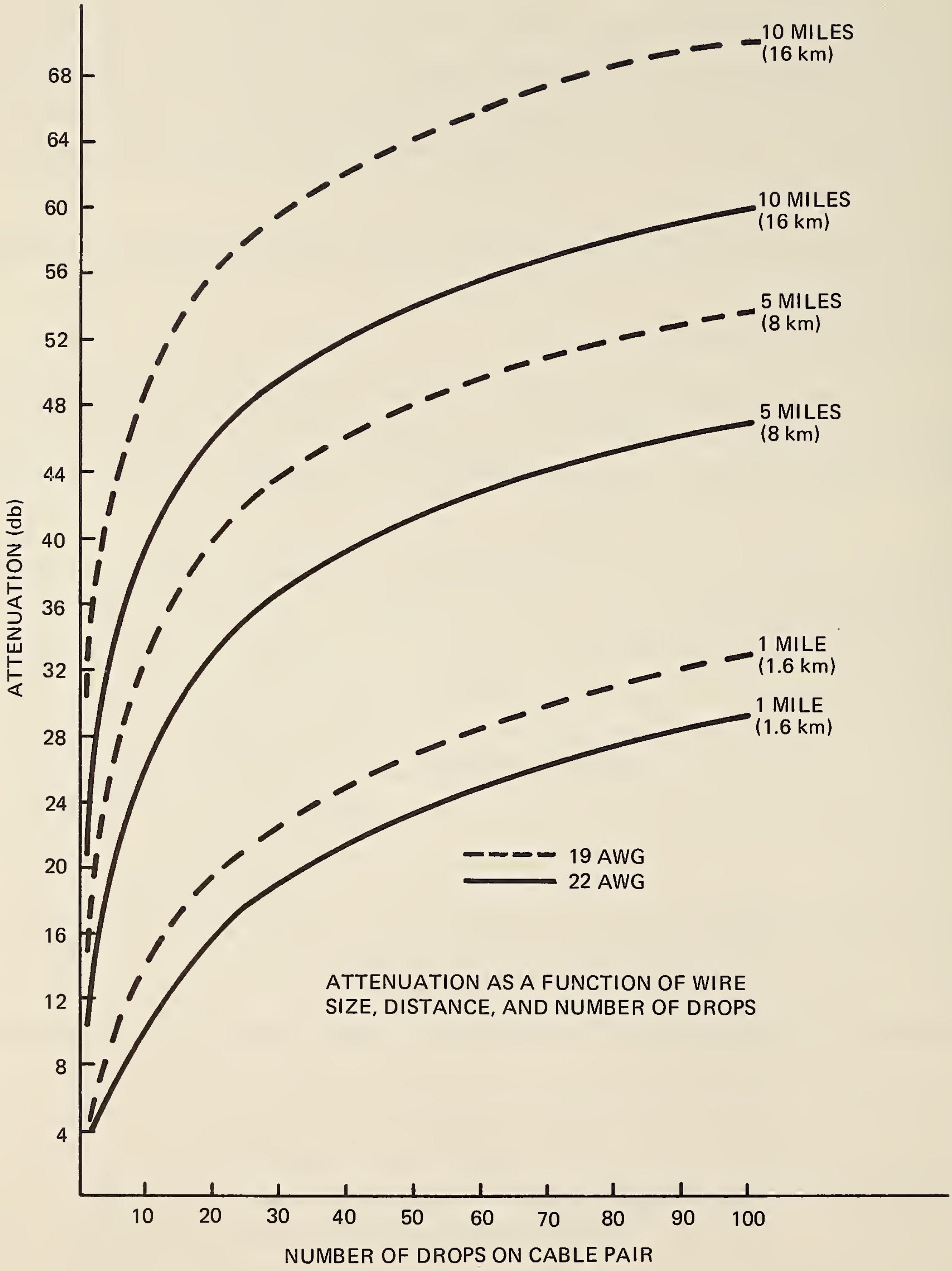


FIGURE F-3. LOADING EFFECT OF MODEMS

drops on that pair. The range can also be increased by the use of repeaters which, in effect, reduce both distance and number of loads on any one wire segment.

F. 9 COSTS OF USER-OWNED WIRE PAIR COMMUNICATIONS

F. 9. 1 General

In a user-owned wire pair system, the total cost of installation and maintenance is borne by the user, requiring a high capital cost but a low operating cost. The operating cost involves maintenance and repair, which is negligible for a buried installation - the system not being subject to damage except for street construction. An aerial system does, however require occasional repair.

The cost of installing a communication system includes:

- Cost of installation.
- Cost of media hardware.
- Cost of communication equipment.

The installation cost involves trenching, plus the installation of conduit, cable, splice boxes and communications cabinets, backfilling and connecting the equipment, and in an aerial system the cost of poles if existing utility poles are not being used. It is a highly variable cost depending upon:

- Type of installation - aerial or buried (conduit or direct burial).
- Local labor rates.
- Terrain - being more expensive to trench through rock than soft soil; whether curbs have to be cut and repaired; whether other utilities have to be relocated or worked around.
- Local restrictions, such as requirement for jacking under rather than excavating through certain arterials, requirements for flagmen and maintenance of traffic.
- Size of installation for a large job, the contractor can amortize his cost of mobilization over a large number of intersections, and might find it cost effective to introduce more efficient machinery.
- Climate - in a severe climate, the installation might require more man-months than in a moderate climate, resulting in higher costs.

Cost of hardware and communication equipment depends upon the type of installation - aerial or buried, quantity of equipment required, and local restrictions such as permitting and/or requiring only certain types of equipment, or specifying maximum distances between pullboxes.

Among the items in the media hardware group are conduit, cabinets, lightning protection equipment, cable, and pull boxes.

Communication equipment consists of all roadside units (including interface circuitry for controllers and detectors) as well as communication units at the control center (including the interface with the central computer).

Costs of all items except cable can be estimated by simply ascertaining quantities and unit costs. Cable costs can also be estimated approximately by assuming the average cost of $100 per thousand feet (305 m) as is done for the examples in Section 4 of Volume 1. However, where the cable cost may be an appreciable part of the total communications cost, (as, for example, in a system using DC communications) a more precise method is required, and is described in Section 5.6.

APPENDIX G

LEASED-LINE COMMUNICATIONS

G.1 GENERAL

Wire communication media for traffic control may be leased from the local telephone company (Telco), of which over 80 percent of those in the U.S. belong to the Bell Telephone System. The Bell System offers several types of service with a wide range of data capacity.[1] These services can be divided into three categories of speed:

- Subvoice grade: designed for telegraph and teletype with speed ranging from 45 to 140 bits per second (bps).
- Voice-band: speeds from 600 to 9,600 bps.
- Wideband: speeds up to 500,000 bps.

Of these, the voice band service's speed and widespread availability best meet the needs of traffic communication systems.

In this service, two types of line connections are available - switched lines (public dial-up network) and private lines. Data transmitted over switched lines is routed through public telephone exchanges as would a normal telephone call. It is subjected to the same queueing delays and network perturbations that private subscribers experience. In a private line system, the line is connected more or less permanently between the communication devices, by-passing the switchgear and signaling devices of the local offices. Table G-1 compares both types of connections.

G.2 SWITCHED LINES

The switched (dial-up) lines are not considered suitable for most traffic communication systems for the following reasons:

- Set-up time might be several seconds.
- Variability of performance - the telephone company guarantees certain minimum standards for private line systems but not for switched lines, although the switched lines meet these standards about 80 percent of the time. These lines are also subject to noise pulses ("hits") caused by switching circuitry and maintenance.

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[1] Martin, James, Telecommunications and the Computer, 2nd edition, Prentice Hall, 1976.

TABLE G-1. COMPARISON OF SWITCHED AND PRIVATE LINES

Line characteristics	Voice grade service	
	Switched line (DDD)	Private line
Type of connection	Point-to-point 2 wire	Either multipoint or point-to-point 2 wire and 4 wire
Conditioning available	No	Yes
Significant performance variability	Yes: (20 percent of time poorer than private line)	No
Availability	Competes with other subscribers	User can select
Call set up and completion time	Subject to dialing, routing and ringing delays (11 second average)	No delays
Bandwidth	3 KHz (not all frequencies available. Several used for signaling)	300 to 3,000 Hz
Back-up capability	Alternate routing available	No alternate routing available
Leasing cost (South Central Bell)	$30/point/month	$1.50 per month per quarter mile to Telco central office (2 wire)

- Availability - since the switched network is utilized for telephone interconnections it is possible that the local branch office is overloaded and no lines are available.
- Requirement of an automatic dialer at each location introduces additional hardware and cost to the communication system. For example, the leasing charge of an automatic dialer from South Central Bell is $40/month/location.

This type of service does, however, have a potential application in a network type of traffic control system where communication between the control center and the remote master site is infrequent, and long distances may be involved. Such a communication path would be used for periodic transmission of reports and for changing stored information in the curbside microcomputers from the central location.

Where the availability of the channel is critical, the telephone company can provide a switched network channel as a backup. The requirement for the use of two switched network connections for backup when a four-wire leased system is utilized introduces another source of degradation in system performance in addition to those mentioned in the switched network discussion; that is, two independent transmission paths with the possibility of significant differences in their transmission characteristics.

G. 3 PRIVATE LINES

The specific service offerings, channel arrangements, performance standards and subscriber charges for leased private lines are spelled out in various tariffs or service contracts. The applicable tariff for interstate voiceband private line channels is Tariff F.C.C. No. 260. Local telephone companies have similar tariffs for intrastate and interexchange offerings and other similar levels of service for intraexchange service. The local interexchange and intraexchange tariffs are most significant for the traffic systems because the geographical limits of most traffic systems are within one telephone exchange, or two or more adjacent exchanges.

Several types of service are offered under Tariff F.C.C. No. 260. The Channel 3002 offering[1] is used for the transmission of voiceband data (300 Hz to 3,000 Hz) and facsimile signals, with five types of "C" conditionings and two types of "D" conditioning being available for this channel.[1] The "C" conditioning attempts to equalize the lines attenuation and delay distortion at several frequencies, and thus improve its frequency response, allowing the transmission of data at higher speeds. The "D" conditioning, which is used to control the signal-to-noise ratio and harmonic distortion, can be used in addition to the "C" conditioning, and allows operation over voice grade lines at 9,600 bps. Reference[2] lists the bandwidth parameters for the various types of "C" conditioning as well as all characteristics of the 3002 channel.

G. 4 NOISE

Telephone lines are subject to several types of noise. They include: white noise, impulse noise, single frequency interference, phase jitter and phase hits.

White noise or background noise is common to all electronic signalling networks. The telephone company separates white noise into "C-message" and "C-notched" noise. "C-message" noise is measured with an averaging instrument through a filter with a C message

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[2] Bell System Data Communications Technical Reference, Data Communications Using Voiceband Private Line Channels, Pub. 41004, American Telephone and Telegraph Company, 1973.

weighting function. The function is intended to weight the spectrum of the white noise to be indicative of the perceived noise by a person listening to the noise through a telephone receiver. This measurement is relevant for digital transmission since its weighting function is relatively flat over the 600 to 3,000 Hz spectrum usually used for data transmission. C-notched noise is measured with the same instrument as C-message noise. A 2,800 Hz tone is transmitted however, to activate companders and quantizers found in the switched telephone network. The 2,800 Hz tone is filtered out ("notched") before the noise is measured. This measurement is meant to reflect an active telephone channel. "C" type noise levels are expressed in dbrnC, relative to 0 dbrnC, which is equal to - 90 dbm. Thus, for example, a 30 dbrnC level is equal to - 60 dbm. C-message noise is specified to be no greater than 28 dbrnC for telephone company lines.

Impulse noise is defined as that component of a received signal that exceeds the RMS noise level by 12 db (measured value of white noise).[3] This noise, characterized by time and amplitude variability, is measured by an instrument designed to measure the number of incursions occurring beyond a selectable power threshold over a specified period of time. In reference 2, the maximum number of counts to be expected for various threshold over a 15-minute period is defined. This number (5 to 15 pulses in 15 minutes) is indicative of the probability of having multiple errors in a message, a subject discussed in Appendix C.

Public and switched telephone network impulse noise sources include: maintenance installations and repair operations within the telephone plant; atmospheric conditions, such as lightning; external man-made sources, such as motors and power lines; and circuit faults, such as poor soldering and dirty contacts. Switched systems are also subject to noise introduced by the switching equipment relays, being most prevalent during the hours of heavy telephone traffic. (The introduction of electronic switching equipment in the future will serve to reduce this source of noise.)

The telephone company defines single frequency interference as the interference of one narrowband channel by a single frequency tone from another channel. This is guaranteed by the phone company to be 3 db below the "C-message" noise limit.

Phase jitter consists of variations in time of the instantaneous phase or zero crossings of a signal at rates below 300 Hz. This change usually occurs at 20 Hz and 60 Hz and the

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[3] Bell System Data Communications Technical Reference, Transmission Parameters Affecting Voiceband Data Transmission-Measuring Techniques, Pub. 41009, American Telephone and Telegraph Company, January 1972.

second through fifth harmonic of each. This parameter is significant in systems utilizing phase shift keying (PSK) modulation.

Phase hits are sudden changes in the carrier phase. The telephone company is presently determining the extent of this phenomena and will then establish guaranteed limits. This parameter also impacts PSK systems.

G.5 INTERFACE WITH THE TELEPHONE NETWORK

The two basic types of transmission techniques using multiplexing, FDM and TDM (discussed in Appendix B), are compatible with leased private lines. The third type, DC switching, is usable in only a limited number of telephone exchanges where end-to-end copper wire connections are available.

The telephone company specifies the communication interface at 600 ohms ± 10 percent with a maximum RMS composite signal level of 0 dbm. In an FDM system, this level depends upon the number of channels operating over the pair and the maximum level of each. Table G-2 shows the signal level to which each channel should be adjusted as a function of the number of channels on each pair in order not to exceed 0 dbm.

Most communication systems are designed for direct interface to the telephone network, having a 600 ohm impedance at 1,000 Hz and operating frequencies in the voiceband spectrum. FDM equipment typically operates from 420 Hz to 2,660 Hz (18 channels) and modems used with the TDM systems operate at speeds up to 1,800 bits per second (bps) without line conditioning, and up to 9,600 bps with conditioning. (Note that the Bell System uses the term "data set" to mean "modem".)

TABLE G-2. MAXIMUM TRANSMITTED SIGNAL POWER FOR EACH OF N FDM CHANNELS[(a)]

Number of channels	Per channel maximum rms power - (dbm)	Number of channels	Per channel maximum rms power - (dbm)
1	0	8	-9.0
2	-3.0	9	-9.5
3	-4.8	10	-10
4	-6.0	11	-10.4
5	-7.0	12	-10.8
6	-7.8	13	-11.1
7	-8.5	14	-11.5

TABLE G-2. MAXIMUM TRANSMITTED SIGNAL POWER FOR EACH OF N FDM CHANNELS(a) (Cont.)

Number of channels	Per channel maximum rms power - (dbm)	Number of channels	Per channel maximum rms power - (dbm)
15	-11.8	18	-12.6
16	-12.0	19	-12.8
17	-12.3	20	-13.0

[a] Results in 0 dbm total power on line (assuming uncorrelated channel signals).

G.6 MULTIPOINT CHANNELS

In the traffic system TDM application, a broadcast polling multipoint arrangement is usually used. This arrangement allows a single station, the master, to communicate with two or more remote stations. Each remote station is identified by a unique address which is included in all transmissions sent to it by the master. The telephone company recommends that a four-wire configuration be utilized with each pair carrying data in opposite directions (one pair to the master, the other pair away from the master), though it is possible to operate over a two-wire system. The telephone company refers to this four-wire arrangement as full duplex. When a single pair is used, the transmit and receive terminals on the modem are connected together. This two-wire configuration has the following disadvantages relative to four-wire[2]:

- Difficulty in providing an electrically stable network for greater than six points per pair.
- Higher modem turn around time - reducing efficiency.
- Safeguards required to prevent false remote station startup.

The telephone company recommends a maximum of twenty data points per channel for 4-wire configurations, since the greater the number of points on a line the longer the length of time to restore service after an outage, and the greater the probability of an outage which would reduce channel availability.[2]

The modems may be leased from the telephone company or customer-owned. When the user leases the modem, the telephone company assumes the responsibility for maintaining the complete communication system from the transmitting modem data inputs to the receiving modem data outputs, guarantees overall system error performance, and maintains components to their individual specification. Many local telephone companies, equipped with test centers, will also provide an auxiliary data set such as the Bell A29 free of charge to facilitate troubleshooting. With this equipment, many problems can be isolated from the test center thereby reducing system down time, usually to less than two hours.

When the customer provides his own equipment, the telephone company will not specify overall system error performance. The components provided by the telephone company will be maintained to their individual specifications. When a customer suspects a problem with the telephone company equipment, he reports the problem to his customer service representative who notifies the maintenance department. If the problem is found to be with the customer's rather than the telephone company's equipment, he might be charged for the service call. The user should be aware of a classification of problems known as "unauthorized impairments". These are Telco impairments, not characterized in the tariffs, and which are usually not detected by the Telco test equipment. The impairments primarily effect new generations of communication equipment, utilizing new techniques and susceptible to line perturbations to which the old equipment was immune. Once the telephone companies realize that a problem exists they will characterize the impairment in the tariff by establishing limits, and modify test equipment to detect it; this can however be a lengthy process requiring several years of investigation. The user can encounter difficulty and delays in having the telephone company correct an "unauthorized impairment" since the telephone company would have trouble detecting it and might consider the users equipment to be at fault; only after insistence by the user is such a problem likely to be solved.

The telephone company requires that either they or the customer provide all the modems, precluding a shared arrangement.

The telephone company recommends that an enclosure separate from the traffic signal controller cabinet be provided for the telephone equipment and lines. This facilitates troubleshooting by providing their servicemen access to the telephone equipment without the presence of a traffic department electrician which they otherwise would require due to the high voltage (115 volts or more) in the controller cabinet.

G.7 COST OF LEASED LINES

The setting of intrastate telephone leasing costs by state regulatory agencies results in a wide variation and eliminates the possibility of generalizing. The assessing of a monthly leasing charge subject to change also makes it difficult to predict the operating cost of the system over its life. At least three methods of measurement for leasing of multipoint private lines are in common use. These are:

- Drop-to-Central Office Mileage, in which the distance from each drop (intersection or traffic control center) to the local telephone company (Telco) central office serving that location is measured in quarter mile (402 m) increments, and the leasing charge per quarter mile (402 m) per month for a pair or a dual pair is assessed (typically $1.50 per pair).
- Drop-to-Central Office Fixed, in which a fixed charge per drop is assessed (typically $10 per drop).
- Airline Mileage Between Drops, in which the straight-line distance between the traffic control center and the nearest intersection plus the sum of the straight line distances between each of the succeeding intersections on that multipoint line is measured in quarter-mile increments and the leasing charge assessed accordingly. This relatively low-cost method of measurement will probably be phased out in those places where it now exists because the charges do not reflect true telephone-company costs.

As an illustrative example, the telephone charges of the South Central Telephone Company are given below. This company provided the telephone service for the New Orleans Traffic System.

<u>Private Line:</u>

Leasing - monthly charges:

Four-Wire (full duplex)	$3.00/quarter mile (402 m)
Two-Wire (half duplex)	$1.50/quarter mile (402 m)

The distance is defined as airline mileage from each of the intersections to the main telephone company central office in quarter-mile increments.

Rental of 202T data set: $30/month/set

Installation charge:

2-Wire	$15.00/point
4-Wire	$22.50/point
202T data set	$50.00/set

Switched Network

Leasing - monthly charges
$30/location
$40/automatic dialer

In addition to the above charges, the customer usually provides the connection between the cabinet on the street corner and the phone line. This involves trenching and installation of conduit. In some cases, the telephone company can be contracted to perform this work - this being a function of local telephone company policy.

In New Orleans, the telephone company charged an additional $1,200 for breaking into each Telco manhole for the customer-installed conduit.

APPENDIX H

COAXIAL CABLE COMMUNICATIONS

H.1 GENERAL

Coaxial cable communications system utilize the equipment designed and manufactured for cable television systems. The manufacture, installation and operation of such systems has become a widespread industry with settled design practices, commercially competitive prices and a large pool of trained technical personnel. The cable television modulators and demodulators used have signal interfaces at frequencies that are compatible with communication and data processing equipment, and numerous contractors throughout the nation have obtained experience in installing this type of equipment. However, transceivers designed for traffic control communication are available from only a limited number of manufacturers at the time of this writing.

The coaxial cable is routed through underground conduit, buried directly, or mounted overhead on poles. Installation practices vary widely with the local utility practices and the easement agreements that the utility has with the local political subdivision. Commercial cable television systems have been installed on local utility poles with minimum charges in some locations and have been required to use separate poles in others. Traffic control cable would have the same utility easement rules as existing communication cable, street lights, controller cabinets and fire box installations.

A coaxial cable system for traffic control communications has been in operation in Columbus, OH since 1976. Other installations are being made in Detroit, MI and Overland Park, KS.

H.2 COAXIAL CABLE SYSTEM PERFORMANCE

The data handling capability of a coaxial cable system can be stated in terms of equivalent voiceband telephone channels, which have a bandwidth of approximately 3,000 Hz. The CATV coaxial cable hardware with its 300 megahertz capability can be considered to be equivalent to 100,000 telephone wire pairs with respect to channel capabity, and thus is theoretically capable of handling data transmission rates of hundreds of megabits per second.

The highest frequency that must be transmitted encounters the most cable attenuation and is the most difficult to amplify. The practical length of a coaxial cable system is set by this attenuation characteristic, and by the repeater amplifier output signal linear dynamic range at the highest frequency. The coaxial cable system maximum length will vary from approximately 20 miles for the equivalent of thirty-channel television use to transcontinental length for data plus several television channels.

H.3 COAXIAL CABLE NETWORK

The coaxial cable transmission network (cable and bidirectional repeater amplifiers) forms the wired electrical interconnect between the traffic control center and all of the transceivers at the remote intersections to be monitored and controlled. The functional block diagram for such a system is shown in Figure H-1. This diagram indicates by dashed lines that additional capabilities such as voice communication, television surveillance and television camera control can be added to the basic traffic control communication system. The transceivers for the various functions can be connected to the cable at any point in any combination as long as the frequency band for the units are properly assigned.

In addition to the coaxial cable and the bidirectional repeater amplifiers, the cable network utilizes other components that have been developed for specific functions and are used throughout the network. These components include directional couplers, splitters, terminators, cable connectors, power inserters and power supplies.

The directional couplers (taps) are used to permit coupling of radio frequency signals to and from the coaxial cable. These couplers are constructed so that the tap point output signal level is attenuated by a specified amount from the trunk signal level. The same signal attenuation also occurs for signals injected into the trunk at the tap point. The coupling has directional characteristics so that a signal path is established between the tap point and the coaxial cable leading to the control-center communications transceiver but no signal path exists between the tap point and the other network branches. The directionality characteristic is such that signals emanating at the outer portions of the network are not wastefully dissipated at any intersection connection point, and therefore most signal energy passes through the trunk to central. The directionality also discriminates against signal perturbations originating "downstream" from the intersections. The attenuation level of the tap is selected to be equal to the difference between the signal existing on the cable at that point and the signal level requirement of the transceiver with its connecting "drop" cable.

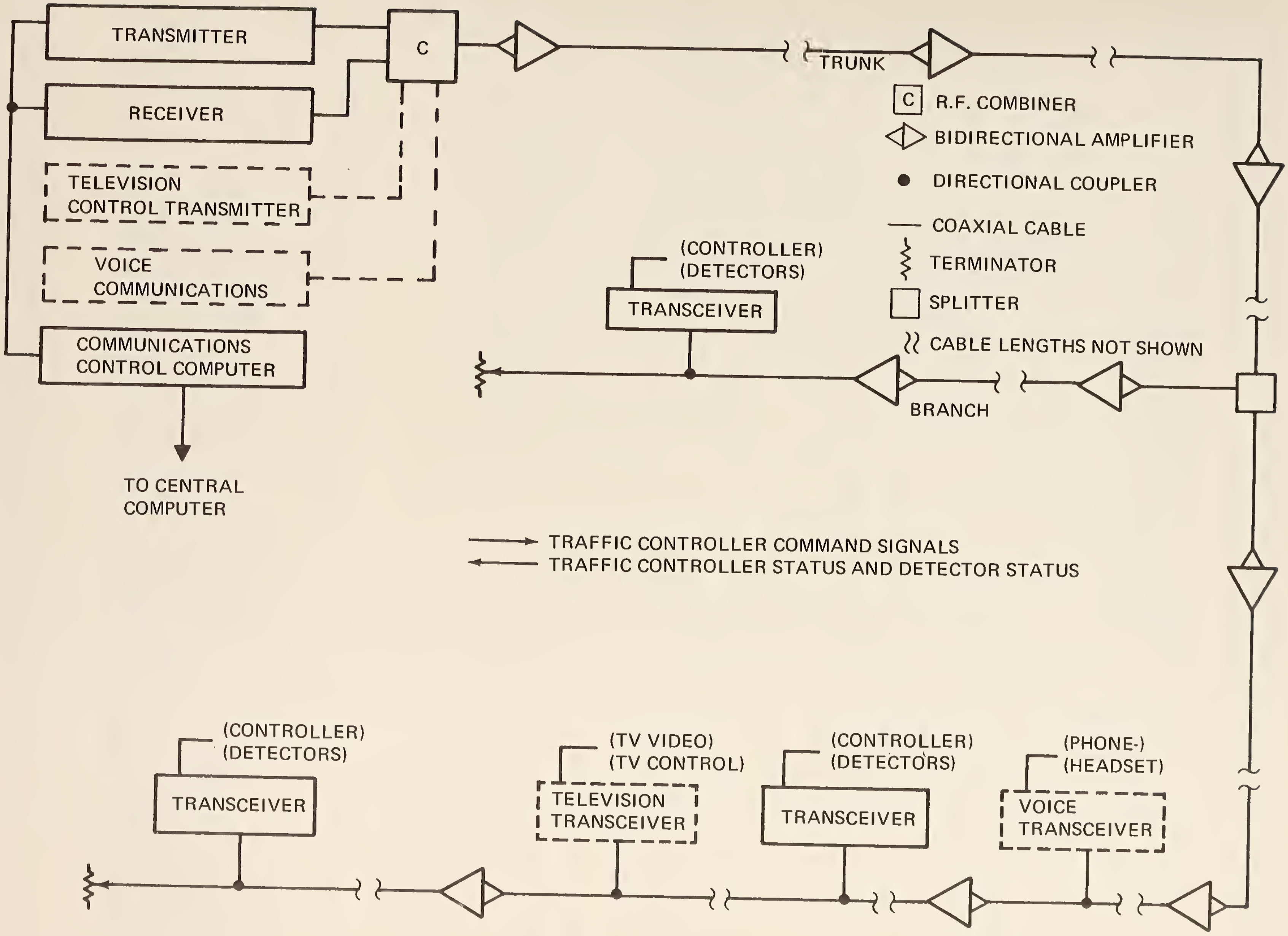

FIGURE H-1. COAXIAL CABLE COMMUNICATIONS

Splitters are power dividers for use at points in the network where it is required to divide the radio frequency signal power into two or three equal levels for distribution to different branches of the network. Terminators are passive impedance devices that are placed at the ends of cables to establish the proper terminating impedance for the cable, and thereby avoid signal reflections that would degrade the desired signals.

Cable connectors are used to splice individual sections of cable together and to connect the cable to the various equipments. These components must provide mechanical and electrical integrity over the entire 300 MHz spectrum. Their design is such that they are watertight and are non-corroding, while passing the radio frequency signals without: harmful reflections (low return loss); signal attenuation (low insertion loss); radiation of signals outward; and, admission of external radio frequency signals into the coaxial cable. Connectors are usually covered with "heat shrink" tubing that has an internal sealant to further enhance the protection to the connector and the cable at the connection point.

The energy utilized to power repeater amplifiers is provided by a 60 Hz power source connected to the inner and outer conducters of the coaxial cable so that separate power inputs are not required at each amplifier position. Typical amplifiers require approximately 0.6 amperes at 60 volts so that a typical 12 ampere power supply could power 20 amplifiers if the resistive voltage drop of the cable does not impose limitations.

The 60 Hz power is connected to the cable through a power inserter. This three-port device is connected between two coaxial cable sections, and allows the radio frequency signal to pass through its input and output ports while its filters prevent the radio signals from reaching the 60 Hz power port. The filters allow the passage of the 60 Hz power to the center conductor of the coaxial cable.

H.4 COAXIAL CABLE NETWORK DESIGN

The coaxial cable network design is relatively straightforward once the location of the intersections and the central communications equipment has been established. These points can be joined to form a natural "tree" network based upon the geometric configuration and local physical features. An iterative design procedure will rapidly establish the most economical network with regard to cable and amplifier cost. Assuming the amplifier has a gain of 26 db with a required output level of 48 dbmV (ratio referenced to one millivolt) and the input level required is 22 dbmV, the knowledge of the cable attenuation (including splices) at the highest frequency of interest* permits the basic amplifier spacing pattern of the network to be established.

Assuming that the intersection receiver at its cable drop requires a signal level of 12 dbmV, the signal level at each extremity of the network is set at 22 dbmV, with a 10 db directional coupler at that point. It is also assumed that the receiver frequency is higher than the intersection transmitter, and that each intersection requires a directional coupler that has a small insertion loss. Starting at the network extremity, the signal level can be set at an increased value at each intersection as the path leads through attenuation components on its way to the control center. The directional coupler tap at each intersection is set at a value such that its output is 12 dbmV. When the signal reaches a required value of 48 dbmV, an amplifier must be provided at that point. When the routes converge to a single point, the path that has the higher required signal level receives the directional coupler main signal path, while the smaller signal level receives the tap path. If the signal levels required at the junction are approximately the same, a splitter is required.

The design process proceeds from all of the extremities to the central point until the amplifier at the central communication site is reached. This procedure may result in a short-spaced central amplifier, but judicious repositioning of some portions of the network may avoid this situation or allow each amplifier spacing to have an additional gain margin. Repeating this procedure several times should rapidly result in an optimum configuration.

A somewhat analogous procedure must be followed to check the transmission path from the intersection transmitter to the central receiver. Practical considerations will dictate that the return amplifiers will be set at the same positions as the forward amplifiers. Signal levels and attenuation paths must be calculated to determine the return amplifier gain and attenuation settings.

H.5 DATA COMMUNICATIONS MULTIPLEXING

H.5.1 General

The coaxial cable communications system utilizes frequency division multiplexing and time division multiplexing to accommodate all of the traffic control signals on a single wire. Signals being transmitted from the control center occupy one portion of the frequency spectrum while the signals being received at the control center occupy a different portion

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*Assuming a maximum frequency of 60 MHz, the cable and splice attenuation is approximately 2 db per 400-foot block for a 0.75-inch diameter cable.

of the available spectrum. Coaxial cable systems are naturally divisible into high and low frequency bands with an unused transition band between the used bands.

Time division multiplexing (TDM) techniques are utilized to transfer information between the central control and the intersections. The details of the TDM system (number of intersections, sampling rate, address code, security coding and synchronization techniques) determine the total baseband bandwidth required. The baseband signal is frequency-translated to the desired area of the radio frequency spectrum. Additional intersection capability is achieved by duplication of the TDM system through translation of its baseband signal to a different area of the available spectrum (frequency division multiplexing). Expansion can be accomplished by frequency assignment until the total spectrum is utilized.

H.5.2 Central Communications Equipment

The central transceiver and communications control computer (front-end computer) provide the link between the central traffic control computer and the coaxial cable transmission system (Figure H-2). The communications control computer receives intersection controller command data, performs the functions of multiplexing the data into a time series pulse train, adds identify information (address or synchronization data), adds parity bits for error detection, and formats the data for modulating the transmitter. The communications control computer also obtains intersection controller monitor data and vehicle detector data from the central receiver, which it decodes, tests for parity, and formats into signals compatible with the traffic control computer. The communications control computer is usually a general purpose minicomputer that is programmed to perform all of the required digital logic functions.

H.5.3 Intersection Communications Equipment

Each remote intersection is provided with a transceiver (Figure H-3). This unit provides the interconnect between the coaxial cable and the intersection controller and detectors. The receiver is fixed-tuned to its assigned frequency and demodulates the encoded coaxial radio frequency signal. It then forwards the signal to digital logic circuits which decode the identity and data information according to its fixed circuit logic, and then convert the information to a format compatible with the actuating signals required by the local traffic signal controller.

The digital logic portion of the unit receives information from the intersection signal controller and the local vehicle detectors. It processes the intersection information

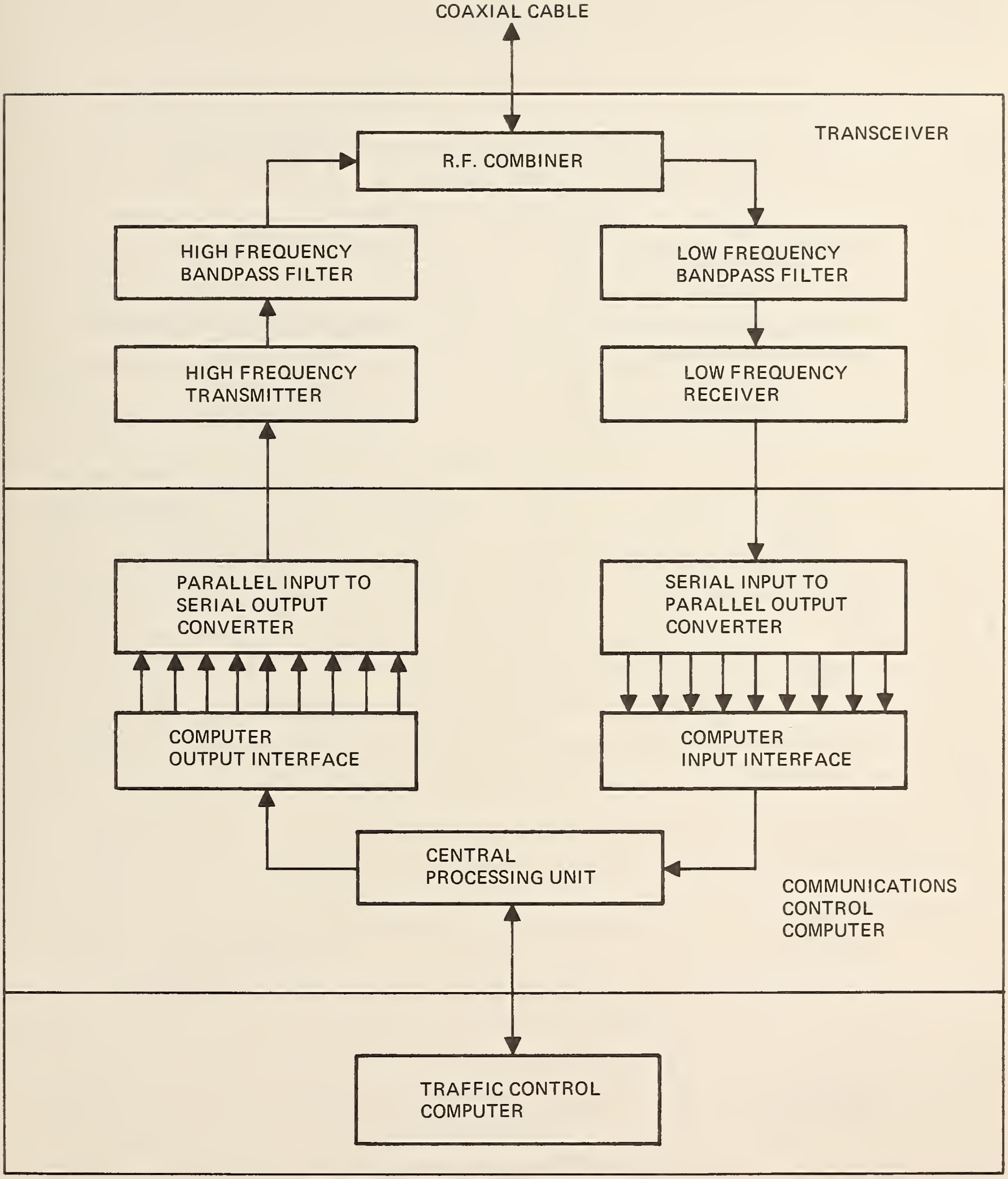

FIGURE H-2. CENTRAL COMMUNICATIONS EQUIPMENT

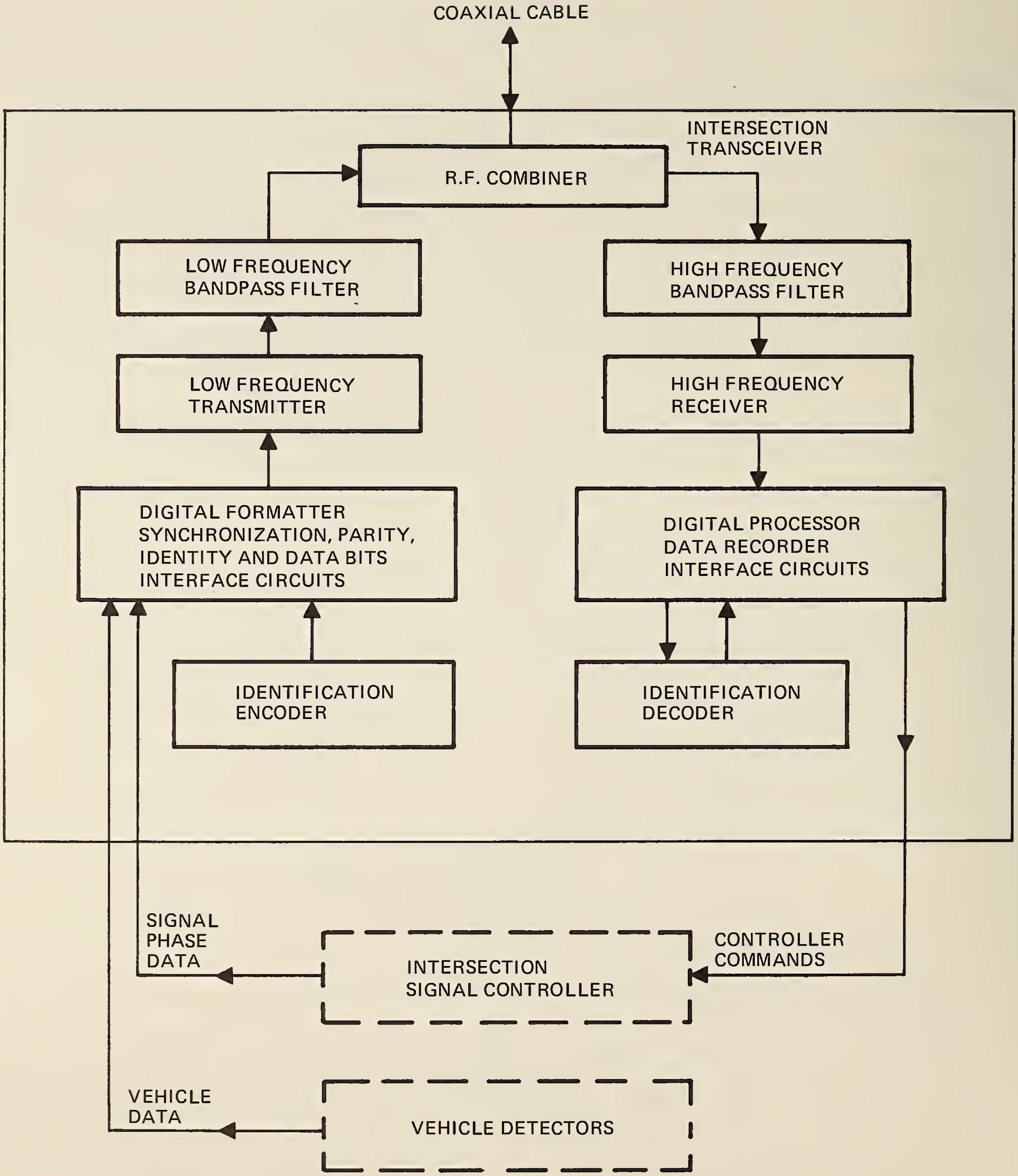

FIGURE H-3. INTERSECTION COMMUNICATIONS EQUIPMENT according to the structure of the address, parity and synchronization code employed and then modulates the output transmitter stages which generate the radio frequency signals to be placed on the cable for transmission to the control center.

H.5.4 Polled TDM System Example

A typical polling sequence starts with the transmission of an interrogation message which consists of a total of 15 bits. The individual bit functions are 1 start bit, 7 address bits, 1 parity bit, 4 data bits and 2 stop bits. Each terminal whose address matches the address transmitted will return 13 bits of information which consist of 1 start bit, 9 data bits, 1 parity bit and 2 stop bits. Assuming that each bit takes 21.4 microseconds, the outgoing 15 interrogation pulses will take 321 microseconds. The received reply pulse train will take 278.2 microseconds so that a total of 599 microseconds are required to interrogate an intersection. If the data sampling rate desired is 13 times per second, a total of 13 x 599 or 7,790 microseconds is utilized for each intersection so that approximately 128 intersections could be sequentially addressed by the multiplexor. The address structure (7 bits) was selected to be consistent with 128 intersections.

The data bits being processed can be interpreted by the equipment to signify the presence or absence of a parameter by the presence or absence of the pulse. Thus a 4-bit data code can represent the state of 4 discrete two state devices such as lamps or switches. If the four bit code is encoded, the message can represent one of sixteen possible independent elements of a monitored system. The number of bits assigned to interrogation address, interrogation data and to the reply data can be varied to satisfy the requirements of the system. In the foregoing example 8 data bits are returned so that the monitoring of the controller A-phase green and seven detectors can be monitored at each intersection.

Security code bits may also be inserted in the outgoing and incoming data stream to check the data for inadvertent noise perturbations. Possible error checking codes include double transmission of data, check sum transmission and various parity checks.

In the foregoing example a total of 128 x 13 x (15 + 13), or 46,592 bits per second are handled by the equipment so that a bandwidth of approximately 46 KHz is required. An R.F. bandwidth of twice this amount is required so that a total R.F. bandwidth of 100 KHz is required on both the outgoing and incoming frequency bands to accommodate 128 intersections operating in this manner.

The use of two different frequencies for the forward and return paths allows the central equipment to transmit continuously without waiting for the receiver reply as postulated in this example. Equipment transmitting (and receiving) continuously can double the number of bits handled without increasing the bandwidths required since no idle time will occur.

H.6 COAXIAL CABLE

Coaxial cable transmission systems use a distinctive type of cable which is specifically designed and manufactured to obtain minimum signal losses, large signal information capacity, low signal leakage and low signal interference susceptibility together with an economical use of materials in its construction.

A cross-section of the cable consists of an inner round conductor and an outer annular conductor whose center is coaxial with the center of the inner conductor. The annular space between the conductors is filled with a dielectric material selected for its electrical properties (insulation resistance, dielectric value, dielectric strength) and its mechanical properties (strength, lightness and water absorption characteristics) to maintain the conductor configuration and the integrity of the dielectric material.

The outer conductor is covered with a protective jacket made of a tough electrical insulation material. When additional moisture protection is required, a "flooding" compound is placed between the outer conductor and the protective jacket. This flooding compound is a gelatinous material which will flow and seal any small holes which may develop in the jacket or outer conductor.

The cable primary mechanical parameters (inner-conductor outer diameter, outer conductor inner diameter and dielectric material) have been optimized to achieve the lowest signal loss per foot with the result that the cable characteristic impedance of the most commonly used cable is 75 ohms. The resulting cable design has been used throughout the cable television (CATV) industry which has also added mechanical requirements to achieve an easily installed cable which is capable of carrying all of the standard VHF (very high frequency) television signals simultaneously while also carrying other signals within its overall bandwidth capability.

The coaxial cable has an intrinsic bandwidth capable of carrying signal information in the band from DC to about 10,000 MHz. Standard CATV practice does not need this wideband capability so that the required active and passive components have not been developed to use this entire bandwidth. Present component availability utilizes the frequency spectrum of 5 MHz to 300 MHz which contains frequency assignments for about 45 standard TV (6 MHz bandwidth) channels.

H.7 REPEATER AMPLIFIERS

Because the cable attenuates the signals, repeater amplifiers must be provided at the proper intervals to amplify the signal for further transmission. The repeater amplifier must have an amplitude gain versus frequency characteristic that is the complementary inverse of the cable amplitude attenuation versus frequency characteristics for the cable section between the repeater amplifier stations.

Since the repeater amplifier is used in a long chain of repeaters, each individual amplifier is required to have good noise and linearity characteristics because each amplifier in the chain will degrade the signal somewhat. To avoid the problems of the cumulative distoration at the output of the amplifier chain, stringent performance requirements are placed upon the individual repeater amplifiers.

The ideal repeater amplifier gain transfer function between input signal and output signal should be linear. If a non-linear relationship exists, the output signal will be a distorted replica of the input signal and it will contain signals whose frequencies are different from the signal input. The spurious signals exist at harmonics of the original frequency and they also are formed at the sum and difference frequencies of all of the frequencies at the input to the amplifier. Since the repeater amplifier is a broadband device carrying many different frequency channels, many possible spurious frequencies can be formed which may appear in channels that are being used. These interfering frequencies must be reduced to an insignificant level by using amplifiers with a stringent linearity characteristic.

The interfering spurious signals result in the modulation of one signal appearing on other signals and is referred to as crosstalk (cross modulation) and interference. These signals, if they exist, are very noticeable in cable television systems because television signals require a high signal-to-interference ratio for good picture presentation. The interfering signals need not be so stringently suppressed for digital data transmission since minor distortion of pulse information is not significant.

Repeater amplifiers used for coaxial systems have been designed so that the interference level is low at the output signal level needed to operate the cable. The levels of harmonics, cross modulation, second order and third order beats, and hum and noise modulation are held at levels about 60 db below the operating level so that crosstalk is not a problem in a data communication application.

The excess noise contributed by the amplifier is held at low levels (noise figure of 8 db) in the design of the repeater amplifiers. The cascading of the noise through the amplifier chain raises the noise level at the end of the output chain and this noise level effectively sets the maximum length of the system. That is, the signal-to-noise ratio desired at the last repeater, when added to the noise level, must not exceed the allowable dynamic range of the amplifier chain. The maximum signal level is set by the allowable distortion introduced by the amplifier.

One cable can be used to transmit information in two directions by using two amplifiers having different bandpass characteristics at each amplifier station. In one standard configuration, one amplifier handles 5 to 30 MHz signals in one direction while the other handles 50 to 300 MHz signals. Bandpass filters are employed with the amplifiers to properly channel the signals. The overall width of each bandpass region, as well as the boundary frequencies, can be set to conform to the overall system information handling requirements. The two-way coaxial cable system is readily adaptable to traffic control systems since data can be received from each intersection, and control commands can be sent to each intersection. Television signals can be added without requiring any cable modifications.

H.8 COAXIAL CABLE INSTALLATION CONSIDERATIONS

Cable attenuation decreases with increasing cable diameter so that fewer repeater amplifiers are required with large diameter cable than with small diameter cables. Cable cost and amplifier cost at the time of construction dictate the most economical design. Practical considerations such as power source accessibility and amplifier station housing restrictions can influence the amplifier station spacing and consequently the most economical cable size. The use of existing conduit and raceways may dictate the use of smaller cable to eliminate problems with regard to maximum cable bending radius, conduit diameter, maximum allowable pulling tension and the number and type of conduit bends. Existing conduit should be used only if it is first carefully inspected with regard to blockages, need for removal of existing cables, its diameter, and number and type of bends. Conduit with any bends between pullboxes will probably be unsatisfactory for coaxial cable use. Pulling coaxial cable through conduit bends subjects all of the cable passing the bend to bending forces on entering the bend and to straightening forces on leaving the bend. Collapse of the outer tubular conductor may occur as well as permanent shift of the inner conductor from the center of the tubular outer conductor. In short, the details of the cable installation should be specified to avoid rendering the cable unfit for use during its installation.

Coaxial cable installed outdoors in conduit should have a waterproof "flooding" compound between the outer conductor and the protective sheath. Amplifiers, connectors, directional couplers, terminations and other such hardware used must be impervious to water entry. Heat shrink tubing with internal flooding compound should be used over all connectors and splice hardware to protect the connector and the cable end. Immediately after the cable is pulled into place, the cable ends must be sealed against water entry to the ends. If a period of time is planned after pulling and prior to connector installation, a temporary water seal must be used.

APPENDIX H

BIBLIOGRAPHY

The following references contain information on coaxial cable communications. Items 1 through 3 provide excellent general information concerning the system design concepts and the required performance characteristics of the various portions of the system. Item 4 gives a detailed mathematical derivation of the types and causes of signal distortion while Item 5 provides information concerning construction costs of conventional CATV systems. Items 6 and 7 contain chapters which describe the cumulative effects of cascaded amplifier networks. Item 8 contains details of the method of designing and constructing coaxial cable systems. Item 9 contains the regulatory requirements for operating commercial cable television and also gives the maximum level of extraneous radiation permitted.

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APPENDIX I

AIR PATH OPTICAL COMMUNICATIONS

In order to illustrate an application of the concepts of air path optical communications, the following paragraphs provide a description of a typical mechanization.

I. 1 EQUIPMENT DESCRIPTION

The bidirectional transceiver used for transmitting information through the atmosphere by means of optical energy consists of a pair of pole-mounted optical "heads", containing the optical and electronic components.* Each optical head is constructed as a cast aluminum cylinder typically 8 inches (20 cm) in diameter and 15 inches (38 cm) long and weighing about seven pounds (3.2 kg). A fresnel lens is mounted immediately behind a protective glass window in one end of the cylinder, with a laser transmitter light source and receiver input located in the lens focal plane. The transceiver electronics unit for a pair of optical heads may be located in the rear portion of one of the housings.

I. 2 TRANSCEIVER ELECTRONICS UNIT

As shown in the transceiver block diagram, Figure I-1, the transceiver electronics unit incorporates receiver, transmitter, AGC, power supplies and all related logic and control circuits.

I. 2. 1 Receiver Section

The received pulses collected from the fresnel lens are refocussed by a lens onto the avalanche photodiode. This circuit is temperature stabilized to maintain constant gain over the ambient temperature range. The APD output then passes through an amplifier whose gain is controlled by the AGC circuit (pre-amplifier AGC). Following another amplifier stage, the final video amplifier is also AGC controlled (video amplifier AGC).

The AGC circuit adjusts the receiver circuit gain as a function of noise level and ambient light conditions. A high gain is provided under conditions of low sky background light such as in fog and a low gain is provided under high brightness conditions.

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*A prototype air path optical communication system was examined as part of this study and forms the basis for the descriptive material contained in this Appendix.

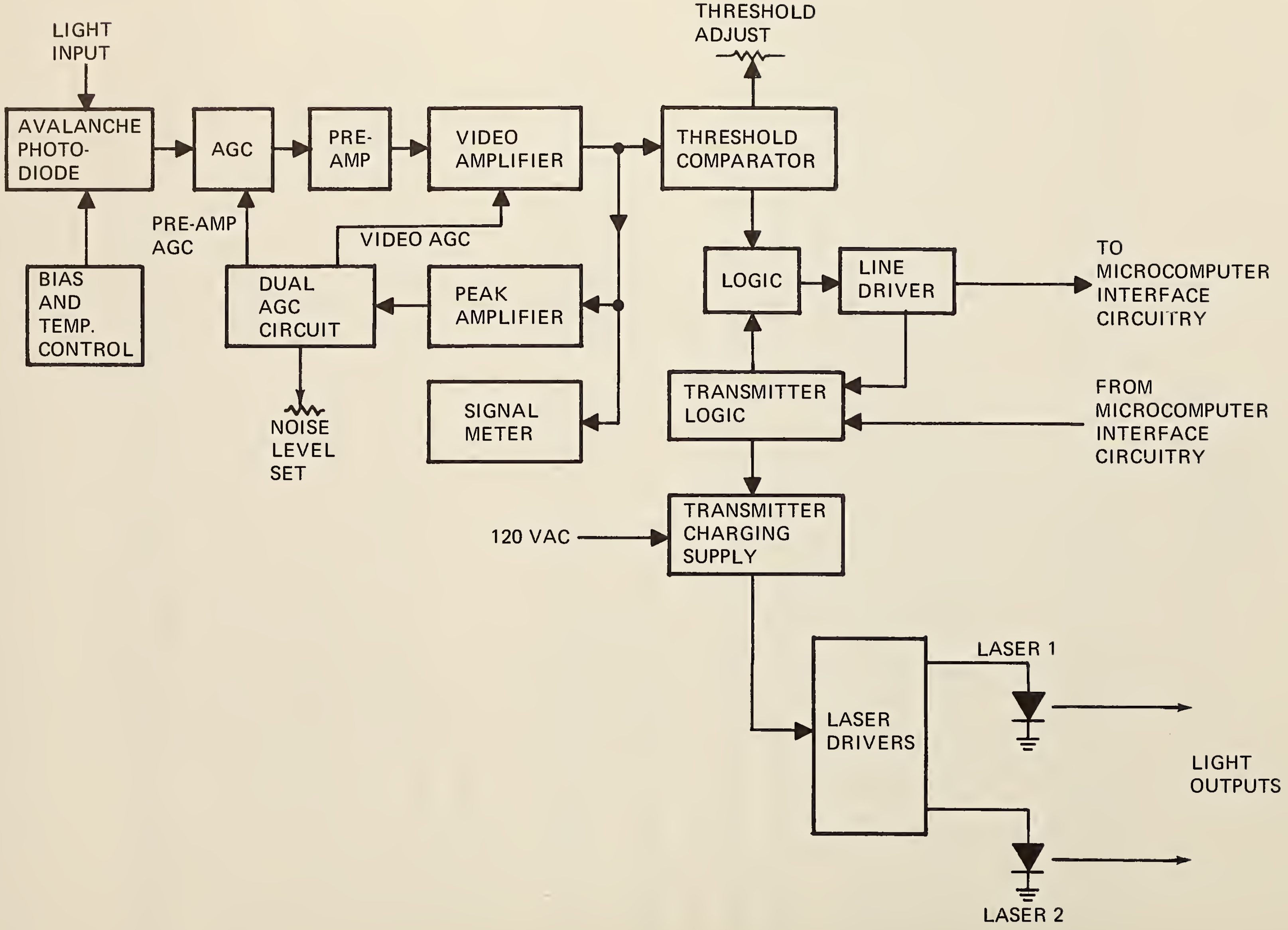


FIGURE I-1. TRANSCEIVER ELECTRONICS

I.2.2 Transmitter Section

The transmitter typically uses two laser diodes, one for each of the two optical heads. Each one has a driver (pulse generator) which provides a drive current. A current monitor circuit may be present at the output of each laser driver to adjust the charging voltage so that the appropriate peak drive current is obtained.

I.2.3 Transmitter Logic Circuit

The transmitter logic circuit provides the following functions:

- It allows both the receiver output pulses and the intersection microcomputer output pulses to trigger the transmitter.
- It limits the transmitter pulse repetition frequency from exceeding a preset limit to prevent transmitted average power from exceeding Bureau of Radiological Health Class I safety limits.
- It provides the receiver blanking function following a transmitted pulse as described above.

I.2.4 Signal Meter Circuit

A circuit is provided in the receiver section to sample the video signal level for purposes of monitoring received signal strength. This circuit integrates the video pulses and then provides a signal which is proportional to the video pulse amplitude.

I.3 INSTALLATION AND ALINEMENT

One installation technique is to mount the optical heads to short mast arms attached to existing traffic signal poles. The location of the mast arm on the pole, and the length of the mast arm is determined by sighting with a hand-held telescope from the approximate location of the mast arm to the adjacent upstream and downstream optical head locations. Where a third or fourth optical head is required, a second mast arm might be used.

A telescope or other optical technique may be used for the initial alinement. A finer alinement of the optical head is possible by using a field strength meter attached to the receiver test terminals while the adjacent optical head is transmitting continuously. Azimuth and elevation adjustments are then made until the field strength meter reading is maximum.

I.4 DATA RATE AND DISTANCE LIMITS

Pulsed laser diodes in the transmitter of an optical (air medium) data link are limited to repetition rates of 5 to 10 kilobits per second for full power output using pulse widths of 40 to 200 nanoseconds. Typical peak power for these devices is 5 to 20 watts. Using a 10 watt peak power pulsed laser, under practical visibility conditions, ranges of 1 mile (1.6 km) to 5 miles (8 km) or more can be obtained depending on visibility. Very few urban environments, in any case, have an unobstructed point-to-point line of sight range greater than this.

For ranges up to 3,000 feet (914 m) under conditions of good visibility, high-power light emitting diodes can be used instead of pulsed laser diodes (with average power output capability of 200 to 500 milliwatts). Commercially available optical communication units will handle bandwidths of at least 10 Mbits/sec (10^7 bits/sec) employing this approach.

A discussion of factors affecting distance capability is contained in Attachment 1 to this Appendix, titled "Air Path Optics System Analysis".

I.5 ENVIRONMENTAL FACTORS

Susceptibility to light source interference of the optical receiver is low due to the narrow field of view (usually under 5 milliradians), and the use of filters used to discriminate against daylight background and sources of artificial light. The use of automatic gain control insures almost total insensitivity to solar reflections and glint, auto headlights, or fixed artificial lights.

Weather conditions have little effect on performance, with the exception of heavy fog, snow amounting to blizzard conditions, and rainfall at rates greater than 1 inch per hour. Actual long term tests at a range of 2,000 feet (610 m) have shown excellent performance with winds to 60 mph (97 km/hr) rainfall up to 1-inch (2.5 cm) per hour, heavy snowfall and fog with visibility down to 1,000 feet (305 m). With weather not worse than these conditions error rates of $1 - 5 \times 10^{-7}$ or less have been obtained. (In an operational installation, simple error detection codes will yield system error rates many orders of magnitude better than this.)

Temperature effects on the performance are negligible, since all equipment can be designed to operate over a temperature range of - 40°F to + 140°F (- 40°C to + 60°C).

I. 6 SUPPORT MEMBER REQUIREMENTS

Performance of a representative system has been demonstrated in the face of thermal expansion and contraction of the optical head support members. The demonstration used a 20 foot (6.1 m) vertical steel pole with the optical heads mounted on a tapered steel cross arm near its top. With relatively fast temperature changes of 10°F (5.55°C) occurring in 2-hours, (or 5°/hr rate of rise) pole and cross arm deflections have been observed to produce a significant optical head line of sight (L. O. S.) deflection. System performance will not be affected under these conditions for optical head separations of up to one mile.

Greater, but slower, temperature changes do not cause as large a deflection; nor do extreme cold or hot ambient temperatures in themselves result in significant angular shifts.

Wooden poles of comparable height are less sensitive to short term temperature excusions than metal due to the higher conductivity and thermal coefficients of steel and aluminum as compared to wood.

I. 7 EQUIPMENT RELIABILITY AND MAINTAINABILITY

Because of its low average power consumption, the reliability of systems of this type will be of the same order as for the other technologies considered. Limited installation data for prototype equipment has demonstrated an MTBF in excess of one year.

Fault isolation to a particular unit in a traffic control communication network is essentially automatic, since the master computer detects the address of a faulty response, and therefore replacement of modules can be done in the time it takes to reach the unit and replace the faulty module (less than two hours in most cases). Repair of faulty modules might be accomplished by returning them to the supplier under a maintenance contract agreement.

I. 8 REGULATORY ASPECTS

Use of laser diodes in the transmitter requires that eye-safety certification requirements of the Bureau of Radiological Health of H. E. W. must be met and the test results demonstrating this must be submitted to BRH. In the typical configuration for the traffic control data link application it has been possible to design equipment so that for data rates under approximately 3 to 4 kilobits per second, the laser emission is completely eye safe and requires no labeling on the outside of the equipment other than vendor identification and date of manufacture. For data rates over 3 to 4 kilobits per second, and pulsed lasers of 5 to 10 watt peak power range, or for CW lasers producing more than 2 to 5 milliwatt average power, Class III identification is required. This category of equipment requires labels on the outside of the equipment warning personnel not to look directly into optical head windows with the power on.

Public exposure at ground level, and at any significant distance from optical heads, are perfectly eye safe in all of these cases. Since beam diameter spreads out rapidly with distance, the beam intensity is greatly reduced at distances at which an observer might be exposed.

A discussion of laser safety certification is contained in Attachment 2 to this Appendix, titled "Laser Safety Certification".

I. 9 SUSCEPTIBILITY TO VANDALISM

Since optical heads are usually located at least 18 feet (5.5 m) above street level and may be packaged in heavy duty castings, vandal susceptibility is low. Use of 1/4-inch (6.4 mm) thick tempered glass, which is about 5 times more resistant to breakage than standard glass, would enable the unit to withstand most instances of rock throwing from ground level. Optical grade ground and polished acrylics, although more expensive than tempered glass, could also be considered as a means of providing even greater protection where such additional ruggedness is necessary.

APPENDIX I - ATTACHMENT 1

AIR PATH OPTICS SYSTEM ANALYSIS

OPTICAL RANGE ESTIMATION

In the air path optical communication system, a short high power pulse of emitted radiation is generated by the transmitter and is received at a remote location. The received power can be related to the transmitted power and the geometry by the equation shown below. Typical values for the variables in the equation are shown in the column to the right of the variable definitions.

$$P_r = \frac{P_t A_r T_r}{(\pi/4)(\theta_t)^2 R^2} \times T_a \tag{I-1}$$

where

	Typical Values
P_r = peak optical pulse received power in watts	
P_t = peak optical pulse transmitted in watts	4 watts
A_r = effective receiving aperture in square meters	.02 m^2
T_r = net receiver optical efficiency	.05
θ_t = transmitter beam divergence in radians	.005 rad
R = range between transmitter and receiver in meters	610 m
T_a = effective transmittance of the atmosphere.	.37

With a given amount of received power, the ability of the system to communicate reliably is limited by the inherent noise equivalent power of the receiver photodiode and the system bandwidth. These factors affect the signal-to-noise ratio obtainable, as given by the following expression:

$$S/N = P_r/P_{min} = P_r/(NEP \times \sqrt{\Delta f} \times k) \tag{I-2}$$

where

	Typical Values
S/N = the achievable signal-to-noise ratio	
P_r = received power as defined above	

	Typical Values
P_{min} = minimum detectable power of the avalanche photodiode (APD)	5.2×10^{-10}W
NEP = noise equivalent power of the APD	5×10^{-14}W
Δf = receiver bandwidth	$7 \times 10^{6}H_{z}$
k = daylight background factor.	4

The above two equations may be used to compute the estimated signal-to-noise ratio obtainable with a given system under adverse atmospheric conditions; that is, for various values of T_a.

When the typical parameter values are substituted into these equations, the received power and the signal-to-noise ratio in terms of atmospheric transmittance for a range of 2,000 feet (610 m) become:

$$P_r = 5.7 \times 10^{-4} \times T_a; \qquad \text{(I-3)}$$

and

$$S/N = P_r/P_{min} = 5.7 \times 10^{-4}/5.2 \times 10^{-10} \times T_a = 1.1 \times 10^{6} \times T_a. \qquad \text{(I-4)}$$

With a value of $T_a = .37$, which is the transmittance at 80°F (21°C) and 80-percent humidity, the computed signal-to-noise ratio becomes 4.1×10^{5}, or 56 db.*

Values of T_a associated with rain and fog are computed using the methods discussed in the following paragraphs. Typical values of T_a, and corresponding computed signal-to-noise ratios for a 2,000-foot (610 m) range are:

	T_a (db)	S/N (db)
Cloudburst	- 14.4	46
Dense fog	- 25.4	35
Thick fog	- 51	9.4

---

*This figure may be used to define the "fade margin" of the system for a 2,000-foot range as 56 - 10 = 46 db. The 10 db difference is the receiver signal-to-noise threshold setting which is used to essentially eliminate false pulse indications due to noise.

These figures show that data communication at a 2,000-foot (610 m) range can be achieved in heavy rain and dense fog, but is eventually limited by thick fog (assuming a receiver S/N threshold setting of 10 db).

A prototype system has been demonstrated to operate within specification at 2,000 feet (610 m) in "dense" fog with visibility below 1000 feet (305 m).

ATMOSPHERIC TRANSMISSIVITY

General

The atmosphere consists of a mixture of gases containing particles in suspension. The atmospheric gases do not usually absorb very seriously in either the visible or infrared spectra. Of more serious sequences is the scattering due to the particles suspended in the atmosphere such as aerosols and fog. An increasing concentration of these particles causes the transmissivity of the atmosphere to decrease rapidly.

The atmospheric transmittance, T_a, over a path length R may be expressed by:

$$T_a = \exp(-\sigma R), \tag{I-5}$$

where σ is the attenuation coefficient or "extinction coefficient". The equation is valid only for very narrow wavelength bands, such as laser transmissions, and for transmission along a horizontal path through an atmosphere of uniform composition. Since this is a good approximation of this communication system's typical operating environment, the above equation was used to estimate expected atmospheric losses.

Transmissivity in Rain

The scattering coefficient in rainfall is independent of wavelength in the visible to far infrared region of the spectrum and may be estimated by the equation,

$$\sigma_{\text{rain}} = 0.248r^{0.67} \tag{I-6}$$

where

σ_{rain} = the scattering coefficient in units of km^{-1}

r = the rainfall rate in mm hr^{-1}

Some calculated values of transmittance are shown in Table I-1.

TABLE I-1. TRANSMITTANCE IN RAINFALL

Condition	Rainfall rates $r(\mathrm{mmhr}^{-1})$	Extinction coefficient, σ (km^{-1})	Transmittance, Ta, at 1.8 km path (fraction)	(db)
Light rain	2.5	0.458	0.438	- 3.6
Medium rain	12.5	1.347	0.088	-10.6
Heavy rain	25	2.143	0.021	-16.8
Cloudburst	100	5.426	$5.73\mathrm{x}10^{-5}$	-42.4
Note: 1 km = 621 mile				

The transmittance for various rain conditions expressed in graphical form with range (R) as the independent variable is shown in Figure I-2(a). As indicated in this figure, at a range of one thousand meters (3,280 feet), a cloudburst results in a loss of 24 db. At a range of 600 meters (1,970 feet), a cloudburst is seen to result in a loss of only 14 db.

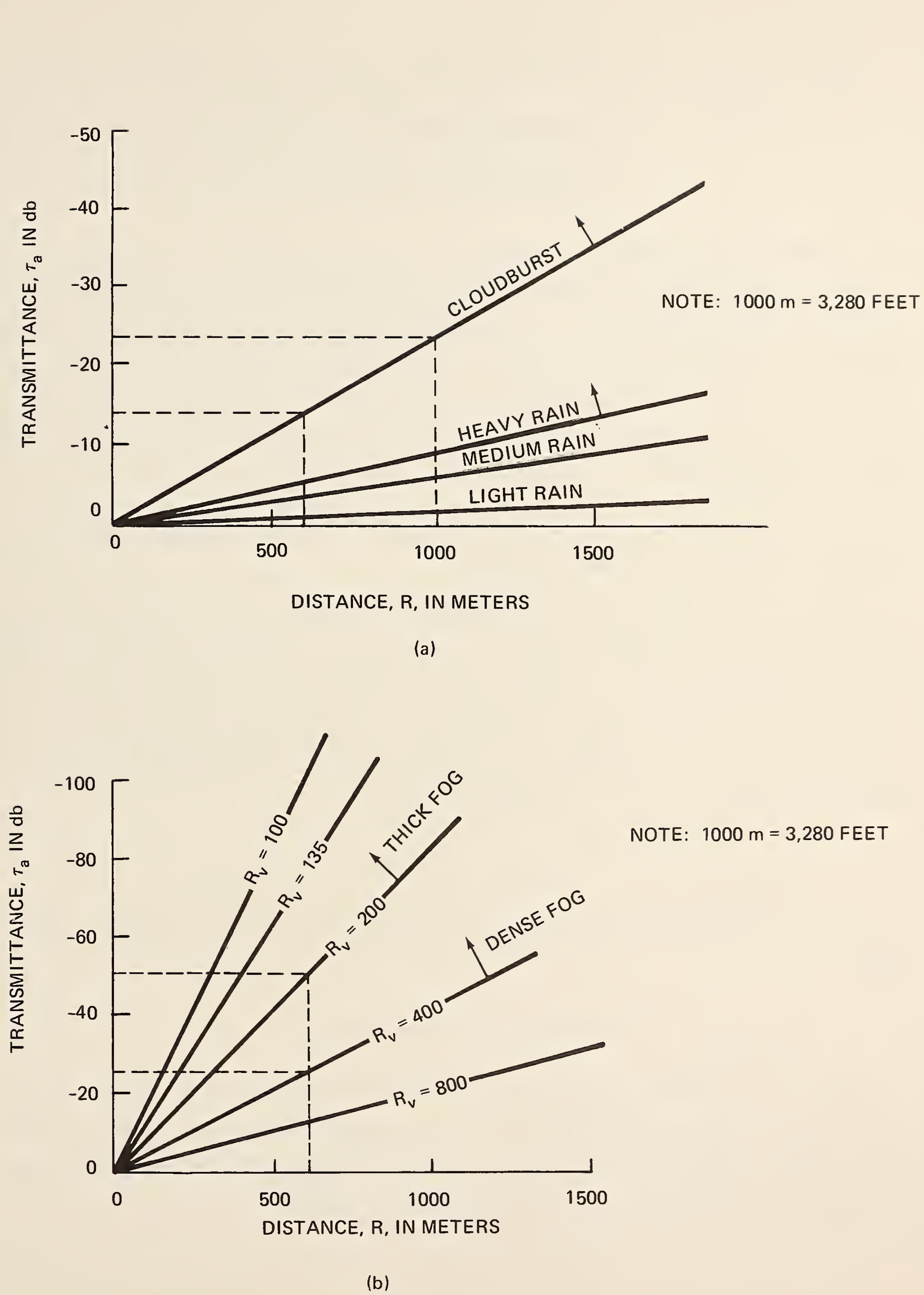
Transmissivity in Fog

The transmittance for various fog levels was calculated using visibility to quantify the fog level. Visibility as defined here is the distance, R_V, under which, during daytime, a black target can be just detected against the sky horizon background by the human eye. This definition assumes that the threshold of contrast for the human eye is always 0.02, under those conditions. This means that the contrast transmission (Cx/Co) of the atmosphere in daylight is 2 percent, where Co is defined as the inherent contrast of an object and Cx the apparent contrast at range R. The apparent contrast Cx reduces exponentially with range R in accordance with the expression $\exp(-\sigma_V R)$ where σ_V depends on the visibility R_V (in meters) as follows:

$$\sigma_V = 3.91/R_V \tag{I-7}$$

The transmittance, T_a, becomes $T_a = \exp(-\sigma_V R) = \exp(-3.9R/R_V)$.

The transmittance in this case is best depicted by a family of curves for various visibilities as shown in Figure I-2(b). ("Thick fogs" are defined to have visibilities (R_V's) of 200 meters or less; "dense fogs" 400 meters or less; "fogs" 1,000 meters, "mist" 2,000 meters; and "haze" 10,000 meters.) As this figure indicates, a "dense" fog of 400-meter (1,310-foot) visibility produces a loss of about 25 db at a range of 600 meters, (1,970 feet), while a "thick" fog of 200-meter (657-foot) visibility produces a loss of about 51 db.



NOTE: 1000 m = 3,280 FEET

(a)

NOTE: 1000 m = 3,280 FEET

(b)

FIGURE I-2. TRANSMITTANCE IN RAIN AND FOG

APPENDIX I - ATTACHMENT 2

LASER SAFETY CERTIFICATION

An optical communications transceiver, when using laser diodes with a peak power output of the order of 10 watts, and with the proper optical head parameters, can be perfectly eye safe. With the proper choice of the primary aperture (fresnel lens) diameter, so as to limit laser emission output intensity, it can be designed to meet the HEW Bureau of Radiological Health federal standards* for a Class I device. Such a device can be viewed at point-blank range through an 8 cm (3.14 inch) diameter optical aid (telescope) with no danger to the eyesight (or any other parts of the body).

The other parameters essential to keep within the limit are laser pulse width and repetition frequency, as described below.

The Bureau of Radiological Health standards for laser device safety (in regard to public exposure) permits the manufacturer of the laser device to employ a criterion defined as integrated radiance in joules (or watts) per cm^2 per steradian. For an exposure duration greater than 10^4 seconds (about 8 hours), the Class I limits permit accessible emission through a 7 mm aperture (representing average human iris diameter) and with a viewer collecting field of view of 10^{-5} steradians, to be:

$$E_{(\lambda, t)max} = 2 \times 10^{-3} K_1 K_2 \text{ joules per cm}^2 \text{ per steradian.} \tag{I-8}$$

With the appropriate values of K_1 and K_2 which are constants related to wavelength and exposure duration,

$$E_{(\lambda, t)max} = 0.488 \text{ watts per cm}^2 \text{ per steradian.} \tag{I-9}$$

Using the above design criterion with 10 watt laser diodes, where peak emission from the fiber optics illuminating the fresnel lens may vary from 4 to 7 watts, the actual measurements through the 7 mm aperture with 10^{-5} steradian field of view will give values of $E_{(\lambda, t)}$ from 17 to 40 percent of the maximum allowed.

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*Refer to HEW standards CFR 1040.10 and 1040.11.

It should be noted also that the BRH Class I limits have been selected to be several orders of magnitude eyesafe in regard to the safe exposure of the human retina and eye-lens. Hence, in meeting this criterion, the laser product would be exceedingly safe (doubtless more so than many non-coherent artificial light sources).

APPENDIX I

BIBLIOGRAPHY

The following references contain information on the subject of air path optical communications. Reference 1 presents a variety of technical articles on the subject of optical communications on earth and in space covering system and device oriented subjects, atmospheric anomalies and high data rate trade-offs.

Reference 2 is a tutorial article on air path and space optical communications.

References 3 to 5 are technical (engineering) articles on specific optical communications systems and components.

Reference 6 is an engineering text on this subject.

Reference 7 discusses atmospheric turbulence problems in air path communications.

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APPENDIX J

FIBER OPTICS COMMUNICATIONS

J.1 NETWORK APPLICATION

In a traffic control system with a multiplicity of intersections, the heart of a fiber optics communications system is a bidirectional repeater (transceiver) which can act as the interface between the fiber optics cable and the electronics at the control center and at the intersections.

A simple, cost effective implementation of a fiber optics data link repeater is described here. Figure J-1 shows a simplified layout of the unit. Fiber optics transmitter and receiver modules are interconnected by a fiber optics "star" configuration, which combines the transmitter and receiver paths at each data link interface, that is, the upstream and downstream fiber optics cable connections at the intersections.

As a repeater, this scheme functions as follows: an optical data signal arriving from the upstream direction enters the fiber optics star leg "4" where it enters an optical receiver. This converts the detected optical signal into an electronic signal which is amplified and coupled electrically to the input of a transmitter. Here a driver with T^2L input is used to modulate a light emitting diode (LED) with pulsed modulation, usually in a serial binary code. This then converts the data pulses back into a modulated optical signal. Fiber optics star leg "2" then couples this energy via fiber optics connectors into the downstream fiber optics cable. Thus the incoming signal level has been boosted as much as 60 db where it can now travel through a fiber optics cable for one kilometer (0.6 mile), or more, depending on the type of fiber optics being used.

Conversely, an optical data signal arriving from the downstream direction is coupled via fiber optics star leg "3" to the receiver. As before, the receiver output is electrically connected to the transmitter which couples the amplified optical signal via star leg "1" to the upstream cable.

As can be seen, the optical power out of the transmitter is split between star legs "1" and "2". Hence, a 3 db (half-power) loss is introduced during transmission. Similarly, half the received optical power is split between legs "1" and "4" when arriving from the upstream direction, and is split between legs "2" and "3" when arriving from the downstream

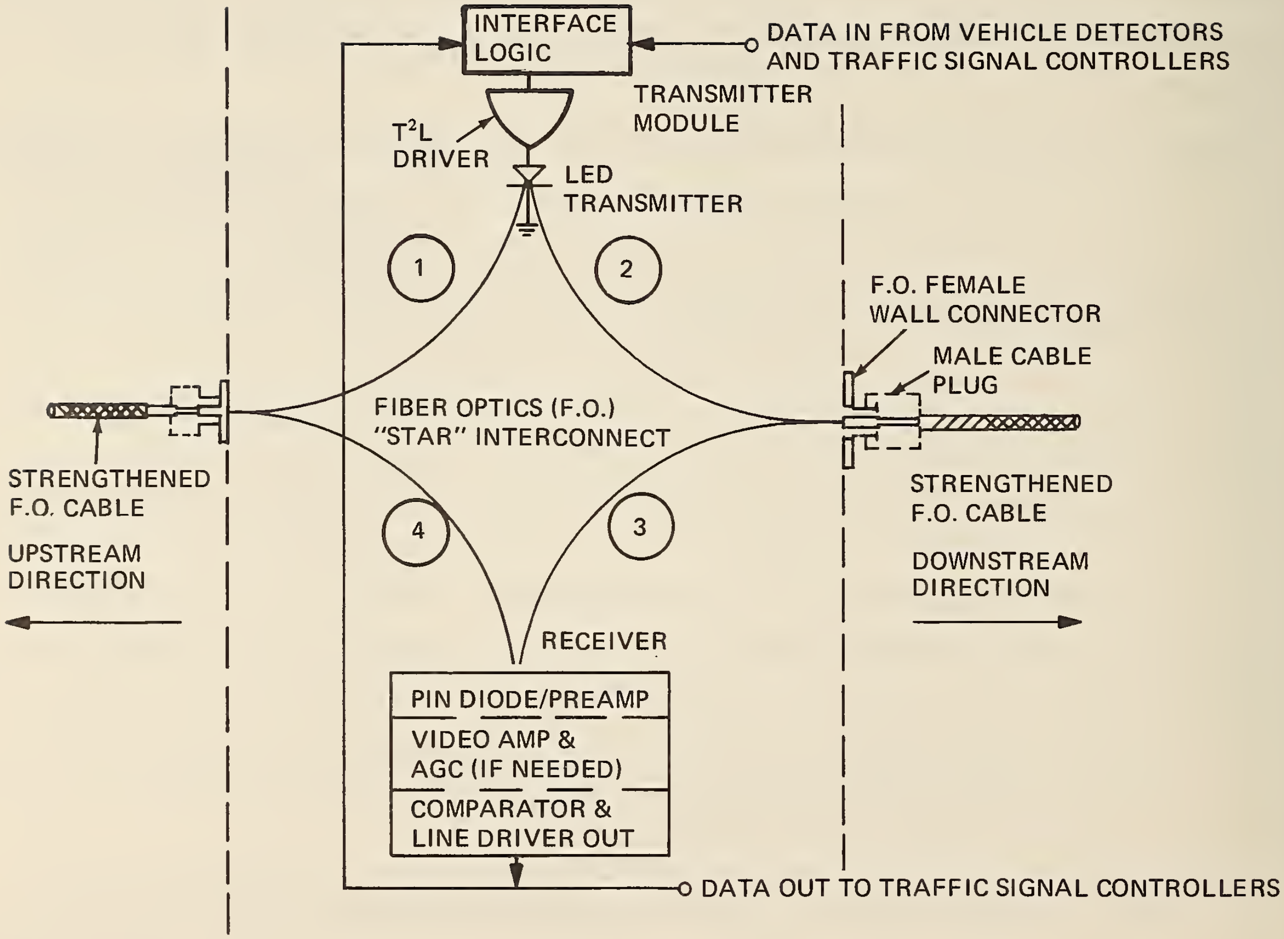

FIGURE J-1. FIBER OPTICS REPEATER TRANSCEIVER direction. With a typical cable loss rating of 32.2 db/mile (20 db km), a spacing of one kilometer between intersections, and an overall gain of up to 60 db in the repeater, an excess gain of 20 db is available. Therefore, even with a reasonable signal-to-noise ratio at the receiver, there is adequate surplus gain in the system to permit the net 6 db splitting losses.

Another situation that is commonly dealt with in half or full duplex systems such as this, is that since the transmitter sends half of its signal back down the same fiber optics cable through which it had just arrived, the receiver in the previous repeater (or in a terminal transceiver) must be protected from responding to this input. This is usually done by blanking off the receiver for a preset time interval, and then unblanking it in time to receive the next legitimate data pulse. However, this approach is not altogether adequate, particularly for high data rate requirements. Therefore a more effective means of separating the upstream from the downstream receiver circuit response is shown in Figure J-2.

In this scheme two separate transmitter drivers and LED sources are used instead of one. The fiber optics star interconnection is opened at this transmitter junction into two separate branches, one dedicated only to the upstream direction and one to the downstream. Each of the two LEDS are likewise dedicated for functioning in only one of these directions. An upstream/downstream logic unit decodes the message from the local receiver and triggers only the appropriate LED so that the data stream progresses in the same direction until the message has been completed.

For example, as shown in Figure J-2, data will arrive from the central processor, or upstream direction, and enter the receiver branch fiber optics from the left or star branch 4. It is then detected, amplified and coupled into the transmitter section. With the simple expedient of an address, or code, preceding each message stream to identify the desired direction in the data link, i.e., upstream to downstream in this case, the transmitter decode logic responds by triggering only the downstream LED which then transmits a light pulse into branch 2 of the star. Thus the local repeater only propagates data in the desired direction, with no feedback going upstream in the wrong direction.

During the reverse sequence, data that is to flow from intersections back to the central processor enters star branch 3, is detected, amplified and coupled to the transmitter section. This time the message is preceded by a downstream-to-upstream address code. Thus the decoder triggers only the upstream LED which then transmits data into star leg 1 which is coupled solely into the upstream fiber optics cable as desired.

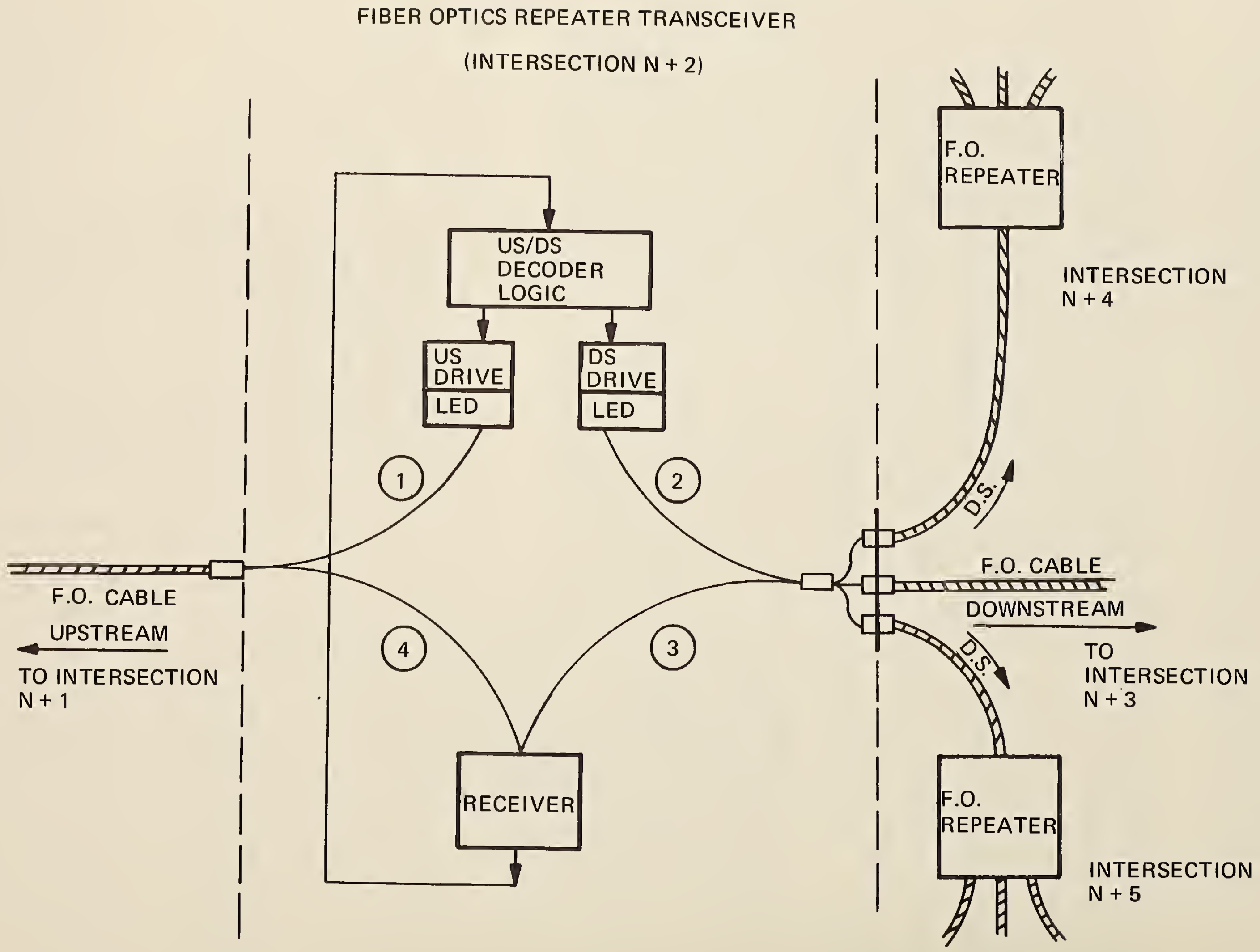

FIGURE J-2. UPSTREAM/DOWNSTREAM ISOLATION CONFIGURATION

There may be the requirement of a short blanking interval to prevent crosstalk, or to prevent reflected light from the transmitter "main bang" pulses feeding back into the local receiver (since star legs 1 and 4 form a common junction, as do 2 and 3) and thus retriggering the transmitter. A simple retrigger prevention circuit can be added to the logic input to accomplish this safeguard.

In order to couple data from the controller monitor output and from the vehicle detectors into the link, signals are simply connected to the fiber optics transmitter via standard shielded cable, or twisted pair cable, into an appropriate interface circuit. This consists of simple logic elements which accept a number of parallel input channels and convert them into a single pulsed data stream at T^2L logic levels. This multiplexing of input data allows for a large number of parallel input (and output) channels due to the wideband capability of the typical fiber optics data link. The same type of interfacing circuit applies to the receiver output which is normally connected to the local controller at each intersection. In this case, the above functions are implemented in the reverse direction, that is, serial data is converted to parallel latched outputs.

In a typical traffic control communication network, as many as three output legs are required for a given repeater in the downstream direction. To this end, the fiber optics transceiver modem must couple from the combined internal star legs (2 and 3) to junctions with each of three downstream external fiber optics cables (Figure J-3). This can be implemented as follows, referring to the fiber optics diagram of Figure J-4. Fibers in star leg 3 to the receiver are randomly mixed with star leg 2 from the downstream LED transmitter. This combined bundle is then evenly divided into three distribution legs. This is called a trifurcated fiber optics assembly, a manipulation now routinely performed by fiber optics assembly manufacturers.

It is important that an even distribution of mixed transmitter and receiver fibers enter each of the output connectors labeled DS1, 2 and 3, so that each of the three downstream legs receives one-third of the optical energy. The receiver input optical energy arriving from the upstream direction is divided by two using this configuration. This is due to the fact that each of the legs from the connectors feeds all of its optical energy to the combined star legs 2 and 3, with half to receiver leg 3 and half to transmitter leg 2. (The latter portion of the optical energy is, of course, unusable.)

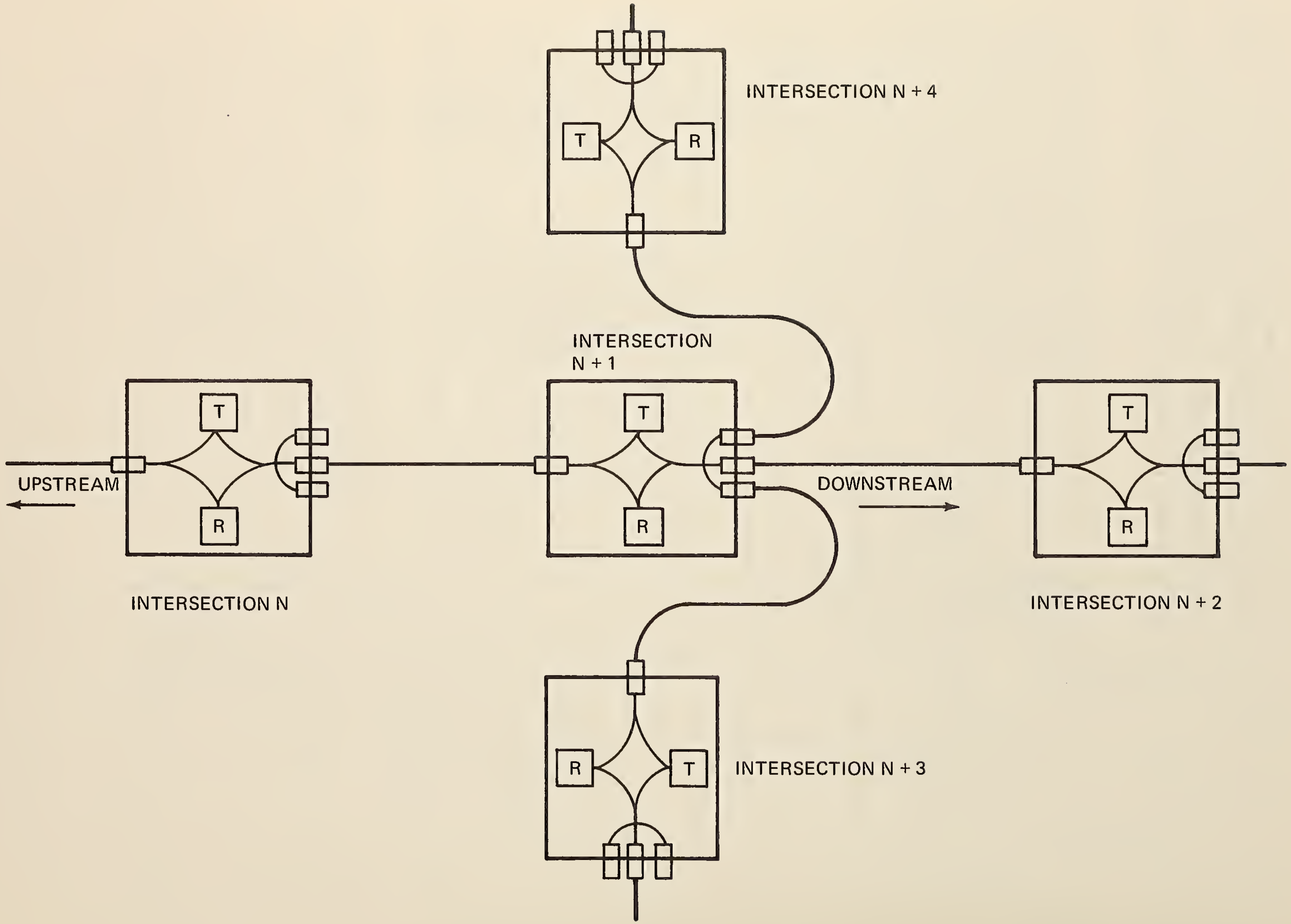

FIGURE J-3. TYPICAL FOUR-INTERSECTION INTERCONNECT

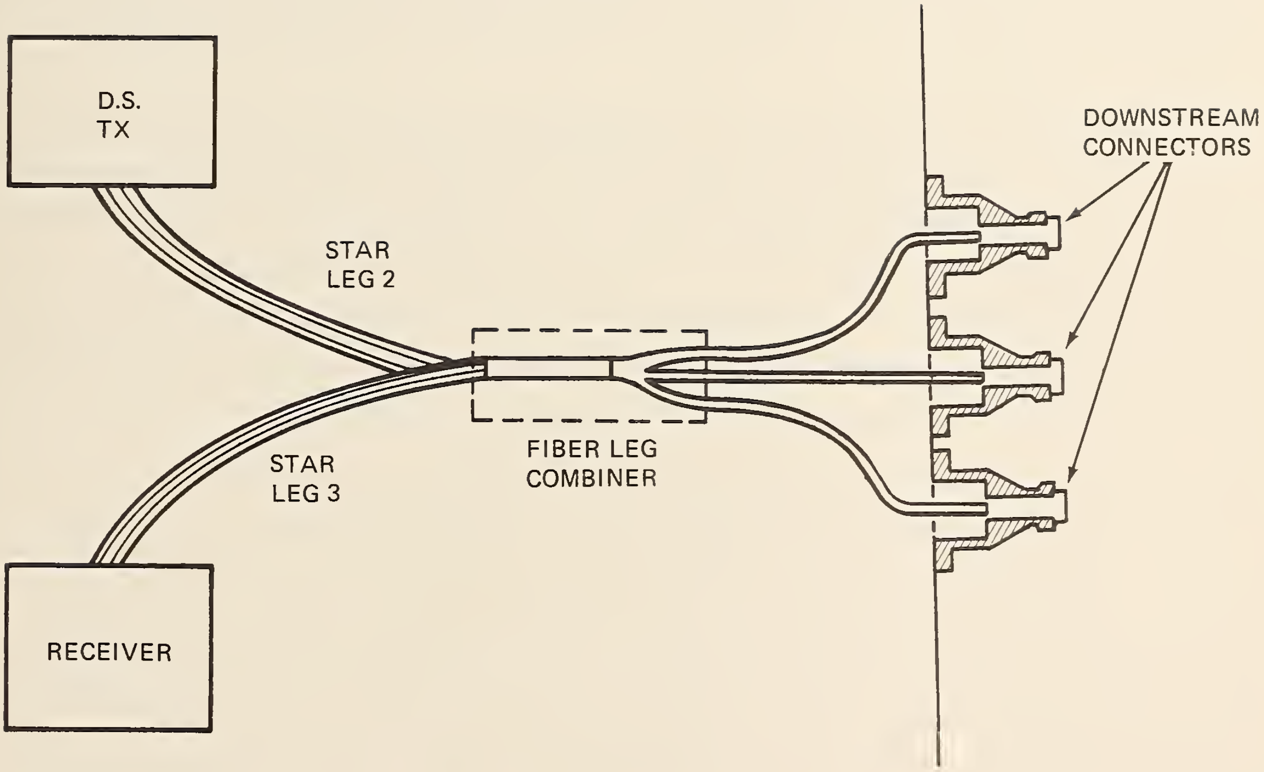

FIGURE J-4. DOWNSTREAM DISTRIBUTION SCHEME

J.2 DATA RATE AND DISTANCE LIMITS

The major limits to data rate for fiber optics are the light emitting diodes (LED) most commonly used in the transmitters; and pulse dispersion, which is a function of length and characteristics of the fiber optics itself. Most production LED's are limited to about five nanoseconds rise time for pulsed modulation. This enables its use at data rates up to about 50 megabits per second. LED's now under development are capable of data rates up to about 250 megabits per second.

Using continuous wave (CW) injection (diode) lasers, a rise time capability of about one nanosecond is obtained now with production diodes, hence data rates greater than 250 M bits/sec can be obtained using these devices. With other CW laser diodes, fiber optics data links have been operated up to from 300 to 650 M bits/sec. There are less significant limitations in the receivers with commercial avalanche and PIN photodiodes capable of bandwidths of 1 GHz or more.

The next limitation to data rates are the optical fibers themselves. A single 2 to 10 mil diameter fiber with graded index of refraction (varying from the center to the edge of the fiber core) has a pulse-width dispersion of about 5 nanoseconds per kilometer of fiber length. This permits bandwidths of 62.1 M bits/sec per mile (100 M bits/sec per kilometer) for each fiber channel. A fiber optics cable 1/8 inch (3.2 mm) in diameter can handle one to 50 jacketed fibers; hence a standard low loss commercial cable with 19 fibers has a data capacity of 1,180 M bits/sec/mile (1900 M bits/sec/km).

Low loss fibers are now commercially available at loss ratings as low as 3 db per kilometer in the wave-length ranges matching typical LED and laser sources. A short fiber optics data link with 10 M bits/sec bandwidth can easily work with 60 db signal-to-noise ratio using a modern avalanche photodiode detector in the receiver. Assuming at least a 10 db signal/noise ratio for low bit error rate, this leaves 50 db allowed cable loss. Thus with 8 db/mile (5 db/km) cable a range of 62.1 miles (100 km) can be achieved. A data rate of 10 M bit/sec would also be the limit for 6.2 miles (10 km) using graded index fibers.

J.3 NOISE AND CROSSTALK

Fiber optics transmission systems are essentially immune to RFI and EMI induced noise sources, except at the electronic interfaces. They are also completely immune to lightning strikes (except direct hits) and power cable faults.

Crosstalk is only a problem where individual fibers carrying separate data channels are not jacketed. However, opaque jacketing of each fiber is now common for multichannel bundles, so crosstalk should be no problem in a properly designed system.

J.4 ENVIRONMENTAL ASPECTS

Strengthened fiber optics cables are available which will withstand 100 to 400 pound (45 to 180 kg) pull tests for cable having approximately 0.25 inch (6 mm) diameter, and can withstand rough handling, crushing, cleavage and abrasion, comparing favorably with commercial small-diameter coaxial cable.

APPENDIX J

BIBLIOGRAPHY

The following references contain information on the subject of fiber optics communications. References 1 through 4 provide general tutorial material on this subject. Reference 5 gives more detailed technical information on the design of a single fiber long distance data link.

References 6 and 7 contain a detailed discussion, with experimental parameters, on the achievement of high reliability light emitting diodes specifically designed for fiber optics use.

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7. "Reliability Aspects and Facet Damage in High-Power Emission from (A1Ga)As CW Laser Diodes at Room Temperature", H. Kressel and I. Ladany, RCA Review, Vol. 36, No. 2, pp 230-239 (June 1975).

8. "Fiber Optic Interconnect for Tactical Data Computer Systems", M. Shoquist, Signal (Magazine), Oct. 1977, pp 45-48.

APPENDIX K

RADIO COMMUNICATIONS

K.1 BACKGROUND INFORMATION

This appendix is intended to provide some insights for traffic engineers who wish to consider the use of radio communications as the means for operating the various elements of a city's computerized traffic control system. Of particular interest is the use of unguided radio waves, i.e., those radiated or propagated in space. Normally, in designing a radio communication system, one starts with known locations of the transmitting and receiving terminals and computes the great-circle distance between them as an initial step for estimating path length, power required, etc. It is obvious that this approach cannot be followed in this report since it is not possible to generalize the characteristics of all of the cities for which traffic control systems might be considered. Therefore, the approach selected is based on an attempt to establish reasonable bounds within which a radio-controlled system could be expected to operate and to emphasize characteristics with which any such system will have to contend.

From an abstract point of view, a radio communication system can be thought of in terms of its ability to transmit information at a suitable rate, with acceptable fidelity, between agreed upon locations, while contending with the electromagnetic environment associated with the terminal locations, the allocated frequency spectrum, and the limitations imposed by the equipment available. A complete analysis of such a system would require consideration of all of the following factors:

- Path Characteristics - attenuation, bandwidth restrictions, parameter variations in time, etc.
- Equipment Characteristics - type of antennas, repeaters, transceivers, terminal devices, etc.
- Message Characteristics - amount of data conveyed, coding requirements, transmission rate, etc.
- Operation and Maintenance Requirements - special functions needed to keep the circuit operational.

It is clear that the performance of a system over time can be affected by each of these items. It follows that, in the design of a specific system, allowance must be made for anticipated variations in these factors if the system's design performance goals are to be met. These allowances generally result from trade-off studies based on information obtained from other systems and the gradually evolving stock of knowledge to which a radio system designer has access.

K.1.1 Path Characteristics

The path characteristics affect the system design in many ways, not the least of which is the modes by which the energy propagates. Radio waves are a form of electromagnetic radiation similar to heat and light radiation. However, they are different in the manner by which they are generated and detected, and, also, in the portion of the electromagnetic spectrum in which they are found. There are a number of mechanisms by which radio waves may propagate from a transmitting to a receiving antenna. The most typical paths include a surface wave (ground wave), a space wave, a sky wave, and a tropospheric scatter wave, all of which are dependent upon antenna directivity, "look" angle, frequency range and power levels. The surface or ground wave consists of electric and magnetic fields associated with currents induced in the ground. The space wave represents energy that travels from the transmitting to the receiving antenna in the earth's troposphere and usually consists of a direct wave and a wave reflected from the surface of the earth. The sky wave depends on the presence of the ionized layers above the earth that refract some of the incident energy that otherwise would behave as a direct wave and escape into outer space. The tropospheric scatter wave, which is used primarily for long-distance transmission, depends upon atmospheric turbulence to produce sections of the atmosphere with refractive indices that are radically different from those of the surrounding atmosphere. When irradiated by a microwave signal in the 100 MHz to 10,000 MHz region, these sections scatter the energy in all directions, including the forward direction, resulting in a signal wave at the receiving terminal.

All of the paths discussed exist in any radio propagation application, but some modes are negligible in certain frequency ranges. At frequencies less than approximately 2 megahertz (MHz), the primary mode is the surface wave which is supplemented by the sky wave at night when ionospheric absorption is at a minimum. The frequency range between 2 and 30 MHz is especially useful for long distance skywave transmissions on the order of thousands of miles. At frequencies above 30 MHz, direct and reflected space waves are frequently the only important paths. At these frequencies, the surface wave can usually be neglected as long as the antennas are not mounted close to the ground and the sky wave is ordinarily a source of occasional long distance interference rather than a reliable signal for communication purposes. At frequencies on the order of 1000 MHz, the direct wave is usually controlling on good optical paths (line-of-sight). Radio waves in this range (microwaves) have many characteristics similar to those of light waves, and certain optical principles are useful in describing their propagation. The most useful of these are refraction, diffraction and reflection, which individually or in combination can influence the system propagation reliability in a significant manner.

It is important to note that a traffic engineer or radio system designer is not free to use the frequency band within the electromagnetic spectrum that seems most appropriate for the physical requirements of the system being implemented. The frequency spectrum is a national resource for which, in this country, the Federal Communications Commission (FCC) acts as custodian by authority granted to it by the Congress of the United States. (The use of the spectrum by Federal agencies is controlled, actually through the Interdepartmental Radio Advisory Committee (IRAC), which operates under the Executive Office of the President.) In its role as custodian of this national resource, the FCC is called upon to balance the sometimes conflicting needs of different segments of our society. Over the years, various portions of the spectrum have been allocated for the exclusive use of those licensed to operate within that region. For example, "Report and Order in Docket 19869", FCC 75-1244, published November 18, 1975[1], detailed all of the rules and regulations relating to the then newly established Private Operational Fixed Microwave Service (Part 94), and allocated several bands of frequencies for the use of this service. Of special interest to traffic engineers is that the lowest band of frequencies allocated for this service contains three frequencies (952.5, 952.6 and 952.7 MHz) which currently are available only for control of traffic signals on an omnidirectional basis. The new service does not preempt the usage of these frequencies for traffic control purposes, nor is it likely that traffic control systems will be denied the use of these frequencies at any time in the foreseeable future. Therefore, the basic emphasis in the material presented here will be on the use of the 952 MHz frequencies rather than on frequencies elsewhere in the spectrum that may become available for traffic control purposes at some other time. For convenience, this area of the frequency spectrum will be referred to as 1,000 MHz or 1 GHz, and an operating range of 15 miles* will be assumed.

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[1] Federal Register, Vol. 40, No. 223 - Tuesday, November 18, 1975.

*1 mi = 1.6093 km

Existing traffic control systems that use this frequency range for signaling to the intersections are one-way systems - from the control center to the signal heads. To date, no authorization has been granted for the use of these frequencies for a two-way system in which information is relayed back to the control center from the intersections. The authorization has not been granted because the FCC has not been requested to rule on such an application. It follows that the first system to be implemented with two-way radio control must schedule time to petition the FCC (a process that may require 6 months after the paperwork is all in order) before operation may begin. The success of a petition before the FCC is often directly related to the effort expended in "making a case" for a favorable ruling. While the process is far from being trivial, it is equally far from being impossible. If a favorable ruling is obtained, usually for a demonstration system, then the test results can be used as a basis for requesting permanent permission for two-way service on these frequencies. If granted, any traffic control system can then be implemented using the approved techniques.

K.1.2 Equipment Characteristics

Equipment characteristics affect a system design to the extent that they provide the designer with options for accomplishing his objectives. For a computerized traffic control system it can be assumed that data to be transmitted will be in a digital format as opposed to an analog voice circuit, for example. From an equipment point of view, the overall system can be separated into the following sections:

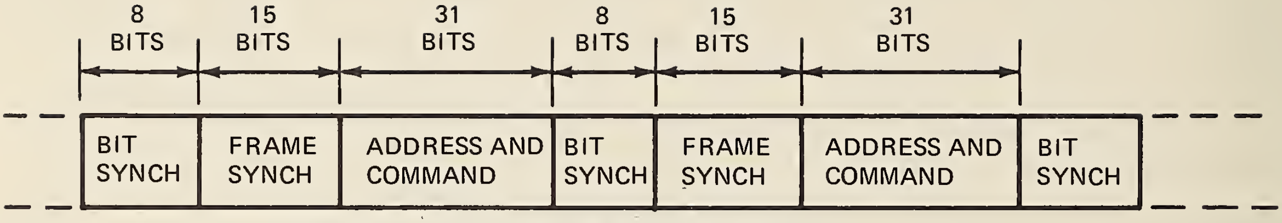
- The encoding unit which accepts and encodes the data to be transmitted and forms a composite baseband signal.
- The modulator, radio transmitter and transmitting antenna that generates, modulates and directs an RF signal toward the receiver.
- The RF transmission path having characteristics dependent upon factors such as antenna beamwidths, path length, frequency, ambient noise, etc.
- The receiving antenna system, receiver and demodulator with pre-detection or post-detection diversity combiner that accepts the modulated RF signals and delivers a replica of the transmitted baseband signal.
- The receiving decoding unit that converts the received baseband signal to its original format.

The way in which a designer chooses to exercise his options will affect directly the fidelity with which data can be transmitted over the system he designs. For digital systems, fidelity usually is characterized as a bit error rate (BER) - the average number of bits in error per unit time. The BER concept provides the designer with a convenient means for evaluating alternative approaches, for assessing their impact on the overall quality of the system, and provides a quantitative basis for determining the suitability of a proposed design for the application under consideration.

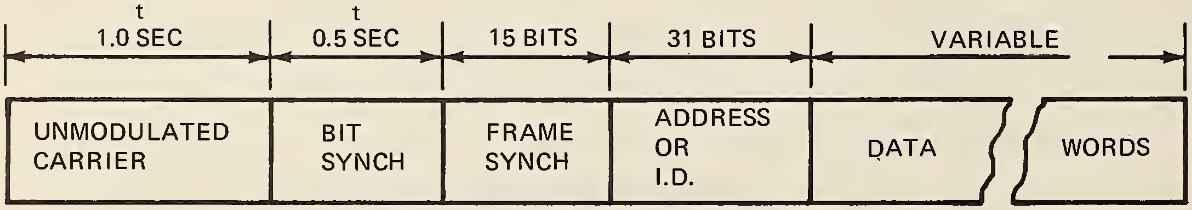
K.1.3 Message Characteristics

Message characteristics are dictated, in part, by other system parameters such as the number of intersections, interrogation rate, etc. For any system, it will be necessary to synchronize the equipment at both ends of the radio circuit. After the RF signal has been acquired and demodulated, the digital data can be processed. First, it is necessary to establish "bit synch" so that the basic timing correspondence is established. This is followed by "frame synch" which extends the timing correspondence to the word level. With the position of the digital words within the bit stream known, it is then possible to seek "address recognition" by which a specific intersection recognizes that a transmitted message applies to it. While the bit and frame synch portions of the message are not usually encoded, the address may or may not include error detecting/correcting code bits depending upon the reliability required for a specific installation. The remainder of the transmitted message contains a digital description of the commands to be executed or data to be monitored. If the transmission is from an intersection to the control center, or base station, the last part of the message would contain the data taken from the traffic signal controllers and vehicle detectors at the intersection.

Obviously, there is no requirement for the messages transmitted from the control center to be the same length as the messages sent from the intersections. In fact, the specific characteristics of the system design will determine the time duration of each message and, therefore, the required data transmission rate. One can envision, for example, computerized control of 256 intersections by a two-frequency system in which the data from the control center is transmitted on one frequency while the responses from the interrogated intersections are transmitted on the second frequency. In such a case, the message format might appear as in Figure K-1. As the signal from the control center is transmitted continuously, the problem of maintaining bit synch is not especially severe. The frame synch word might well be a 15-bit "maximal length sequence" in which the repetitive bit sequence pattern is minimized, thereby providing for positive identification



(a) TYPICAL INTERROGATION MESSAGE FORMAT



(b) TYPICAL RESPONSE MESSAGE FORMAT

NOTE: TOTAL CYCLE TIME WILL DEPEND UPON DATA RATE

FIGURE K-1. MESSAGE FORMATS

of the word occurrence. If the address/command section of the message is encoded, a (31, 21) BCH code word might be used, in that it has the capability to detect and correct up to 2 bits in error per transmission, if the bit errors occur during the address/command portion of the transmission. Given bit synch, frame synch, and address-recognition/ command-execution, it would seem that a 54-bit transmission could be sufficient for control of some 255 intersections (using 8 bits for address), with substantial flexibility in the number of commands that could be executed. As the number of required commands decreases, more of the 21 information bits in the BCH encoded portion of the message could be used for addresses, or other coding schemes providing greater reliability could be employed.

The format of the message from the intersection to the control center should allow for the anticipated differences in the sophistication of the equipment at the respective sites. Obviously, it is desirable to make the equipment at the intersections as simple as possible, consistent with the requirement for operation of an effective radio circuit. Because of the number of intersections to be serviced, cost considerations will dictate the use of minimal equipment at these points; and frequency constraints will require that the available response frequency be time-shared among the intersections. Therefore, the response message format might appear as shown in Figure K-1. Upon recognizing interrogation, the intersection transmitter might well be turned on without modulation for, perhaps, one second to allow system transients to die-out and to facilitate signal acquisition at the control center. Assuming that the response signal is phase locked to the interrogation signal, it should be possible to establish bit synch within 1/2 second, while the frame synch and address or ID bits would probably be the same as in the interrogation format. The remainder of the response format would be used for the data from the intersection detectors and controllers, and will vary in accordance with the requirements for specific systems.

Given the desirability of interrogating each intersection at least once per minute, the suggested timing allocations will require dividing the available radio frequency resources into 10 parallel channels. This "frequency division multiplexing" scheme will permit simultaneous responses from 10 intersections. A response format of two seconds per intersection allows 30 "time slots" per minute which, with 10 channels per time slot, can accommodate up to 300 intersections.

While this discussion of path, equipment and message characteristics is not intended to be exhaustive, it does at least suggest the scope of the effort required to effectively use radio signals in a computerized traffic control system. Considering the many aspects of the radio communication system, the most important factors are discussed in the following paragraphs. The criterion used to select subjects for discussion was the applicability of the topic to almost any system design of which radio communication is an integral part. Therefore, in the design example, consideration is given to the operating threshold, received signal power, and system margin.

The design procedure is based upon setting the desired signal bit error rate for the system, translating the bit error rate to signal-to-noise ratio, and then considering the cumulative attenuation effects of the equipment and the transmission path to determine the transmitter power required. On-site measurements are usually required to obtain information on anticipated sources of noise at the receiving locations. This is combined with information on the signal-to-noise ratio needed for satisfactory performance to arrive at an "operating threshold" which must be exceeded for reliable operation of the radio communication system. In addition, the "received signal power" is estimated by subtracting the computed loss of the transmission path from the effective radiated power assumed to exist at the transmitting site. The excess of the received signal power over the operating threshold constitutes the "system margin" available to compensate for the variation over time in the values of the parameters used in the analysis. A more detailed discussion of these factors is presented in subsection K. 2 below.

K.1.4 Operational and Maintenance Requirements

With regard to the operational and maintenance requirements, the system specification must invoke equipment details explicitly so that uninterrupted and error-free traffic control communications is provided at reasonable cost.

K.2 SYSTEM DESIGN EXAMPLE

K.2.1 Operating Threshold

In all communication systems, noise is the factor that determines whether or not a signal is usable for the transmission of information. In the presence of noise there is a limit to the amount of useful amplification that can be employed since both signal and noise are amplified to the same extent. Thus, it is necessary to have knowledge of the ambient noise with which a signal will compete so that sufficient power can be transmitted to override the noise. Radio noise arises from a number of sources: the thermal noise generated in the "front end" of the receiver; galactic noise from outer space; atmospheric noise from lightning discharges; and, various sources of man-made noise of which ignition noise may be the most relevant for traffic control applications.

It is customary to incorporate all of the noise sources for a specific location into a single noise figure, F_a, which represents the total noise power available in a unit bandwidth relative to the thermal noise in that bandwidth. That is, it is a noise power density. As expected, noise is frequency-dependent and location-dependent and, because of its importance, its variation has been studied extensively. Figure K-2 shows median values of the average noise power density expected from various sources as seen by an omnidirectional antenna near the surface of the earth.[2] It can be seen that, in the frequency range near one gigahertz (GHz) which is most likely to be of interest for traffic control, an F_a of 20 db above KT_0B_n* is typical with urban, man-made noise as being the most significant noise source. The figure shows, also, that this noise level is greater than the "front-end" noise of a typical receiver and, therefore, limits the advantages that can be obtained from increased receiver sensitivity.

It is especially important to be concerned with ignition noise in this application because of the proximity to, for example, stopped vehicles with idling engines awaiting a change in the traffic signal. The ignition spark of an automobile engine is a very short surge of high current (about 200 amperes) that contains significant frequency components through the UHF range, the magnitude of which decreases at a rate approximately equal to the inverse square of the frequency, or 20 db/decade.[3] Work done by the FCC for the Land Mobile Service, as shown in Figure K-3 does show that ignition noise becomes less of a problem as frequency is increased, but their measurements stopped at 450 MHz.[4] Certainly, the F_a of 20 db above KT_0B_n for 1 GHz (in Figure K-3) includes some ignition noise. Whether or not an additional allowance is required for the traffic control application is not known at this time. This is but one of several detail design problems that can be resolved best in an empirical demonstration of the radio communication system.

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2. Reference Data for Radio Engineers, 5th Ed., Howard Sams, New York, 1968, pp. 27-1 to 27-2.
3. Schildknecht, R.O., "Ignition Interference to UHF Communication Systems", IRE Trans. on Radio Frequency Interference, October 1962, pp. 63-66.
4. "Man-Made Noise", Report of the Advisory Committee for the Land Mobile Radio Services, Federal Communications Commission, 1966, p. 20.

*KT_0B_n is the thermal noise power at absolute temperature T_0 and a bandwidth B_n. K is Boltzmanns constant.

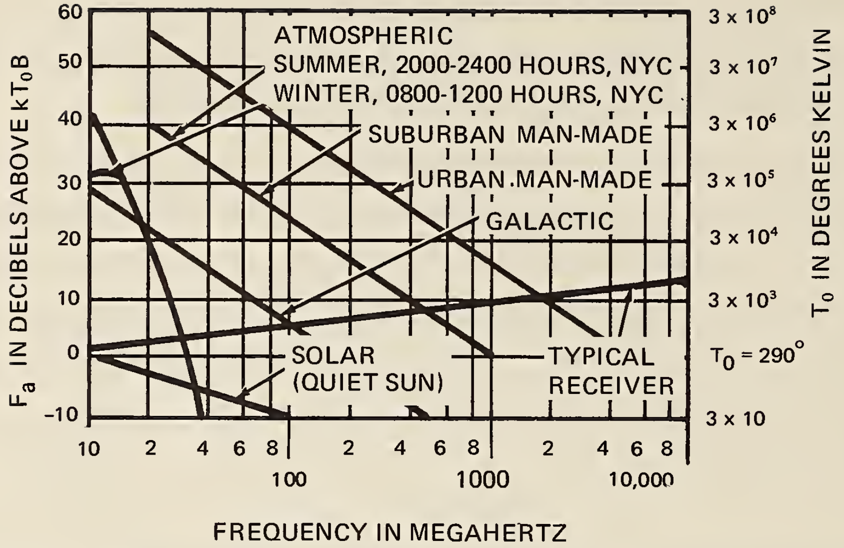
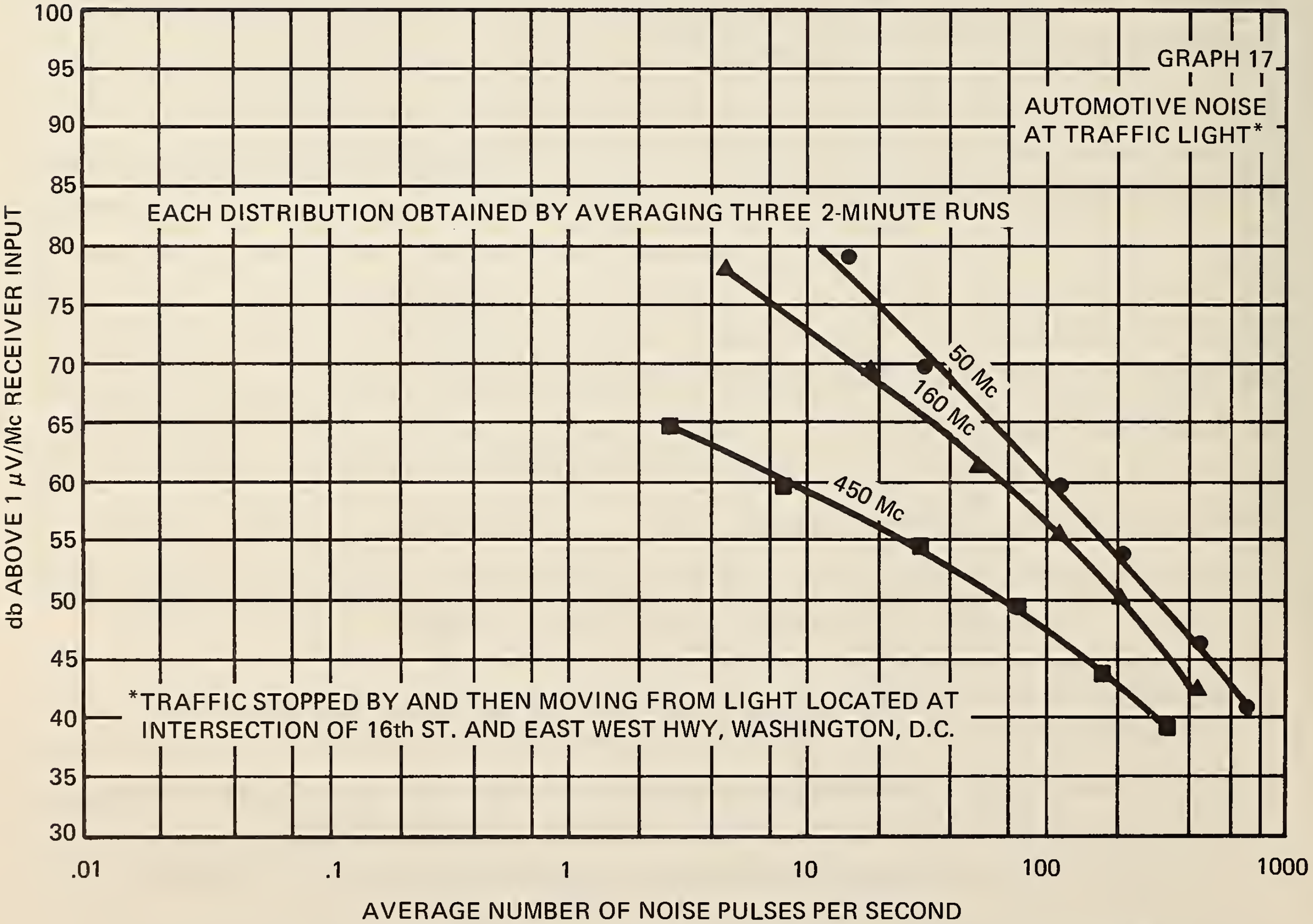


FIGURE K-2. MEDIAN VALUES OF AVERAGE NOISE POWER FROM VARIOUS SOURCES AS A FUNCTION OF FREQUENCY



EACH DISTRIBUTION OBTAINED BY AVERAGING THREE 2-MINUTE RUNS

*TRAFFIC STOPPED BY AND THEN MOVING FROM LIGHT LOCATED AT INTERSECTION OF 16th ST. AND EAST WEST HWY, WASHINGTON, D.C.

FIGURE K-3. AUTOMOTIVE IGNITION NOISE MEASURED AT TRAFFIC LIGHT AS A FUNCTION OF FREQUENCY

The operating threshold is a combination of the limiting noise power with which the system must contend, and the required signal-to-noise ratio at the chosen performance level for the baseband demodulation process designed into the system. It is neither necessary nor appropriate to select a specific modulation scheme at this time. The performance differences among the conventional approaches are too small to matter, and the ultimate selection of, for example, FSK over DPSK will be based on the peculiarities of the system being implemented. It can be shown that most baseband modulation schemes provide a BER (bit error rate) of 1×10^{-4} with signal-to-noise ratios of approximately 10 to 12 db in non-fading media.[5] Further, unless the facilities of the control center are located physically at the transmitting/receiving site, the interconnecting telephone line will limit the baseband to approximately 4 KHz. It follows, therefore, that the operating threshold P_T, for a voice-bandwidth system at 1 GHz can be represented as:

$$P_T = S/N + F_a + (10 \log B_n - 204) \text{ dbw}, \tag{K-1}$$

$$P_{T(4\text{ KHz})} = 12 + 20 + (10 \log 4{,}000 - 204) \text{ dbw}, \tag{K-2a}$$

$$= 12 + 20 + 36 - 204, \tag{K-2b}$$

$$= -136 \text{ dbw} = -106 \text{ dbm}. \tag{K-2c}$$

(Note that because the formulas use logarithms, the + and - symbols signify multiplication and division respectively.)

The number 204 is the expression, in db relative to 1 watt per hertz, of the thermal noise power density, KT_0, and serves to normalize the selected bandwidth so that it can be combined with the other power density factors in computing the total operating threshold in dbw or dbm. For our immediate purposes it is sufficient to note that a traffic control system using baseband-modulated binary radio (operating in a non-fading propagation medium) will probably have to be designed for an operating threshold of - 106 dbm. That is, the signal available at the terminals of the receiving antenna must exceed this amount for satisfactory operation.

K.2.2 Received Signal Power

The "strength" of a signal received at a particular location is a function of its mode of propagation, the distance it has traveled, the degree of absorption along its path, path

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[5] Panter, P. F., Modulation, Noise and Spectral Analysis, McGraw-Hill, New York, 1965, Chapter 23.

focusing and polarization affects, and the relative phase of the several components of the received signal. Some insight into the many factors involved in this problem can be gained through consideration of the System Loss concept described in the International Radio Consultative Committee (CCIR) Recommendation 341.[6]

In essence, the system loss for a radio communication system is the difference between the power put into the terminals of the transmitting antenna and the power available at the terminals of the receiving antenna. As shown in Figure K-4, the total system loss has two basic components - the losses associated with the antenna systems (both transmitting and receiving); and the path losses. The first category includes the ohmic losses in the transmission lines and antennas, the antenna efficiency, which indicates the amount of power radiated into space relative to the amount absorbed from the source, and the gain of the antenna, whereby it radiates power in one direction more than another. The path losses include the spatial spreading of the radiated energy, absorption of this energy by electronic collisions in the troposphere; and signal enhancement or diminution resulting from the multipath environment typical of urban areas. The path losses are time variant and should be treated statistically. The other system losses are essentially time invariant and, being equipment related, lend themselves to reasonable estimates based on the performance of similar systems. Given the availability of information on equipment-related losses, the emphasis here will be on those components of the system loss related to the path losses - specifically, losses determined by range and mode of propagation.

The process by which energy is propagated is frequency-dependent and sufficiently complex to preclude in this work a detailed analysis of all of the factors likely to be involved in any given situation. Even with consideration restricted to frequencies near 1 GHz, the complexity still is too great to be treated comprehensively. Nonetheless, there are aspects of the situation that can be discussed with a view towards estimating the minimum losses likely to be encountered.

The most fundamental aspect of the path losses is the spatial spreading of the radiated energy. This is the so-called free-space transmission loss, L_b, and represents the loss that would be anticipated in transmission through a region free of all objects that might absorb or reflect radio energy. It is measured as the difference between the power passing

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[6] "The Concept of Transmission Loss in Studies of Radio Systems", Spectrum Utilization & Monitoring, Volume I, New Dehli, 1970.

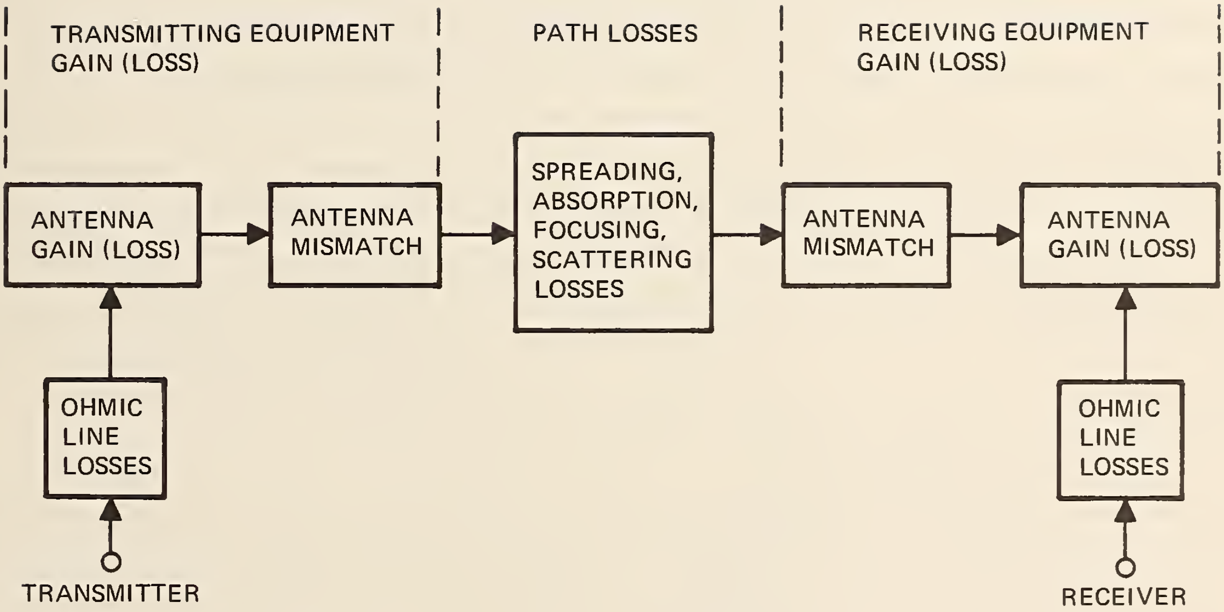

FIGURE K-4. BASIC COMPONENTS OF SYSTEM LOSS one reference point relative to the power passing a second reference point. The underlying concept is, essentially, the inverse square law of optics applied to radio transmission. It follows that the basic transmission loss at a distance d can be represented by:

$$L_b = 10 \log P_r/P_t. \qquad \text{(K-3)}$$

Note that this aspect of the path loss is not an energy loss in the dissipative sense. The ratio P_r/P_t is a comparison between the energy intercepted by the area of a non-directive (isotropic) antenna to the total energy radiated. The total energy radiated from an isotropic source, as seen at a distance d from the source, is proportional to the area of a sphere of radius d since the energy is radiated equally in all directions. With P_t = area of sphere = $4\pi d^2$ and P_r = effective area of an isotropic receiving antenna[7] = $\lambda^2/4\pi$, where λ is the wavelength, the transmission loss becomes: $L_b = 10 \log P_r/P_t$ $= 10 \log \lambda^2/(4\pi)^2 d^2 = 20 \log \lambda/4\pi d$, with the wavelength of the energy "λ" measured in the same units as the distance "d". An alternative form of this equation is:

$$L_b = 36.6 + 20 \log f + 20 \log d, \qquad \text{(K-4)}$$

with "f" being the frequency in MHz and "d" the distance in miles. These equations show, upon examination, that the free space loss over a distance equal to one wavelength of the transmitted energy is 22 db, with a 6 db increase each time the distance is doubled. For a distance of 15 miles (24 km) at a frequency of 1 GHz, the loss will be approximately 120 db. If directive antennas are used instead of isotropic antennas it is necessary to allow for the power gain they introduce.

If free space propagation losses alone were to be considered, the received signal power would be determined simply by computing L_b. To obtain an operating threshold of - 106 dbm, a path loss of 120 db (1 GHz, 15 miles (24 km)) would imply the need for an effective transmitted power of + 14 dbm, or approximately 25 milliwatts. In an urban area, especially for a traffic control application, a line-of-sight path for which this basic transmission loss would be applicable is, more often than not, unobtainable. It establishes an upper limit for the received signal dynamic range, and it must be accommodated by the receiver without introducing excessive distortion.

For most locations in an urban area, the principle modes of microwave energy propagation are reflection and diffraction. As it is extremely difficult to distinguish one mode

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[7] Jasik, H, Ed., Antenna Engineering Handbook, McGraw-Hill, New York, 1961, pp. 2-14 to 2-15.

from the other, it is common to lump the losses from each mode into one and call them "scatter" losses. Given the multiple scattering of the radio energy from the many buildings and other structures in the vicinity of the traffic signal heads, it is necessary to have recourse to statistical communication theory in order to predict analytically most of the observable properties of such a radio circuit. Fortunately, a great deal of work has been done in this area, and analytical models exist that correlate well with empirical measurements.

Without providing the technical details, it can be stated that the path losses in a highly built up urban area are a function of the distance between the transmitting and receiving antennas, their heights above ground, the frequency used, and the way in which the streets are oriented. The last factor is important because, within a city, buildings tend to channel energy parallel to the streets and strongly influence path losses. Radio propagation in the microwave region also undergoes attenuation as a result of the presence of rain, snow, and fog. These losses depend upon the frequency used and the amount of moisture in the path. Above 10 GHz, specific allowance for increased attenuation due to precipitation is mandatory. At 1 GHz, precipitation of 100 millimeters/hour (4 inches/hour) introduces an additional attenuation of less than 0.01 db per kilometer (0.016 db/mile), and for our purposes can be ignored.[8]

The channeling effect of buildings obviously depends upon the way in which the streets of a specific city are laid out. As this factor does not lend itself to generalization, its existence is simply noted. With regard to the distance between the antennas and their respective heights, much useful information is available. As we are interested in the minimum losses likely to be encountered in a computerized traffic control system the empirical results obtained by other workers in this field can provide some valuable insights.

Figure K-5 is a plot of the received signal power versus distance as measured by independent workers in three different cities - New York, Philadelphia, and Tokyo.[9] All of the measurements were made at approximately 900 MHz from relatively high "base station" locations shown in the figure as h_t. The remarkably consistent trend of not only the fall-off

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8. Hagg, D.C., "Statistics on Attenuation of Microwaves by Intense Rain", Bell System Technical Journal, No. 48, November 1969, p. 2949.

9. Rendink, D.O., "Large-Scale Variations of the Average Signal", Microwave Mobile Communications, (W.C. Jakes, Jr., Ed.), John Wiley & Sons, New York, 1974, Chapter 2.

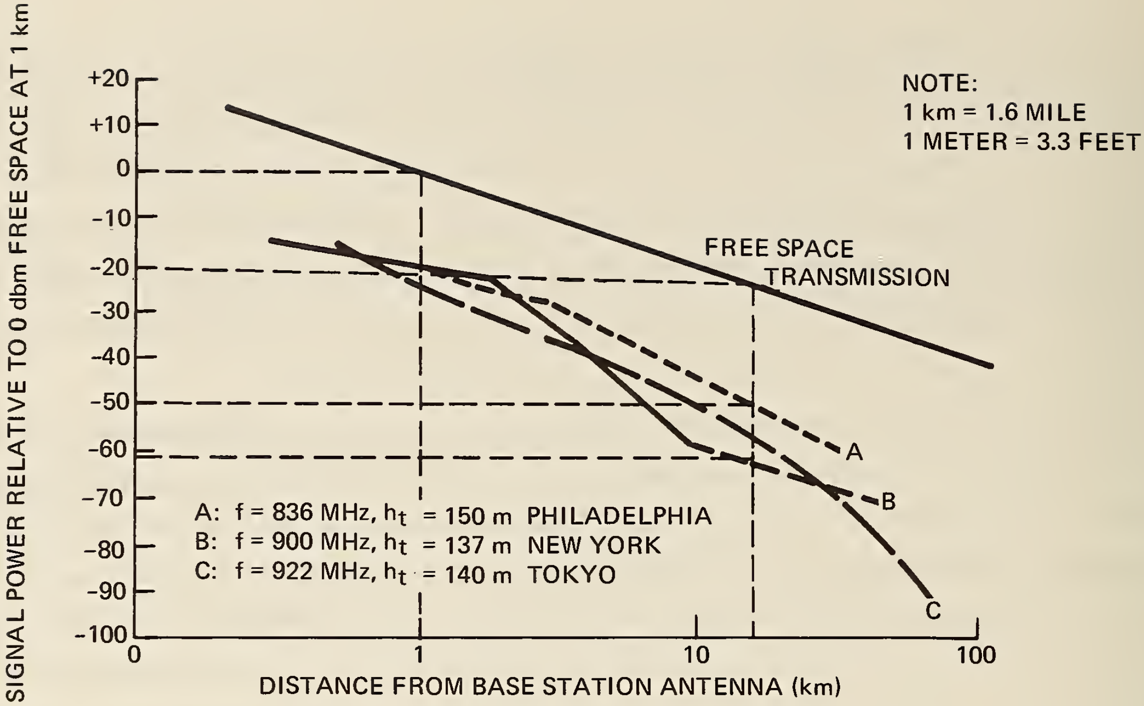

FIGURE K-5. VARIATION OF RECEIVED SIGNAL POWER WITH DISTANCE

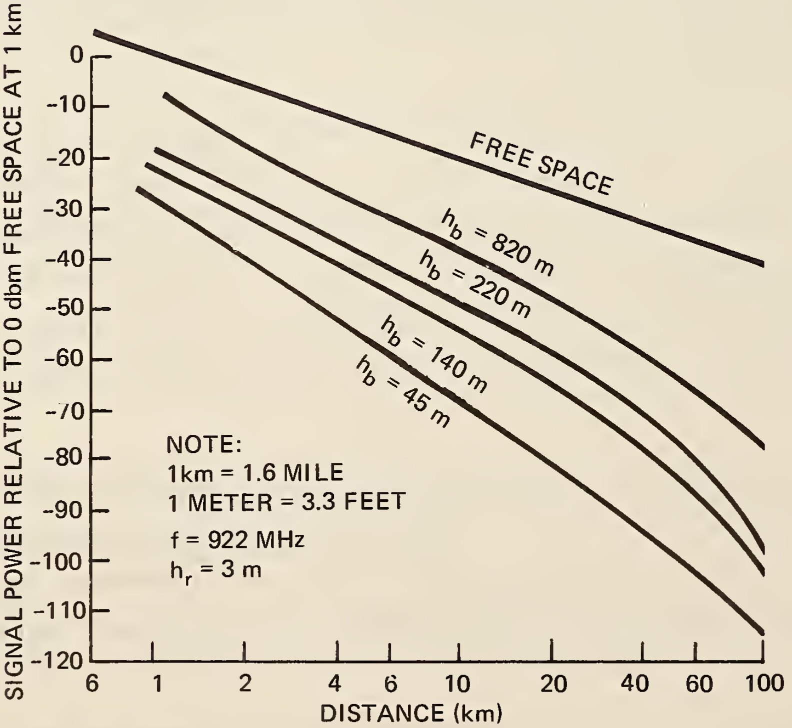

FIGURE K-6. VARIATION OF RECEIVED SIGNAL POWER WITH HEIGHT OF TRANSMITTING ANTENNA of the median signal level with distance, but also the additional attenuation relative to the free space transmission loss serves to encourage the hope that these signal strength characteristics can be applied to many different cities. Figure K-6 shows median field strengths for various antenna heights in an urban area.[9] The rate at which the received signal decreases with distance does not appear to change significantly with increasing antenna height, listed in the figure as h_b. However, raising the base station antenna does tend to decrease the additional attenuation relative to the free space transmission loss - the higher the antenna, the lower the total transmission loss. The results in both figures are based on a receiving antenna height of 3 meters (10 feet). While antennas mounted on the traffic signal poles will be somewhat higher, the difference in performance is not likely to be significant.

In order to continue this discussion of a "typical" application, the data in Figure K-5 will be used. From this figure it can be assumed that the median received signal power at a distance of 15 miles (24 km), with traffic control center transmitting and receiving antenna located at a height of approximately 145 meters and an intersection antenna height of at least 3 meters for a frequency near 1 GHz will be 30 to 40 db less than that expected for a free space transmission loss of 120 db. That is, the received signal power will probably be 150 to 160 db less than the effective radiated power. Given an operating threshold of - 106 dbm, the transmitted power is required to be on the order of + 50 dbm or 100 watts. The empirical results referred to in drawing this conclusion show also that for antenna separation distances greater than 40 km (64 miles), the signal attenuation increases at a rapid rate.

K.2.3 System Margin

In subsection K.2.1 an operating threshold of approximately - 106 dbm was established for a radio circuit to be used in a computerized traffic control system, assuming the use of a binary-modulated 4 KHz baseband and a non-fading medium. The figure was based on the use of a 12 db signal-to-noise density ratio with which most binary baseband modulation schemes provide a bit error rate (BER) of approximately 1×10^{-4} in a non-fading medium, and an ambient noise figure of 20 db above KT_0B_n typical of urban, man-made noise near the frequency of 1 GHz. It was mentioned that, for this traffic control application, ignition noise may well require more detailed treatment in the circuit calculations for an actual system.

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[9] Ibid.

In subsection K. 2. 2, recognizing the probability of utilizing a scatter mode of propagation in an urban area, the conclusion drawn was that the minimum path loss at a distance of 15 miles (24 km) was likely to be 30 to 40 db greater than the free-space transmission loss of 120 db for that distance at a frequency of 1 GHz. By combining the required operating threshold of - 106 dbm with a path loss between 150 and 160 db, the conclusion was drawn that an effective radiated power of approximately 100 watts would be necessary for satisfactory operation of the system as described.

This section indicates the method of determining the system margin, that is, the excess of the received signal power over the operating threshold which is available to compensate for variations over time of the parameters used in the analysis. When combined with the number of variables that can be introduced by the characteristics of each city in which the traffic control system might be used, it is obvious that a definitive solution cannot be provided on a generalized basis. Here, again, it is possible only to provide highlights on a few topics that are relevant to all potential radio systems. What follows includes a brief discussion of modulation characteristics of the radiated energy, means for coupling the energy to be radiated into the propagation medium, and the use of diversity techniques to maximize the received signal power.

Even if the transmitted signal is an unmodulated carrier, the received signal envelope, because of the multipath propagation caused by buildings and structures, exhibits extreme variations in amplitude. Basically, the same signal arrives at the receiving point over paths that differ in length and, therefore, at slightly different moments in time. The signals can arrive with phase relationships that cause signal cancellation or enhancement, depending upon the path length. In any case, the rapid fading exhibited by the signal is sufficient to preclude the selection of amplitude modulation (either double sideband or single sideband) as an RF modulation choice. This is so because the AM approach is based on varying the amplitude of the radio carrier as a function of the variations in the amplitude of the signal representing the intelligence to be transmitted. It is not practical to attempt to distinguish the amplitude variations introduced by the path from those of the signal. This leaves only pulse modulation or angle modulation as potential candidates.

The pulse modulation approach is based on sampling the signal representing the intelligence to be transmitted at discrete intervals and converting the information obtained into variations in a train of pulses of the radio carrier energy. At the receiving end of the system, the variations in the pulse train are used to reconstruct the modulating signal.

In other words, the transmitted energy is grouped into certain chosen intervals and the modulation is carried by changes in location, amplitude, number, duration, or shape of the energy-containing intervals. There are many advantages to pulse modulation systems, especially their error performance at reasonable signal-to-noise ratios. However, there are many disadvantages as well. For example, the pulse modulation approaches are less efficient users of the frequency spectrum than other modulation techniques. Perhaps more importantly, in the traffic control application, this approach would probably increase the cost and complexity of the equipment located at the intersections because of the stringent timing demands that must be observed for satisfactory operation.

It is most likely, therefore, that some form of angle modulation (frequency modulation or phase modulation) will be the optimal choice for this application. In frequency modulation, the frequency of the transmitted radio signal is varied as a function of the modulating signal. The rate at which the frequency is changed is controlled by the frequency of the modulating signal, and the amount it is changed is controlled by the amplitude of the modulating signal. The primary difference in a phase modulation system is that it is the rate at which the modulating signal's amplitude changes which determines the amount of carrier frequency change. As the traffic control application will use a binary modulating signal, the transmitted spectra for frequency modulation or phase modulation will be sufficiently similar that it is not necessary to choose between them at this time.

Given the selection of angle modulation as the preferred technique, it is useful to consider means for coupling energy into and extracting it from the propagation medium. As mentioned previously the radio environment with which we are dealing is typified by a multiple scattering process. Further, the presence of buildings and other structures can be expected to significantly modify the free-space gain patterns of conventional antennas. Therefore, the need in a system implementation is to tailor the antenna design to the statistical nature of the particular radio environment, and no useful purpose would be served here by concentrating on specific antenna designs. The intersection antennas for a system using a radio frequency near 1 GHz will probably occupy less than one cubic foot of space and will be unobtrusive.

From the point of view of "system margin" the total path antenna gain reduces the path transmission loss and increases the received signal power. The total path antenna gain is the sum of the transmitting antenna gain and the receiving antenna gain. The calculations for basic transmission loss, L_b, were based on the use of isotropic (non-directive) antennas that do not exhibit gain in any direction. Therefore, whatever antennas are selected, they can be expected to improve the system margin by reducing the path loss. For example, if the control center antenna provides a gain of 10 db and the intersection antenna provides a gain of 3 db, the path loss has been reduced by 13 db. Also, if it is possible to use a directive antenna at the control center, it is possible that the operating threshold on the radio link from the intersection may be lowered if the antenna's directivity discriminates against noise sources in the control center area. As mentioned previously, there is significant advantage to be gained by having the transmitting antenna as high as practical. As this is a well-known fact, one can expect a cluster of radio services with their associated transmitters to be located in, for example, the top floor of one of the highest buildings in the city. The proximity of many such services provides significant opportunities for mutual interference and, therefore, must be considered in designing the system.

As a final point in this area, consider that the radiated energy has both electric and magnetic field components, and that the received signal strength can be expected to vary considerably over distances of a few wavelengths (the wavelength at 1 GHz being approximately 1 foot*). These factors suggest that diversity techniques should be considered as a means for improving the system margin. The advantages of such techniques have been known to the designers of radio systems for decades. The diversity method requires that several transmission paths be available, each carrying the same intelligence but having independent fading characteristics. The mean signal strengths of the paths should also be approximately the same. Proper combination of the signals from the separate paths yields a resultant signal with greatly reduced severity of fading and correspondingly improved reliability of transmission.

The oldest method of diversity was accomplished by transmitting from a single antenna to multiple receiving antennas. The separation between the receiving antennas was made large enough to ensure independent fading characteristics, and the approach is called "space diversity". This technique has found many applications over the years and is in wide use in a variety of present day microwave systems. It is simple to implement and the method utilizes the frequency spectrum efficiently.

If the frequency resources are available, one can transmit the same signal on different frequencies as a means of achieving independent diversity branches. The frequencies must be sufficiently separated so that the fading associated with the different frequencies is

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*1 ft = 0.3048 m

uncorrelated. The advantage of "frequency diversity" is the need for only one multiple-tuned antenna at each end of the radio path. On the other hand, this method does require that more frequencies be made available from a very limited spectrum and that a separate transmitter be provided for each diversity branch.

A third approach is called "time diversity". It is clear that sequential amplitude samples of a randomly fading signal, if separated sufficiently in time, will be uncorrelated with each other, thus offering another alternative for realizing diversity branches. The required time separation is at least as great as the reciprocal of the fading bandwidth which may imply the need for storage of received data in order to facilitate comparisons between successive samples. However, considering the propagation mechanisms that are at work, the received signal power level would not be expected to change significantly during the time interval available for use in the traffic control application. Therefore, it is not obvious that time diversity will provide significant advantages in a 256 intersection system that interrogates each one at least once per minute. It seems, therefore, that space diversity is probably the best choice for use at the intersections. For systems in which the antenna supporting structures at an intersection are separated by 10 feet (3 m) or more, satisfactory diversity operation can be obtained, assuming that the carrier frequency is near 1 GHz.

With all approaches, the signals from the diversity paths must be combined. There exist three fundamental combining methods: selection of the strongest signal at a given instant in time; summing the signals in proportion to their respective signal voltage to noise power ratios; or summing the signals after the gains of each diversity branch have been made the same. These approaches are called "selection", "maximal ratio", and "equal gain" diversity, respectively.

One advantage of diversity operation is shown by comparison with the fading characteristics of a single channel system. It can be shown that, for the fading statistics typical of those to be expected in this application, the maximal ratio and equal gain techniques each provide an improvement in average signal-to-noise ratio of 3 db, while selection diversity provides approximately 1.75 db improvement.[10]

It is more instructive to consider the improvement in transmission reliability obtained through use of diversity techniques. Any of these approaches, for poor signal-to-noise

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[10] Brennan, D.G., "Linear Diversity Combining Techniques", Proceedings of the IEEE, June 1965, pp. 1095-1102.

ratios, can provide improvements on the order of 20 db for a two-path system over a non-diversity approach.[10] Obviously, as the signal-to-noise ratio improves, the signal strength at each antenna improves also, and the advantages of diversity operation are less pronounced and less necessary. Our concern, of course, is with the worst-case situation and, therefore, the use of space diversity seems to be the most desirable. Considering the relative complexity of the equipment needed to implement the combining methods discussed, and the desire to minimize the complexity of the equipment at the intersections, selection combining of the space diversity signals seems to be the most logical choice for the intersection end of the radio circuit.

It does not follow, however, that this particular combination is the most suitable for the control center end of the radio path. As we are dealing with only one control center the cost penalties associated with the use of more efficient and more complex equipment are less significant and, for example, the choice of the most appropriate combining scheme can be made on a purely technical basis. There are fewer options when it comes to choosing the diversity method to be used at the control center. As stated previously, the primary requirement for effective diversity action is that the characteristics of the signals in the several paths be uncorrelated. At the intersections, because the signals arrive from all angles, the propagation delays introduced by the different paths are sufficient to decorrelate the signals for space diversity antennas that are relatively close to each other. The antenna at the control center will probably be elevated above most local reflectors. Therefore, a small spatial separation of the diversity antennas will not be sufficient to produce the desired decorrelation of the received signals. On the assumption that frequency and time diversity still are not acceptable alternatives, other means for improving system margin must be sought.

It is possible that polarization diversity might provide the separate paths needed for the intersection to control center portion of the radio circuit. In this mode of operation antennas are used which maximize the response from either the electrical or magnetic components of the radiated energy. Recent work[11] at 836 MHz showed that received vertically and horizontally polarized signals were uncorrelated, and that the average signal strengths of the two polarizations were within ± 3 db about 90 percent of the time. This

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[10] Ibid.

[11] Lee, W.C.Y. and Yeh, Y.S., "Polarization Diversity Systems for Mobile Radio", IEEE Trans. Comm., Cm-20, No. 5, October 1972.

result suggests that polarization diversity could be an attractive means for achieving two diversity branches without excessive requirements on antenna spacing at the control center.

In any case, it is probable that some form of diversity operation will be required at both ends of the radio path in order to insure that the system margin is sufficient to provide reliable operation of the traffic control system over the wide range of conditions that are likely to be encountered.

APPENDIX L

POWER LINE COMMUNICATION TECHNIQUES

L. 1 INTRODUCTION

This appendix addresses the feasibility of using power line communication (PLC) techniques for traffic control system data communication purposes. Such techniques have been used by utilities for many years principally for remotely controlling portions of the transmission system.

In recent years, renewed interest has resulted from a desire to employ more extensive control and a two-way information network in the power distribution system for such purposes as remote meter reading and remote load control. These requirements, which generally require low data rates relative to computer traffic control systems, have led to a number of products as well as to studies and demonstrations.

In this study, we have attempted to use this body of knowledge and experience to determine:

- if systems and techniques are currently available which are useful for traffic signal control applications;
- if there are fundamental technical problems which limit the usefulness of PLC for traffic signal control; and
- if there are institutional or other problems which may similarly limit its usefulness.

L. 2 GENERAL COMMUNICATIONS REQUIREMENTS FOR COMPUTER TRAFFIC CONTROL

L. 2. 1 <u>General</u>

As existing power line communications technology tends to be centered around system applications which require low information rates, a study was undertaken to quantify the communication rate requirements for traffic control. In particular, two types of system architecture were considered: a centralized architecture (central computer which communicates directly with curbside controllers) and a distributed architecture using field microprocessors. Figure L-1 summarizes the ranges of communication requirements estimated in this study. The ordinate of this figure depicts the information rate requirements for a specified number of controllers, all of which are interconnected by a single power line communication facility. The basis for the development of these requirements is described in the following sections.

L. 2. 2 Centrally Organized System

A representative example of the data communication requirements for a UTCS type system is given by the communications specifications for the Metro-Dade County traffic control system. In this system the following information is communicated between the intersection and central office each second.

Information from central office to intersection

Intersection address: 3 bits
Standby commands: 3 bits (synch. offset 2, offset 3)
Control data: 5 bits (hold, adv, test, flash, skip)

Information from intersection to central office

Data from 2 detectors @ 5 bits each	10 bits
Four signal states	4 bits
Flasher	1 bit
Preempt	1 bit
Total	27 bits

The Metro-Dade TDM communications system operates eight intersections from each central communication module. The transmission to and from each intersection requires 43 milliseconds (ms) at a bit rate of 1,500 Hz. Thus eight transmissions require 344 ms of transmission time per second. Slightly less than 50 percent of this transmission time is used to communicate traffic information. The remainder is required for the modem self synchronization and intersection identification processes.

If system architectures enabled communications systems of this sort to utilize 100 percent of the TDM transmission time cycle profitably, approximately 628 bits of useful traffic information could be transmitted each second with this scheme on the duplex voice grade telephone line which is assigned. *

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*The "dead time" in the Metro-Dade TDM communications cycle resulted from system design decisions which related to issues other than the communications system.

The upper boundary of the information region for centrally organized computer systems in Figure L-1 is based on the Metro-Dade system's traffic rate requirements (which are quite representative of centrally organized computer systems using conventional controller technology and software similar in requirements to first or second generation UTCS). The lower boundary for this region estimates the information rate requirements based on a somewhat reduced intersection information requirement (with a corresponding reduction in system capability).

L.2.3 Distributed Microprocessor Organization (DMO)

Recent advances in microprocessor techniques have been responsible for developing increased interest in distributed processing concepts for traffic control. From a communications viewpoint these techniques will, generally speaking, reduce the bit rate requirements below those required by the centrally organized system. While the frequency of communication between the intersection and the next higher level of computation may be much slower for the DMO, the potential variety of information to be communicated may be much greater (however, all types of information may not be required with each transmission).

This type of system has generally a greater degree of functional flexibility (operational modes, phasing changes, etc.) than centrally organized systems. Because of this and the relatively early stage of design and development for these systems, no authoritative design consensus is currently available for these systems. Nevertheless, if one considers a DMO which has the potential of achieving a high level of intersection capability and flexibility, communication for the following functions will be required:

- Formats to describe which information groups are to be transmitted.
- Selection of many alternative modes and alteration of phase options in each controller ring.
- Time-of-day data and synchronization.
- Timing pattern transmission.
- Test commands and responses.
- Detailed monitoring of data stored at intersection.
- MOE's computed at intersection.
- Enhanced intersection failure reports.

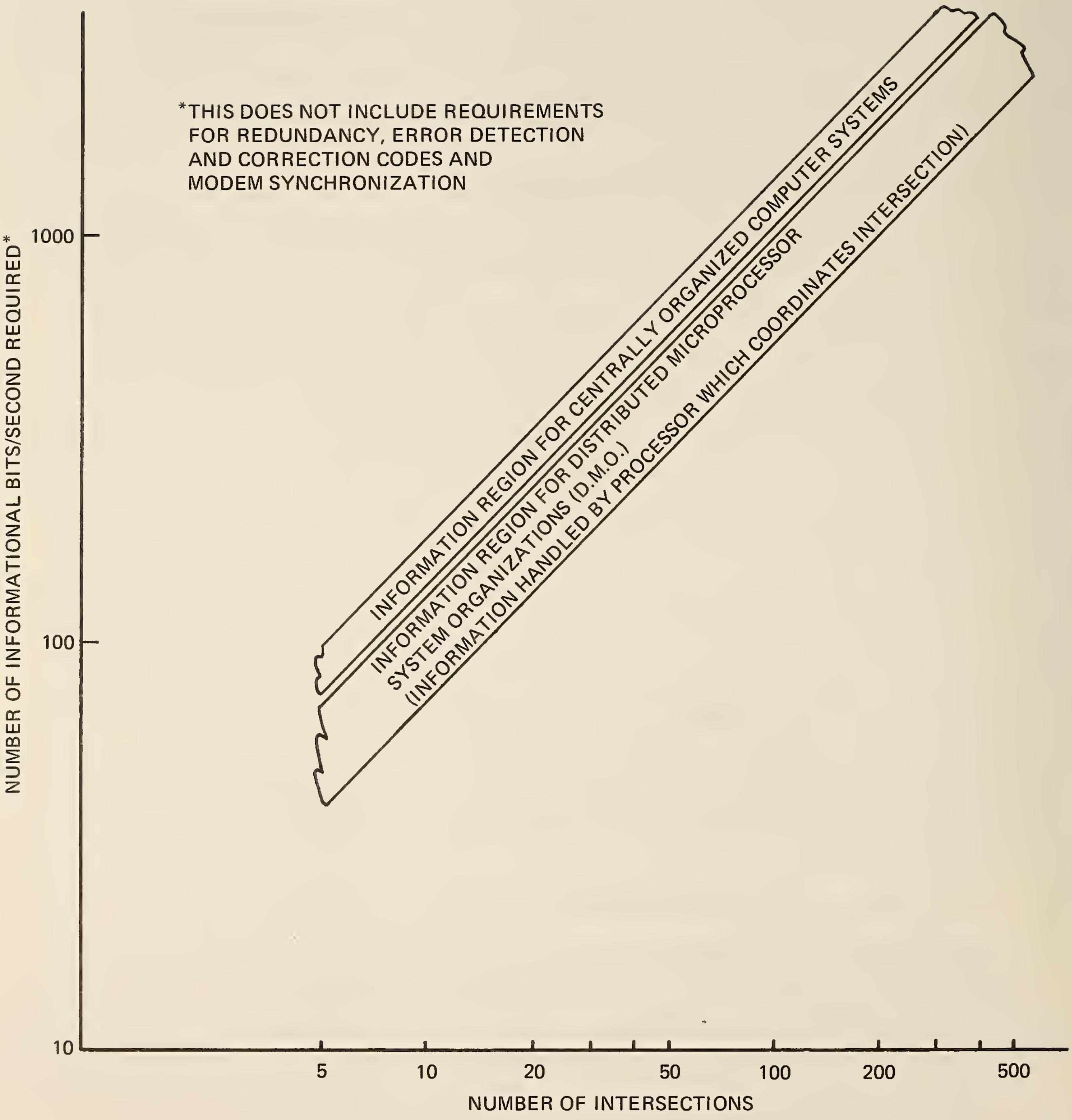

FIGURE L-1. INFORMATION RATE REQUIREMENTS

Under an internally funded research development program, SSM has studied the detailed requirements for a DMO traffic control system which implements UTCS first generation software and which provides the capability to control up to 8-phase intersections in a way which is consistent with NEMA specifications.

Of interest to the current program is the fact that fifty intersections in this DMO organized system can be controlled with a single voice grade telephone channel pair operating at 1,800 bits per second for fifty seconds out of each minute. Four detectors per intersection can be accommodated.

The equivalent modem bit rate for each controller in this system is:

$$\frac{1800}{50} \times \frac{50}{60} = 30 \text{ bits per second.} \qquad \text{(L-1)}$$

To simplify comparison with the previously described centrally organized system, the following compensations were made:

- Redundancy was removed from the data transmission.
- Reduction of the average detector complement from four per intersection to two per intersection.

The resulting represents the traffic information demand for a sophisticated DMO system. It is plotted as the upper boundary of the DMO region of Figure L-1.

The DMO system studied by SSM contains a considerable number of functions which may be eliminated or reduced in scope by alternative design concepts. Some additional communication efficiency may be possible by the use of alternative microprocessors software. Based on these possibilities, the lower boundary of the DMO region of Figure L-1 was taken as .5 times the upper boundary.

L.3 COMMUNICATION OVER POWER DISTRIBUTION SYSTEMS

L.3.1 Media Characteristics

The following communication properties are relevant to using power distribution systems for communication purposes:

- Signal attenuation.
- Noise.
- Pulse delay and pulse distortion.
- Other signal propogation problems.

L.3.1.1 Signal Attenuation

Signal attenuation results from three distribution system components, lines, distribution transformers, and power factor correction capacitors.

Figure L-2 shows representative line attenuation characteristics.[1] At frequencies above 10 KHz, shunt capacitors must usually be compensated by a parallel tuned LC circuit. Distribution transformers are difficult to model at frequencies above the audio range. Generally, input impedance measured at the primary is capacitive, and usually ranges in the hundreds of ohms. Signal voltage attenuation from primary to secondary may range from 10 to 70 db in the 30 to 100 KHz band. A representative value of secondary to primary attenuation is 30 db at these frequencies. As the frequency increases, the change in input impedance with load becomes less sensitive.

Figure L-3 depicts a representative set of measurements taken on a 27 KV feeder in Queens, N.Y. by Consolidated Edison of N.Y. Inc.[2]

While Figures L-2 and L-3 are "representative", other measurements and data exist which report widely different properties as a function of frequency and network configuration, and it is emphasized that attenuation values, particularly for frequencies above 10 KHz vary widely with the configuration of the distribution subsystem (layout, capacitors, transformers).

L.3.1.2 Noise Characteristics

Power line noise is extremely difficult to model.[3] Variations in noise amplitudes may extend through a two order of magnitude range and are typically caused by SCR's and triacs controlling motors, as well as all other load sources, the antenna coupling effects of the distribution line, and the line condition (leaking insulators, proximity to trees, etc,)

Reference 4 states that minimum bit transmission periods of 1 to 2 milliseconds are required (in conjunction with high Q circuit filtering). Thus, the upper limit on traffic information transmission rate appears to be in the range of 250 to 500 bits per second.

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1. Cook, R. F., Adams, R.P., Whyte, I.A. - "Developing a Communication System for Automated Distribution," Westinghouse Engineering Jan 1975, pp. 12-14

2. DiDonato, J.P. and Pritchard, P., "Remote Monitoring of Network Equipment," IEEE 1974 Underground Transmission and Distribution Conference, pp. 610-615.

3. "Automatic Meter Reading & Control System Phase I Study," Arthur D. Little Inc. - November 1973.

4. "The Automated Distribution System: An Assessment of Communication Alternatives," Vol. I, Sept. 1976, MITRE Corporation.

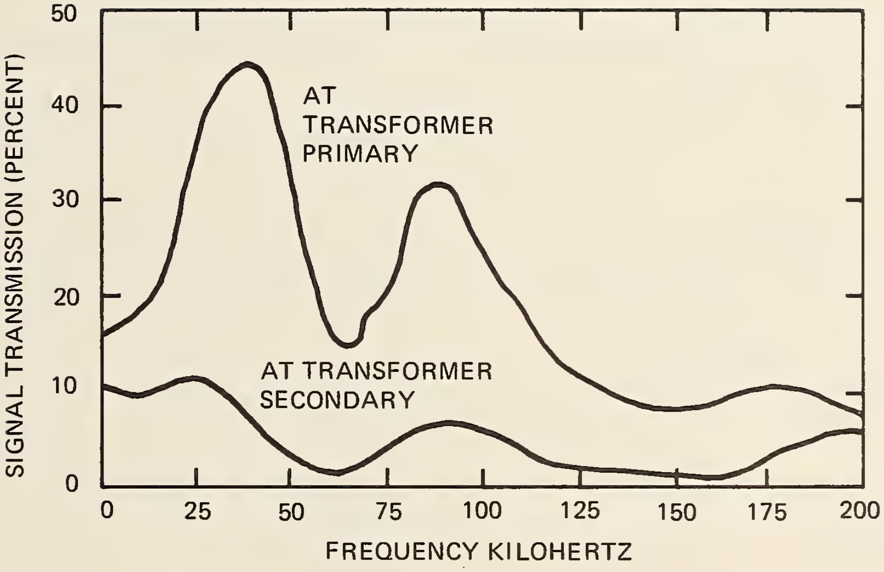

FIGURE L-2. SIGNAL TRANSMISSION PER MILE ON OVERHEAD DISTRIBUTION LINE

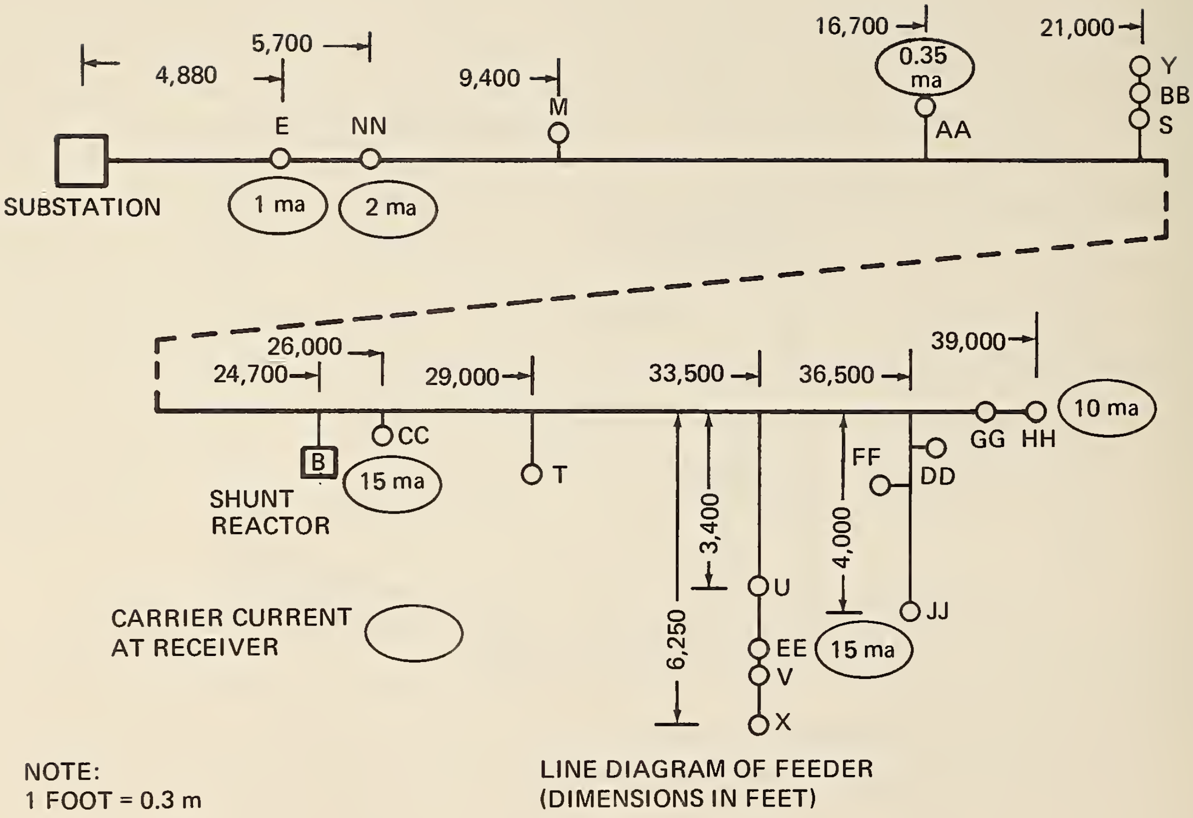

FIGURE L-3. TRANSMISSION CHARACTERISTICS OF REPRESENTATIVE FEEDER AT 100 KHz

Attempts to mathematically model the process are difficult because of the continual reconfiguration of the communication properties of power distribution systems.

Reference 1 states that typical noise values are in the range of 300 to 400 microvolts per KHz at 100 KHz, and between 1 and 20 millivolts per KHz at 20 KHz. Assuming that bit rates used by the PLC are sufficiently low (say under 200 bits per second) and pulse transmission durations are sufficiently long, transmission can generally be accomplished at signal levels obtained from acceptable power sources, and a number of demonstrations of the technology have been performed by various manufacturers and utilities at these data rates.

L.3.1.3 Pulse Delay and Pulse Distortion

A power distribution network may contain several paths of different lengths by which a communication signal could conceivably propogate between two points. The different path lengths may result in different transmission times, thus a new pulse cannot be received until the old pulse has completely terminated (by all paths). In addition, transmission line distortion may further serve to lengthen the pulse. The sum total of these effects is to provide an additional potential limitation to the allowable data rate under certain network configurations.

One approach to mitigate this effect is described in Reference 5. In that reference, the received pulse duration is measured and the transmission rate is modified accordingly.

L.3.1.4 Other Signal Propogation Problems

At frequencies above 10 KHz, impedance mismatches may cause reflections which result in signal nulls at certain locations. This can be countered in a particular application by carefully tailoring the system or more generally by the use of spread spectrum techniques.

The first technique requires a careful analysis of all of the possible variations caused by changing loads and power factor correcting capacitors. Such an approach would not only engender increased costs which may be unacceptable in the design costs but may also decrease the effective reliability of the system to a level which may be unacceptable.

If the second approach, spread spectrum techniques, were to be used, it would reduce the possibility of employing multiple channels on the same transmission facility in addition to raising the communication system cost.

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5. Lusk, et al, "Meter Interrogration System Having Strobe Logic Control, "U.S. Patent 3733586.

L.3.2 State-of-the-Art Survey

A survey was made of the capabilities currently claimed for power line distribution system communications by organizations working actively in the field. The data, summarized in Table L-1 was obtained from technical reports, manufacturers' literature, and through personal communications.

L.3.3 General Requirements for Organizing a PLC System for Computer Traffic Control Applications

L.3.3.1 Organization of Urban Power Systems

Power systems in areas which are most likely to use computer traffic control systems (central cities and suburban areas) may generally be characterized as shown in Figures L-4 and L-5. The power line communications which have been considered for this purpose operate entirely in the primary and secondary power distribution systems. Figure L-5(a) depicts a radial type of system. The secondary distribution systems, although often fed by more than one transformer are of varying length. This type of network is often located in non-CBD and in suburban areas. For PLC applications, the density of traffic signals in these areas is usually sufficiently low to require communication over the primary distribution system in order to accumulate a sufficiently large number of traffic signals in the communication group. (A typical distribution grouping is described in Attachment 1.)

Thus, if the primary and secondary distribution systems are to be used in combination as in Figure L-5(a) a typical design would utilize a telephone line from the central traffic computer to a computer located on the primary distribution network. A modem at this point would address modems in each of the controllers in the power substation service area.

Similarly, in secondary distribution grid applications, the computer and modems would serve a single configuration of the type shown in Figure L-5(b). In Figures L-4 and L-5, note that power factor correction capacitors are not present in the secondary distribution systems. This feature, coupled with the fact that PLC signals, when used on such systems are not required to pass through distribution transformers, leads to higher signal levels and signal-to-noise ratios for these situations.

L.3.3.2 PLC Applications Requiring Use of Primary Distribution System

In order to obtain an indication of how the previously described factors interrelate in a practical sense, a scenario consisting of two arterials in Nassau County was studied. The

TABLE L-1. POWER-LINE DISTRIBUTION SYSTEM COMMUNICATIONS CAPABILITIES

Manufacturer	Operating frequency	Data rate	Features
American Science & Engineering, Inc.	Typically 6,000 Hz	Up to 60 bits/sec	PSK modulation; power line provides reference frequency; good distribution transformer penetration. If good signal is not received at 60 bits/sec, data rate drops to 15 bits/sec. System has been tested by several utilities.
Automated Technology Corporation	150 KHz to 180 KHz	Up to 300 baud including synchronization. May be able to go somewhat higher (say 400 baud)	3 level FSK; high Q filtering; penetrates distribution transformer by capacitive coupling.
New England Electric System - A. D. Little, Inc.	60 Hz	7.5 bits/sec from central; 15 bits/sec from field	Changes crossover points of power wave.
Westinghouse Electric Corp. Meter Division	15 Hz to 100 KHz	128 bits/sec with current equipment; may possibly go to 256 bits/sec	FSK; adjacent channel separation 5 KHz to 8 KHz
Various (Ripple Control)	Less than 1 KHz	Very low	Series or parallel injection of signal on power line. Considerable injection power used.

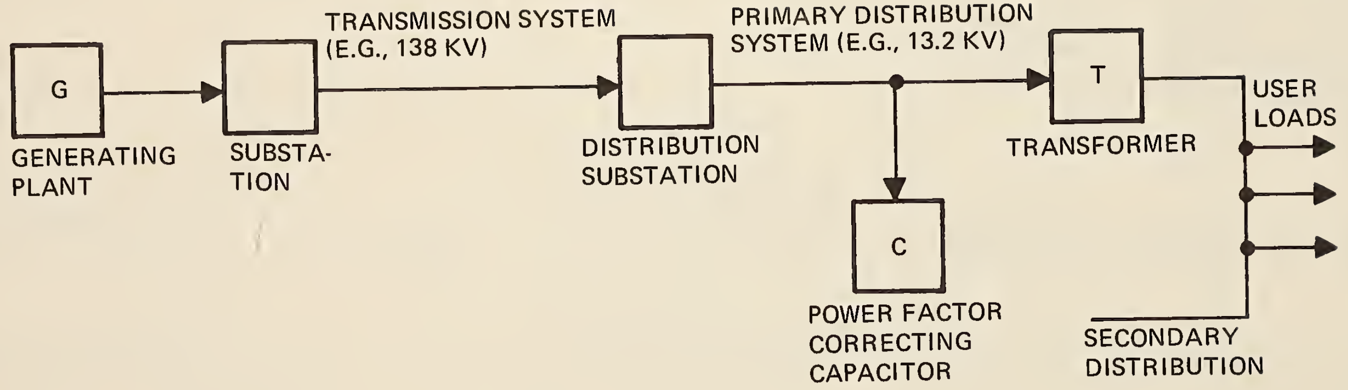
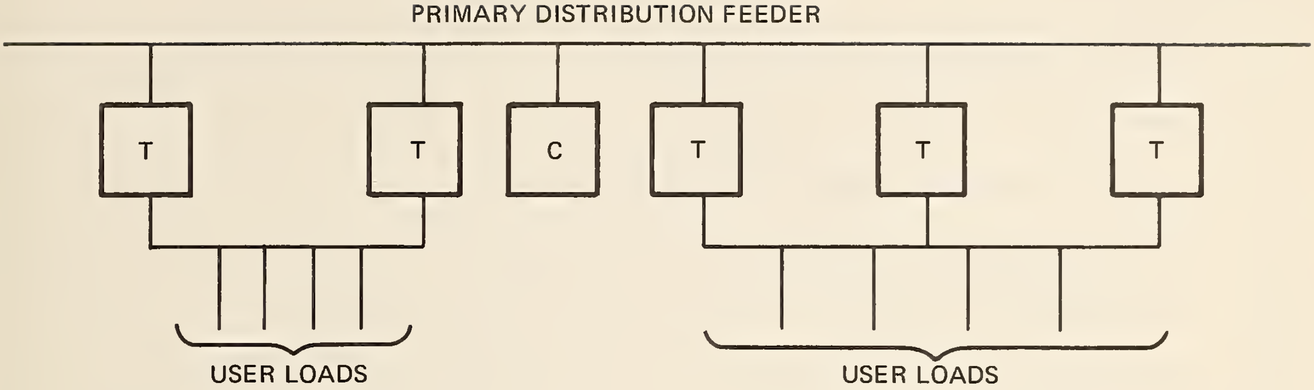
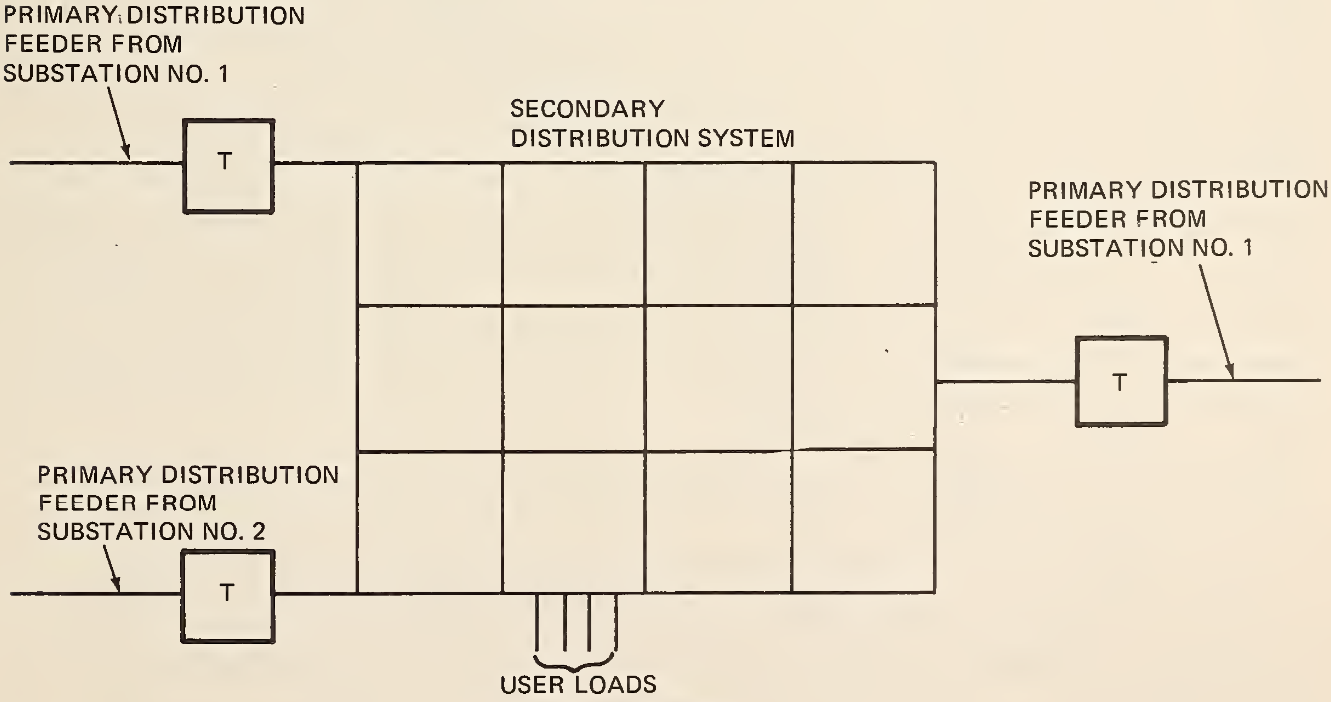


FIGURE L-4. GENERAL ORGANIZATION OF POWER SYSTEMS



(a) RADIAL TYPE SYSTEM



(b) GRID TYPE SYSTEM

FIGURE L-5. TYPES OF SECONDARY DISTRIBUTION SYSTEMS power system organization is such as to require PLC utilizing both the primary and secondary distribution systems. This example,* which is described in Attachment 1, yields the following data:

- Total number of signalized intersections: 75
- Total number of traffic subnetworks: 6
- Variation in number of signals in subnetwork: 6 to 25
- Total number of power substation service areas: 10
- Average number of signals per power substation service area: 7.5
- Variation in number of signals for power substation service area: 1 to 14

In this particular case, 10 additional auxiliary conventional communication channels (e.g., voice grade lines) are required to communicate from the PLC data collectors in the substation service areas back to the traffic central computer.

L.3.3.3 Information Rate Limitations

Figure L-6 shows the traffic information rate which can be handled by certain manufacturers' systems (which operate over both the primary and secondary distribution system) superimposed on the traffic system information requirements of Figure L-1. The information shown includes the PLC systems' current performance capabilities as well as estimates (ventured by certain manufacturers) as to what near term capabilities might reasonably be anticipated. The estimates describe a per channel capability, and under some conditions it might be possible to implement several channels. It can be seen that a single channel of PLC can theoretically satisfy the requirements for only the smallest centrally organized systems. Since, in practice, central systems with so few intersections are a rarity, present PLC systems are not suitable for centralized traffic control for this type of power distribution system configuration.

Although the informational requirements for distributed systems are somewhat less, present technology still limits the number of signalized intersections which may be handled as a single communication grouping (such a grouping is generally defined by the region serviced by a single power substation). Plotted along the abscissa of Figure L-6 is a line showing the likely range of numbers of signalized intersections in a power substation service area.

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*The assistance of the Long Island Lighting Co. in furnishing information on the distribution network is gratefully acknowledged.

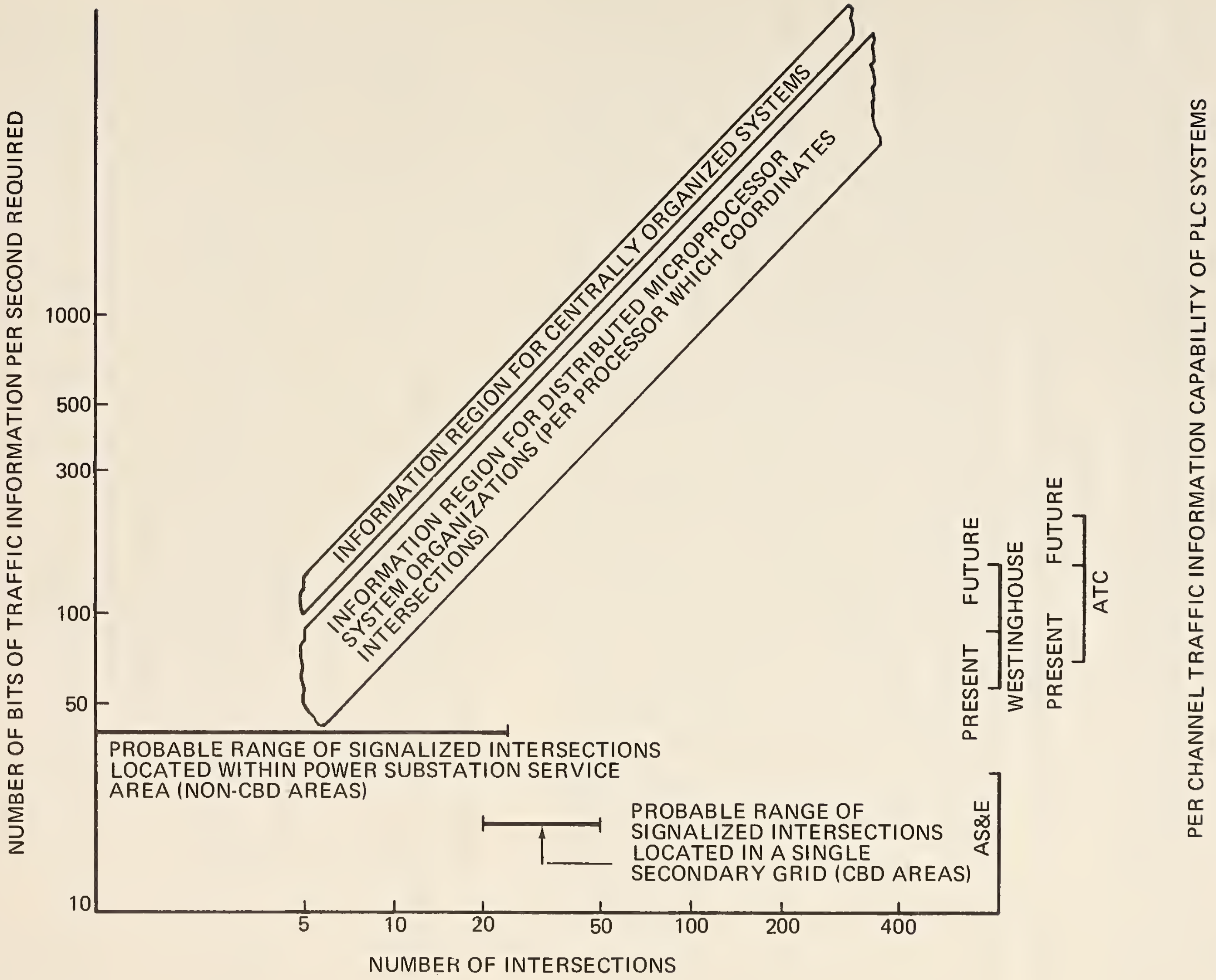

FIGURE L-6. INFORMATION REQUIREMENTS VERSUS CAPACITY

If present PLC and DMO technology is considered, only about 8 intersections can be serviced. This is seen from Figure L-6 to fall short of encompassing the range of intersections likely to be required, thereby limiting the possible usefulness (unless operation over more than one frequency-separated channel can be assured). Even with considerable advancement in DMO software, and perhaps a reduced level of traffic system performance, a service capability of only 22 intersections is achieved. This is still probably sufficiently limiting to eliminate PLC as a generally applicable technology.

If technological extensions in data rate capability or if multiple channels are to be used extensively, this will almost certainly require operation at the higher frequencies of the current operational band. This region, however, has the most uncertain attenuation and reflection characteristics and is most likely to require extensive use of special peaking and tuning devices. It would appear that a high level of effort would be required simply to measure, specify, and design a PLC system tailored to each distribution system of interest. This effort is probably well beyond the budgets which are normally allocated for communications system specification in traffic control applications. Even if this level of design effort were acceptable, the resultant design would be likely to exhibit a considerably lower reliability and to require considerable change over a period of time (as the power distribution system changes) than is commonly experienced with other forms of traffic control system communications.

L.3.3.4 PLC Applications Using Only Secondary Distribution Systems*

If the application of PLC is restricted to the secondary power distribution system, its feasibility is generally enhanced because the attenuating and signal corrupting effects of transformers and capacitors are not present. With this possibility in mind, a scenario consisting of the secondary power distribution grid networks in the Baltimore CBD area was examined. Baltimore has four such networks in the downtown area. The approximate controller count within the service area of each of these power grids is:

Network	Number of controllers
Northeast	34
Northwest	29
Southwest	33
Southeast	31

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*The assistance of the Baltimore Gas & Electric Co., the Consolidated Edison Co. of N. Y. Inc., and the Baltimore Department of Transit & Traffic in preparing this section is gratefully acknowledged.

These numbers were broadened somewhat to include the range likely to be encountered in other CBD's and the resulting values were plotted along the abscissa of Figure L-6. This type of communication would appear to be generally impractical for use with distributed processing types of computer traffic control systems because the power distribution grid generally does not coincide with traffic network and subnetwork boundaries (Baltimore being a case in point).

Now consider the situation for the centrally organized computer traffic control system. As previously mentioned, improved signal propogation characteristics may be expected on the secondary distribution system because of the absence of capacitors and because propogation through transformers is not required. Nevertheless, noise induced by load sources will be present, thus pulse transmission widths of greater than one millisecond are recommended. Under these conditions, and making appropriate allowance for modem synchronization codes, the maximum traffic signal data rates which can be practically communicated on one channel will probably be less than 400 bits/sec. Referring to Figure L-6 it is seen that this transmission rate is too low to satisfy the data requirements for the expected number of signals in the distribution grid. Approximately three multiplexed channels would be required to satisfy the range of likely requirements, and it is not clear whether the system can provide an acceptable frequency band to satisfy these requirements.

L.4 INSTITUTIONAL AND OPERATIONAL LIMITATIONS

In addition to the technical issues described in the previous section, there are a number of institutional and operationally related issues which might tend to limit the deployment of PLC for traffic control purposes.

These issues include:

- The distribution system of power lines for other communication requirements. The electric power industry is currently conducting experiments on both the technical and economic feasibility of such functions as remote meter reading and remote load control. Distribution system power line communications is being explored as one of a number of candidate technologies for this purpose. If utilities adopt this approach, it will reduce the potential access to this technology for traffic control applications.

  Although utilities might not adopt a common or standard approach to PLC usage for these purposes there is a high probability that PLC will be involved in many locations. In any case, it does not appear that this issue will be quickly resolved. The problem is compounded by the fact that in the U.S., no governmental regulation of the use of power lines as a communication medium has been established to date. Thus, no basis currently exists for establishing a priority for the traffic control function over the utility's own needs (or those of any other governmental agency or private party).

- The need to install and maintain certain equipments (equalizers, isolators, tuning circuits) in the primary distribution system may be a difficult problem to work out with some power companies.
- The issue of whether use of power lines for non-power system communication of the type proposed violates any common carrier franchise rights has yet to be resolved.

The issues described above are, unfortunately difficult to resolve until one actually attempts to proceed with the installation of a system.

L.5 CONCLUSIONS & RECOMMENDATIONS

The present state-of-the-art does not permit useful application of PLC for communication over the combined primary and secondary power distribution systems for centrally organized traffic control systems applications. As shown in Figure L-6, the information rate required by these systems and the data rates currently available with PLC and anticipated in the near term are not sufficiently compatible to warrant serious consideration for this application. It is probably not desirable to attempt to reduce the system information rate demand because the corresponding reduction in functions and capability would probably be unacceptable to the traffic engineer. Major improvements in technology would appear to be required to change this picture, and the industry by and large does not currently anticipate that such improvements will occur.

For certain distributed microprocessor organizations, a theoretical possibility of using PLC in conjunction with combined primary and secondary distribution systems would appear to exist under certain combinations of controller distribution in power distribution systems. The problems of design costs which may be excessive, a resulting system which may be more complex and unreliable than desired, and institutional problems which may or may not be reconcilable will probably deter the prudent designer from selecting this communications medium.

As a result, it is recommended that FHWA not sponsor research requiring the use of primary power distributing systems at present. It is recommended that FHWA monitor power industry activity in this area to determine whether future technology advances might change the picture described.

When PLC is used only for communication within the secondary power grids, such as those generally present in CBD areas, transmission is improved. Problems arise, however, because:

- Only a central processor traffic system organization can be used in this case.
- High traffic signal densities in CBD areas lead to data transmission rates which cannot be accommodated by proven existing equipment.
- New system and equipment designs addressed to these data rates currently appear to be only marginally feasible. Field research would be required to make this determination. If such research is contemplated, it should be preceded by a detailed study of the geographic boundaries of secondary power grids and the distribution of controllers within these grids to assess the potential market for this technology.

Because the probability of technical success in a market of sufficient scope is only moderate and because institutional problems may be formidable, it is not recommended that further research into PLC using only secondary distribution system be given high funding priority by FHWA.

APPENDIX L

ATTACHMENT 1 - PLC SYSTEM FOR NASSAU COUNTY, NY

To show the interrelationships of traffic subnetworks (sections) and power substation areas in a realistic environment, an example of PLC communications for seventy-five signalized intersections in Nassau County, N. Y. was considered. These intersections are on two arterials, Jericho Turnpike and Hillside Ave.

Figures L-7 and L-8 show the arterial signals along with the pertinent power substation locations and service area boundaries. The figures also show a reasonable traffic subnetwork configuration based on the traffic conditions for the area. Tables L-2 and L-3 show pertinent statistical data developed from this figure.

Centrally Organized System

The 75 signals are controlled from ten power substations. Assuming that PLC terminates at the substations, one additional conventional voiceband channel would be required to communicate between the substation and the traffic control center, resulting in an average controller loading of 7.5 per voiceband channel.

Distributed System

Assume the following deployment of "field master computers":

- Subnetworks A, B, and C combined in master computer No. 1 (22 intersections).
- Subnetwork D assigned to master computer No. 2 (25 intersections).
- Subnetworks E and F combined in master computer No. 3 (28 intersections).

The interconnection requirements between the substations and the appropriate computers are shown in Table L-4. This results in 12 conventional supplementary channels or a controller loading of 6.25 per supplementary channel.

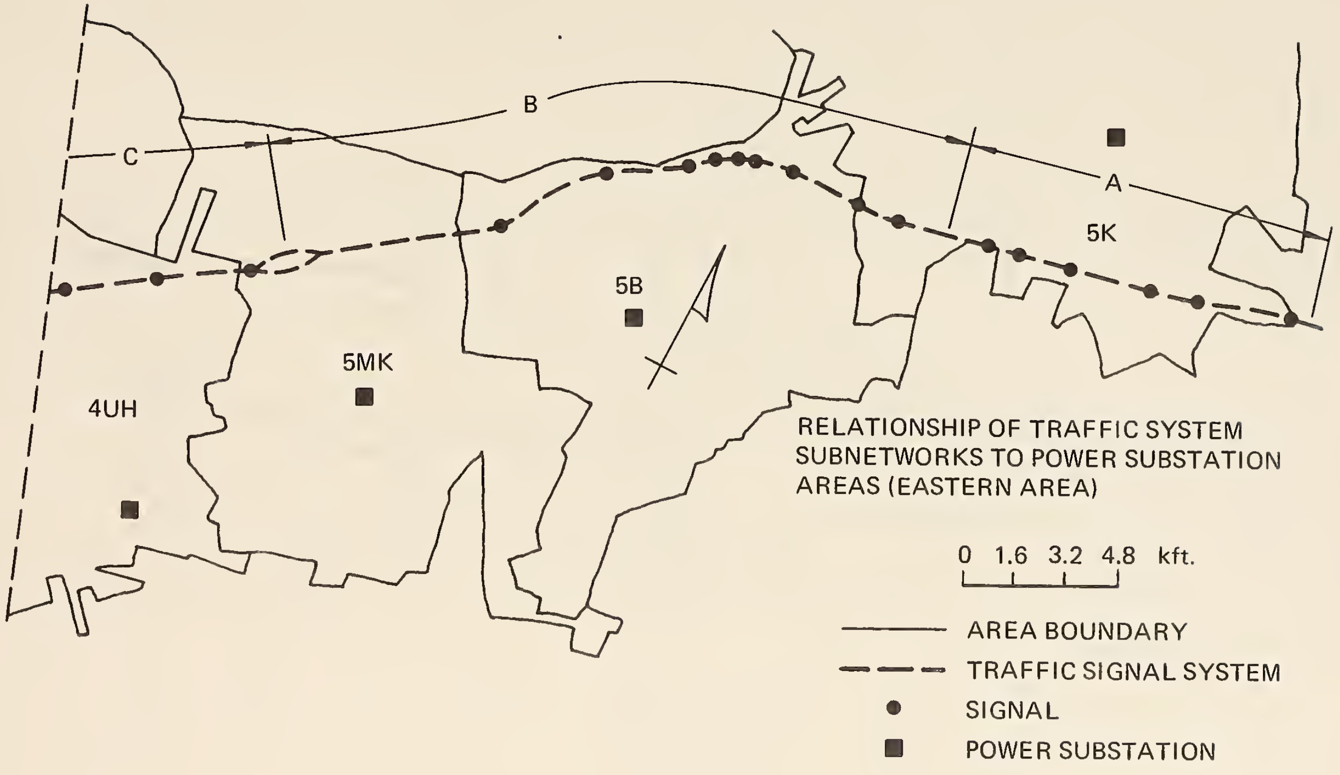

FIGURE L-7. RELATIONSHIP OF TRAFFIC SYSTEM SUBNETWORKS TO POWER SUBSTATION AREAS (EASTERN AREA)

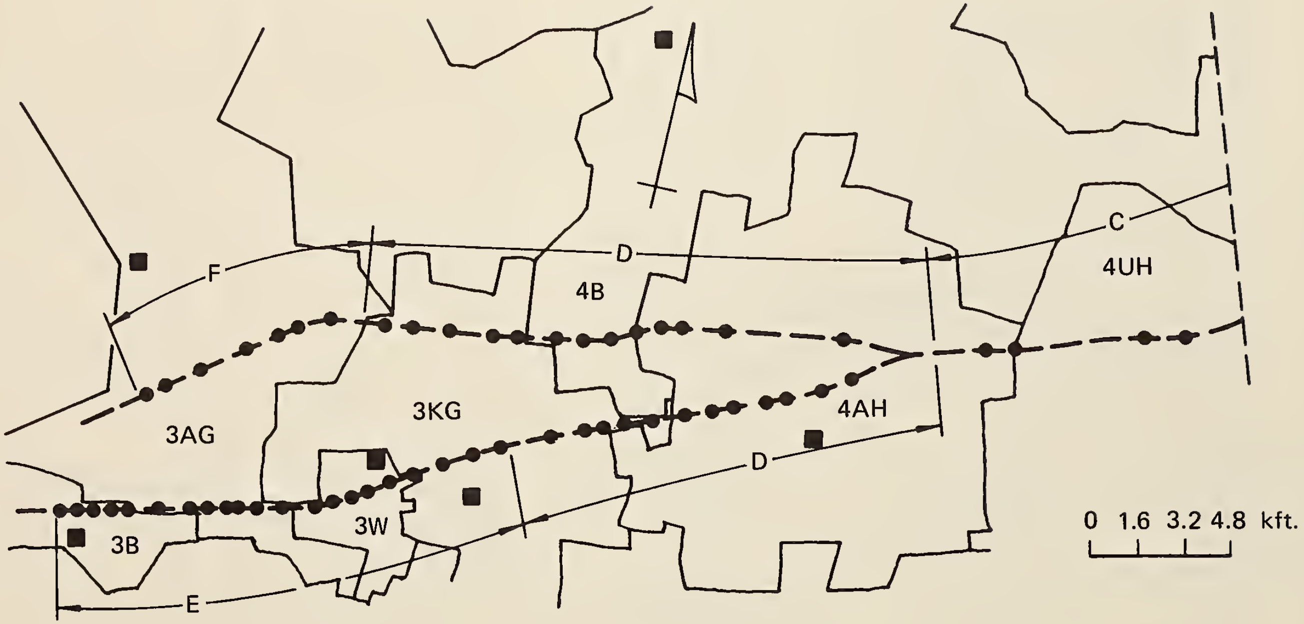

FIGURE L-8. RELATIONSHIP OF TRAFFIC SYSTEM SUBNETWORKS TO POWER SUBSTATION AREAS (WESTERN AREA)

TABLE L-2. DATA BY TRAFFIC SUBNETWORK

Traffic subnetworks	Number of signals	Number of power substation areas per subnetwork	Average number of signals in subnetwork in each substation area
A	6	1(5K)	6
B	9	2(5K, 5B)	4.5
C	7	3(5MK, 4UH, 4AH)	2.3
D	25	3(4AH, 3KG, 4B)	8.3
E	21	4(3KG, 3W, 3AG, 3B)	5.2
F	7	3AG	7
Totals	75	10	5.55 Av.

TABLE L-3. DATA BY POWER SUBSTATION SERVICE AREA

Power substation area	Number of signals in power substation area	Traffic subnetwork	Average number of signals in substation area per traffic subnetwork
5K	7	2(A, B)	3.5
5B	8	B	8
5MK	1	C	1
4UH	4	C	4
4AH	13	2(C, D)	6.5
4B	4	D	4
3KG	13	2(D, E)	6.5
3W	6	E	6
3AG	14	2(E, F)	7
3B	5	E	5

TABLE L-4. INTERCONNECTION REQUIREMENTS BETWEEN SUBSTATION SERVICE AREA AND COMPUTER

Substation	Computer
5K	1
5B	1
5MK	1
4UH	1
4AH	1, 2
4B	2
3KG	2, 3
3W	3
3AG	3
3B	3

APPENDIX L

ATTACHMENT 2 - TECHNICAL CONTACTS

Technical contacts in the form of visits, telephone calls, and letters were made with the following individuals and organizations, and their assistance is acknowledged in the preparation of this report.

- Private Organizations
  - American Science & Engineering: Mr. N. Jagoda
  - Automated Technology Corp: Mr. S. Calabro
  - Rood-Lusk Associates: Messrs. W. Rood, J. Lusk
  - Westinghouse Electric Corp., Meter Division: Mr. J. Goodman
- Utilities and Government Agencies
  - Baltimore Gas & Electric Co.: Messrs. D. Bryan, K. Kern
  - City of Baltimore - Dept. of Transit & Traffic: Mr. J. Erdman
  - Consolidated Edison Co. of NY, Inc: Mr. J. Signorelli
  - Long Island Lighting Co.

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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.

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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.

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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.

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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.

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* 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.

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