NBS-GCR-81-356

Digital Communications Techniques and Equipment for Law Enforcement Use

Urban Sciences, Inc.
5434 King Ave.
Pennsauken, NJ 08109

January 1982

Final Report

Issued March 1982

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DEPARTMENT OF COMMERCE
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Paul Cascarano, Assistant
Director
National Institute of Justice

Acknowledgments

This report was prepared by the Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards under the direction of Marshall J. Treado, Manager, Communication Systems Program, and Lawrence K. Eliason, Chief of LESL. The report is based on research conducted by Dr. John Williams and John T. Furze of Urban Sciences, Inc. and updated by William A. Shand, LESL consultant. Acknowledgment is also accorded to the many police departments who provided invaluable information during the course of the study. The cooperation received from the digital communication equipment manufacturers is also acknowledged. This work was sponsored by the National Institute of Justice, Lester D. Shubin, Standards Program Manager.

FORWORD *

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Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Law Enforcement Standards Laboratory, National Bureau of Standards, Washington, DC 20234.

Lawrence K. Eliason, Chief
Law Enforcement Standards Laboratory

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DIGITAL COMMUNICATIONS TECHNIQUES AND EQUIPMENT FOR LAW ENFORCEMENT USE

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DIGITAL COMMUNICATIONS TECHNIQUES AND EQUIPMENT FOR LAW ENFORCEMENT USE

Urban Sciences, Inc.*
5434 King Ave., Pennsauken, NJ 08109

This report is the result of a study of digital communications equipment for law enforcement use. The primary objective was to determine the suitability of the various types of this equipment for use by law enforcement agencies. The report reviews present voice message traffic on typical police radio networks and discusses operational requirements for digital communications equipment. It further reviews the possible applications of digital communications equipment for law enforcement use, and lists the characteristics of mobile digital terminals being offered at present. A brief technical discussion of mobile digital communications is also provided.

Key words: digital communications equipment; digital techniques; equipment standards; law enforcement; mobile digital terminals; voice message traffic.

1. INTRODUCTION

The objective of this study was to evaluate and determine the suitability of digital communications equipment for use by law enforcement agencies.

Digital communications equipment is of interest to police users in that it can be employed to help alleviate problems that exist with a voice-only radio network, such as congestion. This congestion is due to the high volume of traffic that has to be carried by some communication systems. Under these high volume conditions, the necessary voice communications may exceed the capacity of available radio channels, resulting in queuing and increased waiting time. As the number of these incidents increases, it is not surprising that law enforcement agencies are looking for techniques and equipment that will provide more efficient use of communications channels.

Digital signaling for exchanging information can be carried out at higher transmission rates than voice so that a greater volume of information can be handled. In addition, digital communications has an inherent security in that digital messages cannot be as readily intercepted intelligently as voice can. Because of such attributes, many police agencies are giving a high priority to the procurement and use of digital communication equipment.

This trend towards digital communications is expected to continue. Accordingly, standards for mobile digital communications equipment are being developed by the NBS Law Enforcement Standards Laboratory (LESL) for the National Institute of Justice (NIJ). The primary objective of these standards is to provide voluntary performance requirements and test methods to aid the law enforcement community in the selection and procurement of mobile digital communications equipment.

The contents of this report are to a large extent presented in the sequence that the various tasks of the study were undertaken. The first task was that of analyzing the structure and contents of messages presently being exchanged over the law enforcement voice-only mobile radio network. The analysis and findings of this aspect of the study are discussed in the next section.

Following that, the operational requirements for digital communications are developed. These requirements are a sample of the needs and attitude of the law enforcement user. In order to make a better determination of operational requirements, a number of different types of law enforcement agencies were contacted. The types of agencies contacted consisted of State police, county police, and city police departments from several different sections of the United States. This approach ensured that inputs from several types of agencies would be used in the determination of the operational requirements.

*The company name "Urban Sciences, Inc." was changed to "Communication Systems Sciences, Inc." in August 1978.

Several different types of digital communications equipment applications are detailed in the next section. This section attempts to categorize applications and evaluate them in terms of their suitability to police operations. The characteristics of presently available equipment have been cataloged and included in this section. The section concludes with a discussion of potential applications which may be realized in the future.

A technical discussion of digital communications is also included. The intention of this section is to supplement the knowledge of those responsible for police radio systems who are only conversant with voice communications. It details the parameters and techniques considered in the design of digital communication.

The conclusions of the report are given in the final section. The report has two appendices, the first being a listing of references and the second containing a number of hints to prospective buyers of digital communication equipment.

2. REVIEW OF PRESENT VOICE MESSAGE TRAFFIC TYPICAL OF A POLICE RADIO NETWORK

2.1 General

The early phase of this study was concerned with review of present voice message traffic being transmitted on typical police radio networks. It was determined that a classification or categorization of the various exchanges would be essential in evaluating the impact of the use of mobile digital communications equipment on the channel loading characteristics of the radio network.

At the outset of this task, it was thought that the majority of the data would be obtained through previous work or studies already completed in this area. However, as the research continued, it became evident that a large volume of published data on police radio transmissions was not readily available. A few references of earlier work were located; among these were the "Rochester Police Bureau Communication Study" [9][1], and the "Massachusetts State Police Radio System Plan and Specifications" [19].

To obtain additional information, project personnel established data collection projects with the Boston and Fall River Massachusetts Police Departments. At the Boston Police Department audio tape recordings of police dispatcher/mobile unit exchanges were monitored and data collected for the classification analysis. The Fall River Police Department does not operate recording equipment for the voice radio exchanges so live tape recordings were made with contractor furnished equipment during the peak loading periods.

It was felt that most of the data collected should be that which typifies "busy hour" periods when the communication channels are overloaded and queuing occurs. It is felt that the greatest effectiveness of mobile digital communications will be realized when the phenomenon of queuing on the voice channel occurs.

Other data incorporated into this message exchange analysis is that which has been received from the field via the National Institute of Justice. This data included information on mobile requests made by the department under study by the field site personnel for computer based information and comments on mobile traffic amenable to digital transmissions and on requirements for mobile digital terminals.

2.2 Categorization Analysis of the Police Radio Message Exchanges

In order to collect data to perform a categorization analysis, permission to monitor the radio exchanges of the Boston and Fall River, Massachusetts Police Departments was obtained. These data have been reduced so as to provide information on the following items:

[1]Numbers in brackets refer to appropriate reference in appendix A.

1) Percentage of transmission times used for various types of messages.
2) Overall channel loading factors.
3) Estimates of reduction in channel loading with "status-button" and "full-text" digital terminals.
4) The probability of a repeat of a voice transmission.
5) The lengths of various categories of messages.
6) The transmission speed of the spoken word over a police radio network.

The results of the categorization analysis are presented in the format indicated in tables 1 and 2.

2.2.1 Categorization Analysis of the Boston Police Department Communication Exchanges

Boston, Massachusetts has a population of approximately 700,000 and spans 45 mi^2 and as such has police management and preventive patrol characteristics which typifies a metropolitan area. This city is divided into three preventive patrol zones designated A, B, and C. Each zone has its own mobile and portable communication frequencies backboned by city-wide communications on both mobile and portable frequencies. All the channels are UHF and are used in the half-duplex mode.

The mobile frequency for zone A was selected for the study because it achieves the highest channel loading. Between 20-30 patrol cars use the zone A frequency at any one time. The categorization analysis which follows does not include data base inquiries because they are made on the city-wide channels. The city-wide channel was not monitored because it was felt that enough data on data base inquiries would be received from other sources.

The data samples were recorded during the "busy hours" on Friday and Saturday evenings, which represent the times that digital communications equipment should be most effective. The data collected is shown in figure 1, while the actual numbers pertaining to the data points are tabulated in table 3.

2.2.2 Categorization Analysis of the Fall River Police Department Communication Exchanges

The population of Fall River, Mass. is approximately 90,000 over an area of 20 mi^2. The preventive patrol forces are served by a VHF simplex communication link. Between 15-20 cars use this radio channel during peak patrol hours. This frequency is used for all communication, including data base inquiries. However, the data base exchanges made during the monitoring period were limited and did not form a large enough statistical sample to be included in this report.

Various surrounding towns also share the same radio frequency. The voice exchanges of these communities are not included in this analysis, as they operate from their own dispatching centers. The only impact of this time-sharing is to increase the channel utilization indicated in this report by approximately 5 percent.

Again, the data recorded was that of busy hour communication exchanges. The reduced data is shown in figure 2, and the sample data is presented in table 4.

2.2.3 Discussion of Results

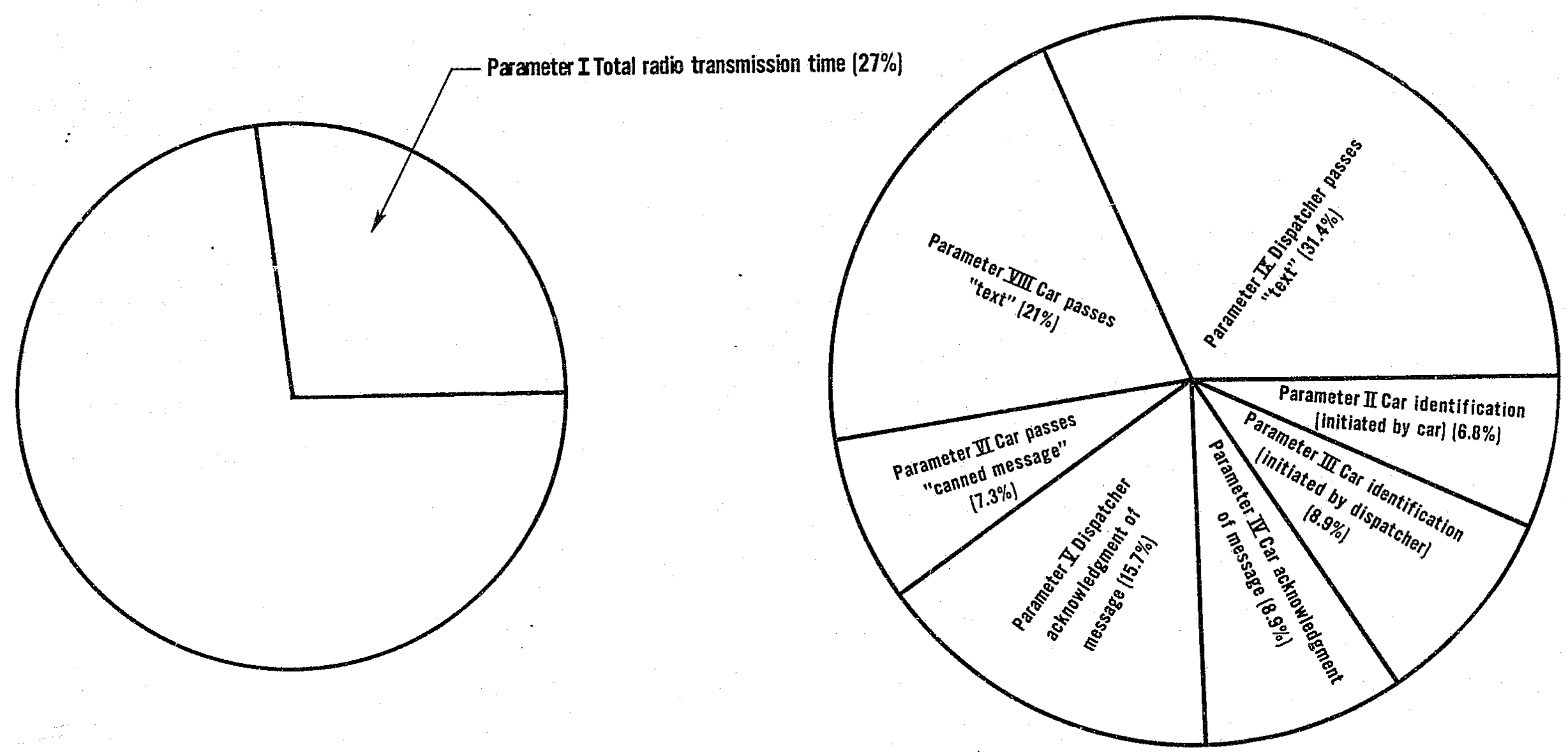
Data similar to that presented in the previous sections, along with sufficient background information, should be a prerequisite in determining the impact of a digital transmission system on channel utilization. Although the increase in data base inquiries afforded by the installation of a digital communications system can actually increase the channel loading, no estimate can be made of the resultant loading without establishing some basic data on status and text communications.

Table 1. Basis for the categorization of the Boston and Fall River police communication exchanges.

Transmission type	Description
A	Car identification (initiated by car).
B	Car identification (initiated by dispatcher).
C	Car acknowledgment of message.
D	Dispatcher acknowledgment of message.
E	Car passes "canned message."
F	Dispatcher passes "canned message."
G	Car passes "text."
H	Dispatcher passes "text."

Table 2. Parametric description of Boston and Fall River police communication exchanges (reference table 1).

Parameter	Description (percentage of)
I	Total time used for radio transmission.
II	Transmission time used for "type A" messages.
III	Transmission time used for "type B" messages.
IV	Transmission time used for "type C" messages.
V	Transmission time used for "type D" messages.
VI	Transmission time used for "type E" messages.
VII	Transmission time used for "type F" messages.
VIII	Transmission time used for "type G" messages.
IX	Transmission time used for "type H" messages.
X	Transmission time utilized by car.
XI	Transmission time utilized by dispatcher.
XII	Car transmission time "feasible to digitize" (i.e., in this analysis "text messages" are not considered to be digitized).
XIII	Dispatcher transmission time "feasible to digitize."
XIV	Total air time "feasible to digitize."



a) Total radio transmission time as a percentage of observation time

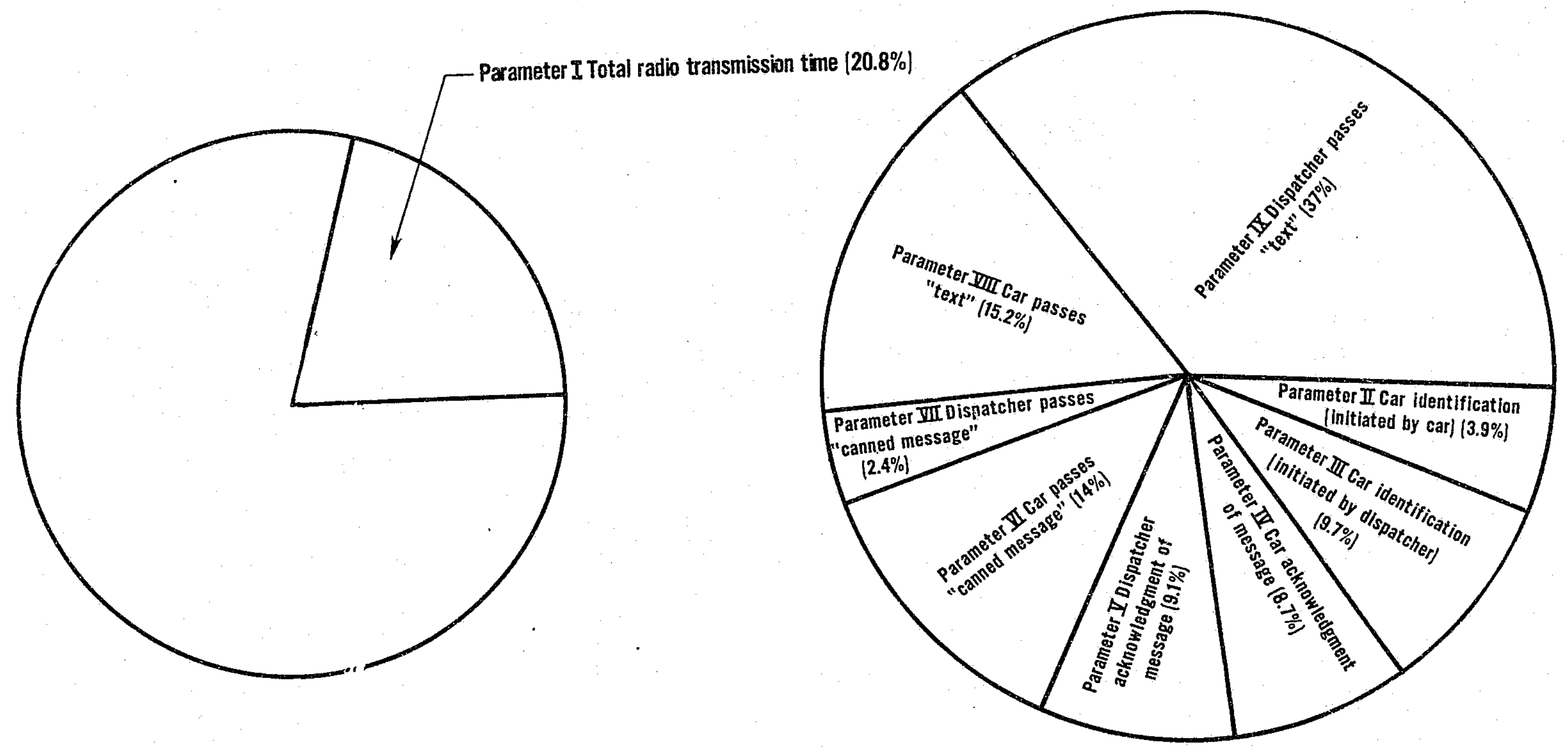
b) Parametric distribution (type of message exchange as a percent of total radio transmission time)

Figure 1. Sample averages of voice message exchanges for the Boston Police Department. (Note: Numbers in parentheses are a percentage of 27%. See table 3.)

Table 3. Parametric analysis of Boston Police Department message exchange (parameters recorded as percent of total transmission time)

No.	Transmission parameter	Observation period 1	2	3	4	5	6	7	8	9	Mean value (%)	Standard deviation (%)
I	Total channel utilization	30	24.6	12	17	41	13	36	36	33	27	10
II	Car I.D., mobile to base	6	13.5	5.6	2	7	4.3	7.3	12.3	2.8	6.8	3.7
III	Car I.D., base to mobile	17	17	12.5	6	4	5.4	1.5	17.4	16	8.9	5.7
IV	Car acknowledgment of message	12.5	8	11	10	3	13.4	8	5.4	8.4	8.9	3.1
V	Base acknowledgment of of message	15	17	13	18	18	25.5	15	11.5	8.3	15.7	3.6
VI	Car - "canned message"	6.6	19	6.5	4.5	4	8.6	6.2	6.3	4	7.3	4.4
VII	Base - "canned message"	No Boston dispatcher messages could be classified in this category.										
VIII	Car - text message	11.6	14	35	12	41	23.9	28	18.2	7.3	21	10.9
IX	Base - text message	34.3	14.6	25	48	20	19.1	35	28.6	54	31	12.7
X	Car transmission - time	36	55.4	58	28.5	56	50.2	49.5	42	22.5	44.2	12
XI	Base transmission - time	64	44.6	42	71.5	44	49.8	50.5	58	77.5	55.8	12
XII	Car transmission time "feasible to digitize"[a]	25	41.3	23	16.5	14	26.3	21.5	24	15.2	23	7.7
XIII	Dispatcher transmission time - "feasible to digitize"	29	29.5	16	24	22	31	16.5	19	24.3	24.6	5.3
XIV	Total air time - "feasible to digitize"	54	70.8	39	40.5	36	57.3	38	53	39.5	47.6	10.7

[a]In this analysis, "text messages" are not considered to be digitized.



a) Total radio transmission time as a percentage of observation time

b) Parametric distribution (type of message exchange as a percent of total radio transmission time)

Figure 2. Sample averages of voice message exchanges for the Fall River Police Department. (Note: Numbers in parentheses are a percentage of 20.8%. See table 4.)

Table 4. Parametric analysis of Fall River Police Department message exchanges (parameters recorded as percent of total transmission time)

No.	Transmission parameter	Observation period 1	2	3	4	5	6	Mean value (%)	Std. deviation (%)
I	Total channel utilization	19	26	23.4	10	17.4	29.1	20.8	6.3
II	Car I.D., mobile to base	2.3	6.2	4.3	1.5	3.4	5.9	3.9	1.7
III	Car I.D., base to mobile	13.4	9.7	15.4	5.5	9.3	4.8	9.7	3.8
IV	Car acknowledgement of message	12.8	7.6	9.7	5.2	7.3	9.5	8.7	2.4
V	Base acknowledgment of message	7.5	8.3	6.1	13.3	9.4	10	9.1	2.3
VI	Car - "canned message"	8.4	7	6.1	39.4	7.4	15.9	14	11.8
VII	Base - "canned message"	2.5	0	4.8	1.8	4.6	.4	2.4	1.8
VIII	Car - text message	4	16.6	9.4	21.5	18.4	21.5	15.2	6.5
IX	Base - text message	49	44.6	44.3	11.8	40.1	32	37	12
X	Car transmission time	27.5	37.4	29.5	67.6	36.5	52.8	41.9	14.1
XI	Base transmission time	72.5	62.6	70.5	32.4	63.5	47.2	58.1	14.1
XII	Car transmission time "feasible to digitize"[a]	23.5	20.8	20.1	46.1	18.1	31.3	26.7	9.7
XIII	Dispatcher transmission time - "feasible to digitize"	23.4	18	26.3	20.6	23.3	15.2	21.1	3.7
XIV	Total air time - "feasible to digitize"	46.9	38.8	46.4	66.7	41.4	46.5	47.8	9

[a]In this analysis, "text messages" are not considered to be digitized.

An example of simple calculations that will allow one to evaluate the impact of a "status-only" type digital terminal on channel utilization is shown below:

Status Only

The basic operating characteristics of a digital unit are as follows:

- o Vehicle identification transmitted with all messages.
- o Vehicle status transmitted with all messages.
- o Automatic acknowledgment relayed to vehicle from base.
- o Time for initial transmission and acknowledgment is of the order of 1.2 s (typical with approximately 300 ms "front porch" delay - "front porch" delay is usually slightly greater than the time constants associated with the transmission path electronics).

Table 5 illustrates the channel utilization both before and after installation of a digital status mobile unit as described above. This table was derived by inserting a transmission time of 1.2 s for a status exchange into the actual voice data used to develop the charts previously presented.

If the categorization analysis is examined, a direct relationship between the effective reduction in channel utilization and parameters II and VI in each sample can be seen. For example, parameter II is a measure of the transmissions initiated by the patrol car. See figure 1.

Table 5. Channel utilization with digital status.

Boston Police Department

Sample No.	Original Utilization (ρ)	Utilization with Digitized Status (ρ')
1	.30	.225
2	.246	.155
3	.12	.095
4	.17	.152
5	.41	.331
6	.13	.11
7	.36	.318
8	.36	.327
9	.33	.302
	mean = .27	mean = .224

Fall River Police Department

Sample No.	Original Utilization (ρ)	Utilization with Digitized Status (ρ')
1	.19	.188
2	.26	.23
3	.234	.213
4	.10	.072
5	.174	.161
6	.291	.239
	mean = .208	mean = .184

These results are in agreement with arguments presented in a previous study [7]. This study also points out that more reduction in channel utilization is achieved on a highly loaded channel. This is also true in the case of the Boston and Fall River data. It can be seen that Fall River is definitely more "status-oriented" than Boston, but Boston achieves a higher reduction in channel utilization because their channels are more heavily loaded. The Boston Police Department has a channel loading of 30 cars/channel, while Fall River has 20 cars/channel. Another factor that significantly affects the reduction in channel utilization is the time it takes to pass a status message by voice. If a department has a voice status code scheme which requires the transmission of more characters than another, the department with the longest code words will achieve the most reduction in channel utilization. Because of this, the average status transmission in Boston takes 5.7 s, while in Fall River the average status message is passed in 2.5 s. Also, if a department has a radio discipline problem, the bulk of the utilization reduction may be attributable to the forced improvement in radio discipline achieved by the installation of digital units.

If voice transmission data pertaining to various police departments are available in varied formats, estimates in the reduction of channel utilization can be obtained through the use of simple formulas derived from queuing theory.

For example, if one wishes to determine the new channel utilization with digital status (ρ'), given the following data:

ρ = the original channel utilization

N = the number of cars/channel

S = the number of status messages/car/8 hr shift

T_v = the time in seconds for passing a voice status message and an acknowledgment

T_d = the time in seconds for passing a digital status message and an acknowledgment.

The following formula can be utilized:

$$\rho' = \rho - \frac{N \times S \times (T_v - T_d)}{3600 \times 8}$$

Applying the formula to the Boston and Fall River Police Departments:

<u>Boston Police Department</u>

$\rho = .27$

N = 30 cars/channel

S = 8.7 status transmissions/car/8 hr

$T_v = 5.7$ s

$T_d = 1.2$ s

$$\rho' = .27 - \frac{30 \times 8.7 \times (5.7-1.2)}{3600 \times 8}$$

$\rho' = .27 - .04$

$\rho' = .23$

<u>Fall River Police Department</u>

$\rho = .208$

N = 20 cars/channel

S = 20 status transmission/car/8 hr

$T_v = 2.5$ s

$T_d = 1.2$ s

$$\rho' = .208 - \frac{20 \times 20 \times (2.5-1.2)}{3600 \times 8}$$

$\rho' = .208 - .027$

$\rho' = .181$

As seen from the above results, it is difficult to justify the use of digital status units solely on the basis of reduction in channel utilization except in the case of highly loaded channels (i.e., >150 cars/channel). These figures are confirmed in [7]. However, there are other characteristics of digital status units that can be of significant benefit. The use of these units with an associated base station display will provide current status information to the dispatcher. This will relieve the dispatcher workload, as he will no longer be required to make voice inquiries to obtain mobile status information. This reduction in dispatcher workload could be a significant factor in the improvement of law enforcement communications operations.

Full Text

The same formula used in the previous section will be used here to estimate the reduction in channel utilization achieved with the digital transmission of "full text" messages (status messages are also included in this category).

The parameters ρ, ρ', and N have the same meaning as before, while:

M = the number of messages/car/8 hr shift

T_v = the time in seconds for passing an average message and an acknowledgment

T_d = the time in seconds for transmitting an average voice message and acknowledgment digitally.

Again:

$$\rho' = - \frac{N \times M \times (T_v - T_d)}{3600 \times 8}$$

Applying this formula to the Boston and Fall River Police Departments:

Boston Police Department

$\rho = .27$

$N = 30$ cars/channel

$M = 37$ message transmissions/car/8 hr

$T_v = 7.3$ s

$T_d = 1.7$ s

$$\rho' = - \frac{.27-30x37x(7.3-1.7)}{3600x8}$$

$\rho' = .27-.215$

$\rho' = .055$

Fall River Police Department

$\rho = .208$

$N = 20$ cars/channel

$M = 60$ message transmissions/car/8 hr

$T_v = 5.2$ s

$T_d = 1.5$ s

$$\rho' = .208 - \frac{20x60x(5.2-1.5)}{3600x8}$$

$\rho' = .208-.154$

$\rho' = .054$

These results indicate a significant reduction in channel utilization using the digital transmission of text. However a word of caution is to be noted with regard to using these results. In actual practice, with a digital transmission capability of full text, it is only to be expected that if this capability allows for direct data base inquiries (e.g., license checks) from the mobiles, the field officers will initiate a larger number of such inquiries than when such inquiries have to be made over a voice-only channel. Therefore, the actual channel utilization will probably be significantly higher than that obtained from the above derivations.

Some of the other information deduced from the data in the categorization analysis is presented in the following paragraphs.

An important consideration for mobile digital terminals is the determination of the number of errors that will actually be tolerated. This parameter is a function of many variables and, in general, law enforcement agencies at present have insufficient experience with mobile digital terminals to set threshold values on this parameter. In order to determine an "acceptable error rate" for transmissions from mobile digital communications terminals, the probability of a voice message

being misunderstood was examined. This can be used as a basis for defining an "acceptable error rate," as a digital transmission should be at least as error free as a voice transmission.

The analysis was divided into two message categories: status and full-text. The results from the Boston and Fall River data are given below:

Boston Police Department

P_e(status) = .13 P_e(full-text) = .27

Fall River Police Department

P_e(status) = .13 P_e(full-text) = .15

One may observe that the difference in error probability (probability that a message is misunderstood and a repeat is requested) between status (1-2 words) and full-text (10-12 words) messages can be small, especially in the Fall River case. This result is expected because a high level of inherent redundancy is present in a spoken text message. Code-word schemes, on the other hand, have a low level of redundancy and a correspondingly small "minimum distance." By "minimum distance," it is meant, the least amount of change one must make to a code word before it could be interpreted as another word. For example, the code words 10-18 and 10-80 have a small "minimum distance" when being detected by the human ear.

For mobile digital transmissions to be as reliable as voice transmissions their error probabilities should be equal to or better than the error probabilities identified above, i.e., those associated with voice transmissions.

Other interesting data that can be obtained from a message analysis is the average number of characters per message. This type of information proves useful when determining a digital communications display size. The data for Boston and Fall River are as follows:

Boston Police Department

Base to Mobile	$\bar{x}$ = 60 characters σ = 19.5 characters
Mobile to Base	$\bar{x}$ = 54 characters σ = 18 characters

Fall River Police Department

Base to Mobile	$\bar{x}$ = 61 characters σ = 19 characters
Mobile to Base	$\bar{x}$ = 36.5 characters σ = 13.3 characters

The spoken word rate is said to average approximately 18 characters per second [63] where a character is defined as any letter, numeral or punctuation designation. However, using this analysis, the spoken word rate over the police radio networks of the Boston and Fall River Police Departments was found to average 13 characters per second with a standard deviation of about two characters per second. This is to be expected because police radio communication exchanges are usually quite deliberately spoken.

If we average the normal spoken rate of 18 and the Fall River Police Department rate of 13 characters per second we can assume a spoken rate of 15 characters per second and expect to transmit these same characters digitally with an ASCII[2] code, the resultant data of 7 x 15 = 105 bits per second (b/s). A somewhat reasonable efficiency factor for digital mobile transmission of voice derived messages should be that the digital transmission speed be at least five times that of the spoken word rate. Allowing 25 percent redundancy to improve reliability, this "minimum data rate" becomes 5 x 105 x 1.25 which is approximately 650 b/s. Standard data rates will be discussed later.

2.3 Other Police Message Data

To supplement the data used in the previous analysis, the Law Enforcement Standards Laboratory asked the National Institute of Justice for the following information:

1) an assessment of current mobile-initiated message traffic amenable to digital transmission, and

2) need for mobile digital equipment and the performance characteristics required of such equipment.

In the following sections, a synopsis of findings of a representative number of NIJ field sites with respect to question one is presented. The comments obtained on question two are discussed in a later section, which details the application of digital communications equipment for law enforcement use.

2.3.1 Jacksonville, Ill. Sheriff's Office

The data classified mobile-initiated traffic into three capability levels. They are:

1) Formattable numerics which include mobile identification, message acknowledgment, status and location reporting, call for help, call disposition, and priority control of communications.

2) Inquiries and short descriptions which includes data base inquiries on wanted persons or stolen vehicles and short descriptions of wanted or missing persons.

3) Longer descriptions which include longer descriptions of crimes having names and identifying characteristics of suspects, wanted vehicles, and properties.

Based on an analysis of local message traffic the following estimates of message lengths and transmission times were determined.

Type of traffic	Estimated number of characters[3]	Time required for voice entry (Mean)
Formattable numerics	1-5	2.5 s
Inquiries and short descriptions	8-52	15 s
Longer descriptions	53-250	35 s

[2]American standard code for information exchange which has seven information elements per character or $2^7=128$; which gives 128 combinations of marks and spaces available for characters or graphics.

[3]Excluding those for mobile identification number.

2.3.2 Michigan State Police

A voice message traffic survey was performed at the Flint Post of the Michigan State Police. The Flint Post is the busiest post, and has five cars on patrol at all times. The messages were categorized in keeping with tables 1 and 2 of this report, except for two additional categories designated as follows:

Transmission type	Description
I	Car passed "semi-text"[4]
J	Dispatcher passes "semi-text"

and

Parameter	Description
IX A	Percentage of transmission time used for "type I" messages
IX B	Percentage of transmission time used for "type J" messages

The data are presented vs. time of day in table 6.

2.3.3 Los Angeles Police Department

The voice radio message analysis performed in the Los Angeles Police Department was divided into two categories: mobile data and base station data.

Mobile Data

The mobile initiated voice communication data was derived from nine sampling periods randomly selected in four divisions. The types of calls were subdivided into three categories:

1) Data base inquiries
2) Status-button calls
3) Alphanumeric calls

The data base inquiries into Los Angeles Police Department included license checks and checks of a persons identity. License checks are also made through the Division of Motor Vehicles. The results presented here are averages of all three types of calls averaged over the nine samples.

Calls related to data base inquiries = 14%
Air time attributed to data base inquiries = 29.1%

[4]"Semi-text" consists of a "canned message" followed by a "text message" which could be easily handled by an officer from a mobile keyboard (e.g., a file check on a license plate).

Table 6. Sample values of the Michigan State Police Department voice message exchanges
(parameters are recorded as percent of total transmission time)

No.	Transmission parameter	6-12 a.m. (%)	12 a.m.-5 p.m (%)	6-12 p.m. (%)	12 p.m.-6 a.m. (%)	Average (%)
I	Total channel utilization	6	4	6	10	6.5
II	Car I.D., mobile to base	4	6	9	5	6.0
III	Car I.D., base to mobile	8	10	5	9	8.0
IV	Car acknowledgment of message	5	9	5	12	7.8
V	Base acknowledgment of message	13	14	21	16	16.0
VI	Car - "canned message"	5	8	7	4	6.0
VII	Base - "canned message"	7	4	3	4	4.5
VIII	Car - text message	19	16	19	12	16.5
IX	Base - text message	25	26	19	20	22.5
IXA	Car passed "semi-text"	14	8	10	14	11.5
IXB	Dispatcher passes "semi-text"	1	1	1	5	2.0
X	Car transmission - time	47	45	50	47	47.2
XI	Base transission - time	53	55	50	53	52.8
XII	Car transmission time "feasible to digitize" [a]	29	48	43	44	41.0
XIII	Dispatcher transmission time - "feasible to digitize"	52	52	59	54	54.2
IV	Total air time - "feasible to digitize"	41	50	51	49	47.8

[a]In this analysis, "text messages" are not considered to be digitized.

The status-button calls have a low ratio of air time to number of calls as indicated below:

Calls related to status = 54.6%
Air time attributed to status = 22.8%

The alphanumeric calls are categorized as those that would require the use of a keyboard if transmitted over a digital communication link.

Calls related to alphanumerics = 15.3%
Air time attributed to alphanumerics = 19.9%

As shown, 84 percent of the calls can be transmitted digitally and these calls account for 72 percent of the total mobile air time.

Base Station Data

Due to the nature of the command and control network of the Los Angeles Police Department, the data presented here represents the workload of three or more dispatchers sharing the same base station frequency. Three statistical samples of base station communications were taken, each of one-hour duration. The base station initiated messages are divided into the following categories:

1) Data base replies
2) Calls-for-service and status dispatching
3) Status-button calls
4) Alphanumeric calls

The totals of the data base replies are indicated below:

Calls related to data base replies = 9.5%
Air time attributed to data base replies = 14.9%

The totals of the calls-for-service and status dispatching are:

Calls related to calls-for-service, etc. = 16.1%
Air time attributed to calls-for-service, etc. = 32.6%

The totals for status-button calls are:

Calls related to status = 58.0%
Air time attributed to status = 28.8%

The totals for alphanumeric calls are:

Calls related to alphanumerics = 15.8%
Air time attributed to alphanumerics = 21.6%

2.3.4 Miami, Fla. Police Department

Data was obtained on the distribution transmission times of voice exchanges from the dispatchers and the mobile units. Channel occupancy was also determined. A curve of channel occupancy (percent vs. the number) of dispatcher transmissions per hour was generated and it is shown that message length compression begins to occur at a channel occupancy of 45 percent. Distribution functions of transmission times pertaining to data base inquiries are also developed. The mean and standard deviation of these various distribution functions are shown below.

OPERATIONS CHANNEL

Dispatcher transmission length $\bar{x} = 1.8$ s, $\sigma = 2.9$ s

Unit transmission length $\bar{x} = 2.4$ s, $\sigma = 2.4$ s

DATA BASE INQUIRY CHANNEL

Operator transmission length $\bar{x} = 2.1$ s
$\sigma = 3.6$ s

Unit transmission length $\bar{x} = 4.7$ s
$\sigma = 9.9$ s

2.4 Summary of Voice Message Data

It is to be expected that communications discipline and other characteristics of a police radio network will vary among police departments and be a direct function of the operating procedures established. However, from the data presented in this section it would appear that similarities exist in the parameters that are important in defining voice communications as presently used by law enforcement agencies.

For instance, the percentage of total air time occupied by status message in a number of cases (e.g., Boston, Fall River, Michigan State Police) fell into the range of 47 to 48 percent. Also, if one were to categorize messages by types as in the case of a Massachusetts State Police analysis [19], similarities would again be noted. In the Massachusetts State Police study, certain criteria were developed in order to determine an outline for the classification of status messages. It was determined that 56 percent of the State Police messages were status oriented. The same criteria were used to categorize the Boston and Fall River messages. Forty-five percent of the Boston and 47 percent of the Fall River Police messages were categorized as status. Another similarity is that a categorization analysis of the Los Angeles Police Department's communication exchange shows that 58 percent of their messages may be type classified as status. However, in the case of Los Angeles, the percentage of air time occupied by status messages is about half that of the previous cases. The reason for this discrepancy is that data base inquiries are made on the "operation's channel" of the LAPD quite frequently as opposed to the other police agencies and the long transmission time of these messages tends to decrease the percentage of transmission time used for status messages.

In the case of data base inquiries for criminal information and motor vehicle license checks another general similarity exists among various police departments. The format of many criminal justice information systems is generally similar to that used to access the National Crime Information Center (NCIC) files, and hence, there are similarities in the voice and data transactions that are addressed to NCIC.

Also, during the analyses performed, it became common practice to determine statistical parameters (e.g., averages and standard deviation) that characterize the length of all voice message exchanges over the network. The determination of the statistics of the lengths of the types of messages planned to be displayed on a digital terminal should be a prerequisite for determining the size of display needed. Display sizes will be discussed later.

3. OPERATING REQUIREMENTS FOR DIGITAL COMMUNICATIONS EQUIPMENT

3.1 General

This section details the efforts to determine the operational requirements for mobile digital communication equipment in the law enforcement environment. Although there are many interrelated factors that have an impact on this determination, the primary consideration was to establish the needs for such equipment as viewed by police agencies.

To ensure that the law enforcement aspect was properly included in the determination of the operating requirements, considerable attention was given to police communication problems and extensive discussions were held with responsible personnel of many different types of law enforcement agencies who have knowledge and experience of police communication operations. The types of agencies with which discussions were conducted included agencies servicing large to medium size urban/metropolitan areas, county police organizations and state police agencies. In most instances the respective agencies had already evaluated or were planning to

evaluate digital communications equipment so discussions were timely and appropriate.

In section 3.2 the responses obtained from discussions of 30 topics with these various law enforcement agencies are presented. In sections 3.3 and 3.4 applicable comments received from the Federal Communications Commission and the Associated Public-Safety Communications Offices, Inc. (APCO), are analyzed.

It was observed in these meetings that some jurisdictions had special problems which brought on different types of requirements. These are discussed in section 3.5.

3.2 Law Enforcement Agency Requirements

In making a determination of operational requirements from the viewpoint of police department needs, information was sought from various types of agencies knowledgeable in the area of digital communications. Data was collected on some 30 topics relating to different aspects of digital communications. The information collected from the discussions was analyzed to determine priority considerations and prevalent attitudes of the law enforcement community in specifying operating requirements for digital communications equipment.

The salient points of the operating requirements as characterized by law enforcement agencies are summarized below.

- Two-way digital communications is a definite requirement for law enforcement, and 80 percent of the departments surveyed wanted the digital units to interface with existing radio equipment. Most departments, 80 percent, did not feel that computer aided dispatch on a prerequisite to using digital communication systems.

- In the case where mobile-to-mobile communications occurs on the same channel that is used for mobile-to/from-base communications, there is a requirement to provide a digital capability for mobile-to-mobile exchanges. On the other hand, if the communication system is of the type where mobile-to-mobile transmissions take place on a separate channel, then mobile-to-mobile digital communication is unlikely to be needed, unless that channel is heavily loaded or there is a need for privacy in communications.

- In isolated cases there is a requirement for monitoring the digital exchanges with a terminal unit located at satellite command stations, e.g., precinct stations, etc. In these cases the unit should be capable of being powered from an ac outlet and of interfacing with telephone line channels.

- There is a definite requirement for a digital transmission system that provides both full-text and status capability. The preference indicated for the full-text capability is primarily due to the fact that many departments have access to some form of on-line computerized files and the extra cost of allowing direct access from mobile units can be more readily justified. However, it must be recognized that most departments require digital status capability, so that for those agencies with no on-line computerized files status-only units would provide a significant capability particularly with regard to relieving dispatch workload.

- Only 25 percent of the police departments contacted would require that the status code scheme be based on the APCO-10 code. There appears to be some resentment against using any fixed code scheme, evidenced by the fact that 75 percent of the police departments surveyed would want the capability to change the number or types of "status-codes" provided by a digital system.

- Half of the police agencies surveyed indicated that they would plan to equip all vehicles with digital communication capability. The other 50 percent indicated that not all mobiles would be equipped. This was due to two factors. Most often, some precincts experience a heavier workload than others, and in these cases, only the over burdened patrol area mobiles would be supplied with digital equipment. Also, in a limited number of cases, installation would be made only in selected vehicles which would then be assigned to making the bulk of data base inquiries. Most agencies, 85 percent, would equip all mobiles with both full text and status capability and 90 percent required selective address capability.

- In the area of information display at the base station, approximately half of the police departments require both a visual and a hard copy display, while the other half require only a visual display. For information display in the mobile the following was true:

  Approximately 40 percent required a CRT - type display with the addition of a "printer add-on" in a selected number of vehicles.

  Approximately 35 percent required both CRT - type and "printer add-on's" in all vehicles equipped.

  Approximately 20 percent of the agencies had no definite opinion.

  Approximately 5 percent required only a two-way printer.

- The survey indicated that the digital equipment should be made to interface with present existing radio systems, but that the channels used should be dedicated to data transmission.

- More than half of the police agencies indicated that automatic polling of mobile units for status update would be necessary. This requirement does not imply the necessity for a synchronous system with constant polling. What is meant here is that a mobile unit should be "queried" for an indication of status, if after some specified time period no change in status has occurred. This is similar to what a dispatcher might do on an existing voice system if he has not heard from a particular vehicle.

- The advantages and disadvantages of a continuous polling system vs. a data contention system used on a dedicated channel are not clear-cut and a very fine line exists between their respective performance characteristics. Because of this, the systems could be classed as similar. The major advantage of a polling system is in gathering data from mobiles at fixed time intervals, such as in an automatic vehicle locating system. This advantage has sometimes falsely been affixed to achieving more efficient status updates. However, no matter how many times a minute a mobile unit is polled for status information, the system concept still relies on the officer in the car to manually change his status and insert it into memory for polling. In a contention system, the status information implied by the operation of the "canned message button" is usually received at the base station and is then subject to delays similar to a polling system.

- The general consensus of opinion is not to let the mobile units respond solely under the control of the base station system. Another party, the dispatcher, should be allowed to monitor all automatic functions of the system, especially in the case of data base inquiries. The monitoring in this case is to provide security for limited access material. Although about half of the respondents required manual acknowledgment procedures, it was strongly recommended that human, along with machine (error control) acknowledgment be standard operating procedure.

- Along with improved response time and "better utilization of patrol force resources," "security" was considered a major benefit of a digital communication system. It should be noted that the security offered by present law enforcement digital communication systems is quite comparable to that attained in many scrambler systems. However, it is possible for unauthorized personnel to acquire a mobile unit and, with some technical expertise, receive and decode all digital transmissions even if they are on a selective basis. In order to upgrade the security features of a digital communication system, "code of the day" schemes could be employed.

- All police agencies voiced considerable concern over the bulk or physical size of many of the digital terminals presently available. This is a very important requirement as the "front" space of police vehicles is becoming more and more

crowded with accessories and equipment. The agencies would definitely prefer that the bulk of the electronics associated with the digital units be located in the trunk of the vehicle.

- The message display characteristics for CRT-type terminals as determined by the law enforcement survey are:

  Indication of a new incoming message,
  Special indication for a critical message,
  Message held until manually cleared, and
  Capability to store more than one received message.

- In most cases the indicators for a new incoming message and a special message were desired to be audible.

- Environmental tests, including shock and vibration, were high on a list of things to be done. Some departments have already experienced high temperature environment and salt spray problems with the digital units. Similarly, there was concern about life testing, most departments expressed the need for manufacturer maintenance and training programs, and almost all required equipment warranty.

- The typical allocation of number of cars per channel will probably be about 50. This is due to the fact that most police departments will tend to replace existing voice communications (recommended loading of 50 cars/channel) with digital communications. This is probably a reasonable approach because of two factors. The modification of existing systems or the installation of new systems to provide more area coverage to service the additional vehicles would probably be high. Also the present "precinct" management structures of many departments would probably be disrupted because of changes in precinct (zonal) determined frequency allocations.

3.3 Federal Communications Commission Rulings and Their Effect on Operating Requirements

The initial report and order of the Federal Communications Commission to permit general nonvoice operations on voice frequencies was adopted in late 1971. The docket number is 19086. The following requirements were specified:

1) Authorizations are limited to mobile service frequencies below 950 MHz.

2) Operations must be on a secondary, noninterference basis to any authorized radiotelephone operation.

3) Sensoring or monitoring devices must be employed to minimize interference to co-channel transmissions and shall be incorporated as automatic circuitry in the associated receiver, to prevent nonvoice signaling in the presence of another signal.

4) Maximum duration of a nonvoice transmission, including automatic repeats, may not exceed 2 s.

5) Required station identification for nonvoice operations must be made by A3 or F3 emission and may be given by the base station for a base-mobile system, even in the case when the mobile frequency is different from the base frequency.

6) Applications to use nonvoice operations must include detailed description of the coding systems to be employed for message content.

In a memorandum pertaining to docket number 19086 the word "must" in statement 3 was changed to "may" due to the technical difficulties some vendors were having in developing such a sensing device.

Comments with respect to the statements of the report and order and subsequent memorandum are given below:

Statement number two stems from the FCC's feeling that "licensees must have a primary voice requirement and further, since nonvoice techniques are expected to improve efficiency, we will not authorize an additional or separate frequency for this use". This statement was recorded before much operational experience with "full-text" digital equipment was acquired. Generally, in operational systems, data and voice communications have been found not to be compatible when they are in constant contention and subsequently they have been separated from an operational standpoint. Discussions with the FCC revealed that this type of operation may be acceptable as long as co-channel interference is not experienced and that the "dedicated data channel" provides emergency voice communication and voice back-up communications (when the data system fails) over the same frequencies. The FCC will not allow one to apply for new frequencies to support data systems and maintain voice back-up on existing frequencies. Also, the FCC will not allocate new voice frequencies to be used for voice back-up to data systems which have become operational on existing voice frequencies. This is perfectly reasonable, since data transmission is considered to be "more efficient" than voice.

With respect to statement three, it appears that the memorandum issued to ease the requirements on sensing channel activity was premature. As a matter of fact, most present digital systems can successfully perform the required channel sensing.

The "two second" limitation on digital transmission including repeats to assure correct reception should be defined differently. This ruling, as it reads, is probably violated by many of the "full-text" terminals in isolated cases when long messages are transmitted to fringe areas. It is also violated when long "front porch delays" proceed the data. A requirement such as the following, is recommended:

> The average time duration for nonvoice emission shall be less than or equal to 2.0 s plus any associated front porch delay. The average time duration shall be determined by a valid statistical sample of the time durations of nonvoice emission over the entire system area of coverage.

Base station identification should be made digitally through a standard information code and a standard modulation technique. Standard monitors for the decoding of base station identification should be provided. The standard information identification could perhaps be based on the ASCII code. However, flexibility should be allowed in implementing various types of error control coding and modulation techniques for messages other than base station identification.

Docket number 19261 also pertains to mobile digital communications. In this docket the disposition of 10 pairs of frequencies in the 460-470 MHz band reserved for radio teleprinter usage was resolved. Since radio teleprinter usage had not been as widespread as expected, nine single frequencies were removed from radio teleprinter usage. Five single mobile only frequencies were assigned for telemetry transmission of bio-medical information. Two pairs of frequencies were originally allocated to the 30 largest cities for development and operation of digital systems for information retrieval (data base inquiries) and other purposes.

These two allocated pairs had a data priority and secondary consideration is given to voice. More of these dedicated frequencies are needed in the larger cities and perhaps smaller cities should be allowed to use these frequencies if co-channel interference is avoided. When one utilizes these frequencies, no detection of voice usage is necessary. However, these same frequencies should be used in the back-up voice mode in the case of system failure and should be provided with a microphone and speaker.

3.4 Use of the APCO-10 Code in Mobile Digital Data Transmission

As indicated by the results of the requirements analysis, there is a strong tendency on the part of law enforcement not to restrict the designations used to identify "status buttons" to the APCO-10 code. Throughout the years, a multitude of police departments have developed their own voice code schemes, while others have restricted themselves to the pure APCO-10 code series and some use no code at all. Because of this, there is a tendency for police departments to request that status-

buttons be identified with their own code words. On the other hand, many of the agencies indicated that they would like to be able to change the number and basis for the digital status code schemes. This point reflects some uncertainty about what codes should be used. APCO has assigned a committee to review the situation. In an interview with a member of this committee, the expected output of this effort was discussed.

Probably, 10 or 12 standard codes will be developed based on a survey and will be recommended for widespread usage in voice communications. Any additional coding beyond these will be at the direction of the user, however, certain codes will be recommended. The output of this survey should provide enough information for the standardization of status-keys if a standard keyboard is recommended. The additional coding, if used, would be implemented with a thumbwheel type switch or similar arrangement as for status-only units, or through the use of alphanumeric keys with a special function-key in the case of full-text units.

3.5 Additional Operating Requirements

In the course of many of the discussions with police agencies, it often developed that there were additional operating requirements peculiar to individual agencies. In some cases these requirements are frequently a function of a department's projected communications plans and it is therefore likely that these kinds of special requirements will, at future times, be applicable to most agencies. The requirements that were identified are listed below:

- System should be compatible with requirements for an automatic vehicle monitoring system.
- System should be compatible with computer-aided dispatch requirements.
- System should be operable through a satelite voting receiver system.
- Portable hand-held units that provide data base inquiry capability are required.
- Motorcycle units are required.
- Digital transactions should be recorded on magnetic tape.
- Mobile units should not restrict officer movement in the vehicle.
- Some "special" keys should also be located outside the vehicle.
- Some of the "special" keys should be remotely activated.
- Mobile unit should be operable from both the driver and passenger positions.
- Display must be readable in direct sunlight.
- Message should not be displayed when an officer is away from the vehicle.
- System should provide a channel switching control for multiple channel systems.
- System should provide digital identification of radio channel in use, in a multiple channel system.
- System should operate in the "request to talk" mode under the absolute control of a dispatcher.
- System should accommodate simultaneous two-way data transmission when a duplex radio channel exists.
- The mobile unit should have a keyboard that provides a physical separation of function keys, status or canned message keys, and alphanumeric keys.
- System should provide the mobile unit with an indication of whether or not an information system is down or just running behind in response to data base inquiries.

o Portable hand-held units that provide digital identification (I.D.) and status are required.

These operating requirements that have been identified above do not present any significant constraints to digital communications as applied to law enforcement. This is particularly true considering the importance of communications in day-to-day police operation.

4. APPLICATIONS OF DIGITAL COMMUNICATIONS EQUIPMENT FOR LAW ENFORCEMENT USE

4.1 General

This section of the report deals with the applications of mobile digital communications equipment for law enforcement use. It will present various types of specific applications and the methods and techniques employed to realize them. Equipment characteristics will be discussed which will allow for a determination of the suitability of digital equipment in mobile police communications.

The number of agencies with operational digital communications systems are limited. However, during the course of the study, it was noted that consideration was being given to the purchase of systems on a widespread basis. This could eventually result in a great increase in the number of such applications. A significant reason for this potential increase is the severe constraints that are now being imposed on police patrol force operations by existing voice-only radio networks.

The constraints associated with these networks are primarily those of high channel utilization and dispatcher work load. High channel utilization is a condition that exists for many police agencies and results from the volume of radio calls being made during the day-to-day functioning of the police forces. On the other hand, dispatcher work load increases result from the growth in the number of citizen requests for police service. It is not uncommon for conditions in the dispatch-communications center to become hectic during the so-called busy hours, and such conditions do not create an efficient operation for controlling and coordinating the critical exchanges to and from the patrol forces.

Yet another contributing factor to these conditions is the result of data processing technology. This technology has resulted in a growth of a capability that provides for access in real-time to on-line files containing criminal justice information. The availability of this information to service the needs of the officer in the field has compounded the dispatcher work load and channel utilization problems.

In view of the problems that exist with the present voice mobile system, it is to be expected that police agencies would turn to other methods, such as digital communications, to provide them with a capability that will alleviate these problems.

In order to determine the suitability of digital communication applications as an aid to police operations, it is necessary to separate the voice messages into various classifications, as was illustrated earlier. The classifications, in conjunction with the operating requirements detailed previously, will provide a meaningful framework for discussing the suitability of mobile digital units in various types of applications. The discussion will also take into account the knowledge and experience of those departments that are currently assessing and operating mobile digital communications systems. Another important consideration when examining the suitability of the types of application is the difference in equipment that is presently being made available by various manufacturers. These equipment differences cover a wide range of technical and operational characteristics.

In the first parts of this section some fundamental concepts of digital systems are examined to determine how they can be used to supplement the existing voice-only radio network. The advantages and disadvantages of some of these systems will be highlighted to ascertain the implications and impact on police operations. These

are, to some extent, supported by an evaluation of those systems that have been in operation for any length of time.

Following these discussions, a description of the types of mobile digital equipments that are now available will be given. To assist in the examination or evaluation of the equipment, charts are included which detail the important features of the equipments. The charts also contain currently available pricing information as supplied by each vendor. Where it has been found that differences in equipment functional characteristics exist that could affect the application suitability, the differences are explained in more detail.

The concluding part of this section contains comments on the types of future applications that may result as digital communications in law enforcement become more common.

4.2 Interfacing with the Existing Operational Environment

4.2.1 General

With rare exceptions, the present police mobile communication systems were not designed with data in mind. In some instances this can present a severe problem to the application for mobile digital equipment designed for law enforcement use. Although compelling reasons exist for police agencies to turn to digital communications to help alleviate the problems created by the congestion of the voice-only radio networks, it is most unlikely that these networks will undergo major redesign just to incorporate data channels. There are few departments that are able to afford the luxury of a redesign of their present communications systems. Furthermore, voice communications will continue to be the most important communications medium in police operations and thus will require the highest priority.

This condition must be taken into account in the development of digital systems so they can readily be integrated into the mobile police communications network. It is possible that some restructuring of these networks will be necessary to facilitate a digital capability. However, it must be recognized that the digital systems should be compatible with the existing radio systems rather than vice versa. Compatibility should be the responsibility of the newer digital applications if they are to be used in police work.

A complete understanding of the present operating environment of the existing police radio network is therefore necessary, particularly with regard to interfacing of digital transmission systems.

4.2.2 Types of Messages

In section 2 of this report the results of a classification of voice messages were presented. The various categories of these exchanges represent the basis of the aspects of police communications that can be transmitted digitally.

An important class of exchanges was identified as status type messages, and it was noted that during the test samples, approximately 50 percent of all mobile voice messages fell into this category. It would appear that these communications represent a significant amount that can be transmitted as digital exchanges. Equipment exists, which can be installed in mobile units so the officer can select a code corresponding to his status and transmit this information by operating an appropriate switch. The status code corresponding to each mobile unit is then displayed at the communications dispatch center.

This type of information, status of mobile units, is transmitted one way from the mobile to the base station, except for "acknowledgment" (ack) and I.D. requests. Therefore, a one-way digital capability could be used for exchanging approximately half of the mobile originated police voice messages. However, there are characteristics of the status type category which should be examined to determine the value of this type of digital systems.

Although it was shown that the number of status messages is approximately 50 percent of all mobile exchanges, the air time required for these communications is not necessarily an equivalent percentage of total air time. The amount of air time actually required depends upon factors such as the use of codes to identify status, the types of other exchanges on the radio network and particularly the amount of inquiry information that must be passed on the channels. For instance, when there are a large number of inquiries the air time of status messages is a low percentage of total air time.

Another characteristic of status messages is the type of voice code, if any, that is used to identify mobile unit status. If status is based on a code this provides a good basis for using the same codes with a digital system. However, when departments communicate status through descriptive text type messages rather than codes, code oriented digital status units are not suitable unless the department is willing to modify its operations and train its officers to use a system of codes. To retain the same format of status communications would require some keyboard type capability in the patrol units, which the officer could use to generate a complete description of his status. This would require a considerable amount of "typing" time on the part of the patrol personnel, which is a very inefficient use of the capability of keyboard type units when used in this mode of operation. In addition, the dispatch center would require a companion unit that has the capability to display the whole message in written form.

It was noted earlier that most agencies require a digital communications capability for exchanging status information. Also, there was a general consensus that codes would provide an acceptable basis for identifying status although the code should not necessarily be based on the APCO-10, as most departments indicated a need for flexibility in the assignment of status codes.

Another category of voice messages was identified as text type exchanges. Included in this category were those messages that are inquiry oriented such as license checks. The existence of these kinds of messages is due mainly to the availability of computerized information. This operation previously required the patrol officer to request the information by voice exchanges with the dispatcher. The dispatcher in turn either accessed the information system from his console or he passed the request to another operator assigned to perform this operation. When the computer system returned the information, the dispatcher passed the contents back to the patrol officer via the voice channel.

Inquiries such as these can be performed by digital equipment in such a way as to substantially reduce the dispatcher work load. The field mobile units can be equipped with digital terminals that allow the officer to compose the inquiry by using a keyboard unit. Once the message has been structured, it can be directly transmitted into the information system via the communications center. As the channel is a two-way link, the information in response to the inquiry can be communicated directly back to the mobile terminal and displayed. This approach, which replaces voice messages with digital transmissions, is a very effective method of using digital communications.

Although inquiry type communications represent a suitable candidate for the use of mobile digital equipment, it does not necessarily follow that channel utilization will be reduced. Typically, an individual inquiry will be exchanged and processed faster digitally than it will be during voice-only operations. However, the implementation of mobile digital terminals in patrol units provides a capability that tends to establish its own message traffic pattern. Compared to a voice-only system, a digital system with mobile terminals is more flexible and efficient for making inquiry type exchanges. Once it becomes accustomed to using the terminals as a matter of routine, the patrol force tends to use them more so the level of inquiries increases well beyond the normal or typical level with the voice-only system. Communications traffic can increase to the extent that channel utilization may be increased rather than decreased. Some of the implications of this condition are discussed in a following paragraph.

Another type of voice message can be classified as descriptive or conversational exchanges. They occur frequently during emergency situations such as hot pursuit. In these situations conversations are developed between the dispatcher and mobile, and it is not uncommon for other patrol units to monitor the communications as many base stations rebroadcast the mobile messages. Theoretically, all such exchanges

can be made digitally by equipping mobile units and the dispatcher with keyboard type units. This would allow for a total digital communication system.

There are a number of implications with this mode of operations. With voice communications there is a natural tendency to develop invaluable conversations between dispatcher and mobile in instances such as emergency operations. If there is a rebroadcasting of mobile messages, other members of the patrol force will be aware of pending actions as they develop. The other mobiles may also recognize characteristics or features about the conversation between dispatcher and another mobile, and may be able to contribute valuable information.

If these exchanges were to be initiated digitally, the tendency to develop conversations would disappear. This is because the officer has to "type" his message rather than using the spoken word. An invaluable aspect of communication would inevitably disappear. Also, if all mobiles were equipped to receive any message from any other mobile, the method of monitoring all communications by reading a display would be more restrictive than that of listening to a voice channel. Most police agencies agree that descriptive/conversational types of communications must continue to be exchanged as voice-messages.

4.2.3 Propagation Environment

The law enforcement community has access to the frequency bands which have been allocated for land-mobile radio usage by public safety agencies. The bands available are the very high frequency (VHF) and ultra high frequency (UHF) bands. These bands each have different propagation characteristics which, coupled with the condition that the power spectrum of man-made noise is not equally distributed among the bands, can adversely affect data communications to different degrees.

The low band portion of the VHF band is prone to what is referred to as "skip" interference. Skip occurs when a users' receiver is captured by a signal, at the same frequency, that is being radiated from a very distant user. This condition is caused by the reflection of a signal off various ionspheric layers and occurs in skips of 500 to 3000 mi. A short range skip phenomena can occur from ducting of co-channel signals through ionsphere layers. The range of this interference is typically from 100 to 400 mi. This short range skip (ducting) is more prevalent at the high band portion of the VHF band. The UHF band is generally not affected by the skip form of interference. In voice radio systems tone-coded squelch techniques are frequently employed to protect against this type of interference. However, with digital signaling, the interferring signal can effectively destroy the information contained in the signal.

Another propagation phenomenon that is present in communication systems of interest is multipath. This phenomenon is most prevalent in the UHF band, and it is manifested by the occurrence of fades consisting of different amplitudes and time durations in the received signal. This explanation is a simplification and a more detailed discussion of this effect is given later. The overall effect of multipath is a substantial increase in the number of errors in the received digital signal. To protect against these errors, detection and correction methods are required as part of digital communication systems.

Another propagation characteristic of radio communication is ambient noise, frequently referred to as man-made noise. This noise is particularly prevalent in areas with a concentration of automobiles, whose ignition systems produce interfering signals. Other causes include radiation from high voltage breakdown across insulators on transmission lines and transients emanating from locations where electrical connections are periodically being switched.

A receiver in this environment will also be subjected to time-varying interference of its own received signal. This type of interference is different from multipath in that it occurs in bursts of short time duration with very high amplitude peaks. The effects of this noise are most pronounced on VHF low band signals and less severe on VHF high band and UHF. The ultimate effect on digital communication is to cause errors in the received signals. Its effect can be combatted through the use of detection and correction coding of the digital signal.

The major significance of these propagation characteristics is that while they may not adversely effect voice communicatons, they can seriously disrupt digital communications. Digital systems must employ features to combat these phenomena if reliable communications are to be obtained.

4.2.4 Characteristics of Existing Voice Networks

The voice communications systems of most law enforcement agencies are configured about a few basic building blocks. These are the location of dispatching points, the location of base station equipment (particularly antennas), the channel structure (single frequency vs. multifrequency) and the network structure (single channel or multiple channel). No matter how these existing systems are laid out, the data transmission to and from a mobile terminal must function in this environment. However, the most cost-effective configuration may not be to replace voice with data on a one-to-one basis, but to reconfigure the existing system at minimal cost. Examples will be used to illustrate the features of these building blocks in various configurations and the limitations on data transmission.

One area that does not depend on the agency operational procedures is the type of channel structure. Basically, there are three types:

Single frequency simplex
Dual frequency simplex
Dual frequency half-duplex

In the single frequency simplex case, one frequency is used for both base-to-mobile and mobile-to-base communications. The application of a mobile digital system to such a channel is quite straight forward as long as simultaneous communications are inhibited. In some cases, a single frequency simplex channel has been used for implementing a one-way or a two-way time multiplexed mobile printer, and these channels can also be used for time-multiplexed two-way status or full-text systems.

When dual frequency simplex voice systems are employed for voice communications, the base-to-mobile and mobile-to-base frequencies are different. There is a noted advantage in transmitting data over these channels that is not always utilized. Even though mobile-to-base and base-to-mobile data transactions can take place simultaneously, data systems with this channel arrangement usually employ nonsimultaneous transmission. However, it is possible to use techniques that take advantage of two-way simultaneous data communications when existing system hardware permits. This approach entails fewer problems than doubling the data rate on time shared single frequency systems.

In the case of dual frequency half-duplex communications systems, some other features must be incorporated into the digital system to take full advantage of the channel. Duplexing normally occurs at the base station where voice communication on the mobile-to-base frequency is duplexed and repeated on the base-to-mobile frequency to allow mobile awareness of mobile-to-base transactions, and also to permit mobile-to-mobile communications. If this type of channel is time shared by digital communications of base-to-mobile and mobile-to-base, the repeat function of the base station can remain untouched. If any data feedthrough onto the base-to-mobile frequency occurs, it will not be decoded by the mobile terminal because it is preceded by a base station data identification preamble. However, if the automatic repeat feature of such base station equipments is inhibited for data transmission, two-way simultaneous base-to-mobile and mobile-to-base data communications could take place.

Mobile-to-mobile data communications are generally considered to be a special requirement. This type of transaction is usually relayed from mobile one-to-base and then base-to-mobile two in the case of simplex and half-duplex systems. Direct mobile-to-mobile digital communications would probably require additional considerations.

The consideration of mobile digital communications systems as they apply to operating voice networks involve many problems that are characteristic of the systems. These problems are compounded by the fact that many differences exist from one operating system to another. However, an example of the application of a mobile

digital communication system to an existing voice system is given as an hypothetical example. Some of the problems associated with the proposed system will be presented.

In the hypothetical example, a city of approximately 500,000 people has 60 patrol vehicles on the road at one time. The city has been sectioned into two zones, designated A and B, in order to provide better allocation of patrol forces and better administrative control. There are two base-mobile communicating channels which are used for dispatching and mobile-to-mobile communications designated on the zoned basis. There is also a city-wide channel for data base inquiries and emergency communications. There are two dispatching positions, one for zone A and the other for zone B, both with access to the city-wide channel. There is also a clerk who has access to both an information system terminal and the city-wide channel as this channel is used to make voice data base inquiries.

The control center is located in a building physically separated from the base station equipment and connected to the base station by leased telephone lines. This centrally located base station houses the transceivers for zone A, zone B, and city-wide frequencies. There are four voting satellite receivers: two used in conjunction with the base receiver for talk back coverage for zone A mobiles on zone A frequency and city-wide frequency; and two used in conjunction with the base station receiver for zone B mobile talk back coverage on zone B and city-wide frequencies. The voting selector is located at the control center and is connected to the voting receivers by leased telephone lines. The voice-only system is illustrated in figure 3.

A diagram of the mobile digital system implemented on the same channel is shown in figure 4 where the operational characteristics are also outlined. The following additions have been made. The entire patrol force has been outfitted with 60 two-way keyboard-type terminals with full text capability. The 30 units in zone A operate on the zone A frequency and exchange status and data base inquiries over this channel. Similarly, the 30 units in zone B exchange the same information on the zone B frequency. The dispatchers each have base station displays of the messages being exchanged along with status indicators and a data base inquiry monitor. The remaining messages are exchanged over the city-wide frequency by normal voice communications, possibly supplemented by automatic digital identification. Mobile-to-mobile communications are also implemented on the city-wide channel.

The most severe problems that would probably be encountered in implementing such a system would be data transmission through the telephone lines associated with the voice system and data transmission through voting receiver system. The problems encountered are varied. Frequently leased telphone lines are of the unconditioned type, perfectly adequate for voice and control tones but totally inadequate for transmission above 1000-1200 b/s. This is due to many factors such as ambient noise, crosstalk, amplitude and phase vs. frequency distortion. The transmission of data through the voting receiver system adds two other factors. These are the transients that occur when switching from one receiver to another, and the notch filter characteristics that cut out part of the system audio response in order to use audio tone control of these systems.

The switching transient problem can be overcome by locking on to one receiver during the data burst and inhibiting voting during this period, or by the design of burst error correcting codes to "ride through" the votes. Another technique that can be applied is to receive and store the data from the three satellite receivers and then implement a two or more out of three decoding scheme with the stored data.

The problem that will probably remain in the future will be the severe attenuation and phase vs. frequency distortion caused by the notch filter response. The basic approach to solving this problem has been to shift the audio data carrier to a clear portion of the audio band and lower the data rate in order to restrict the frequency spectrum to a unused portion of the available bandwidth. Often the data rate may have to be reduced significantly.

Although the example is for a hypothetical city, the type of network described is typical of existing police radio networks. Therefore, the problems identified

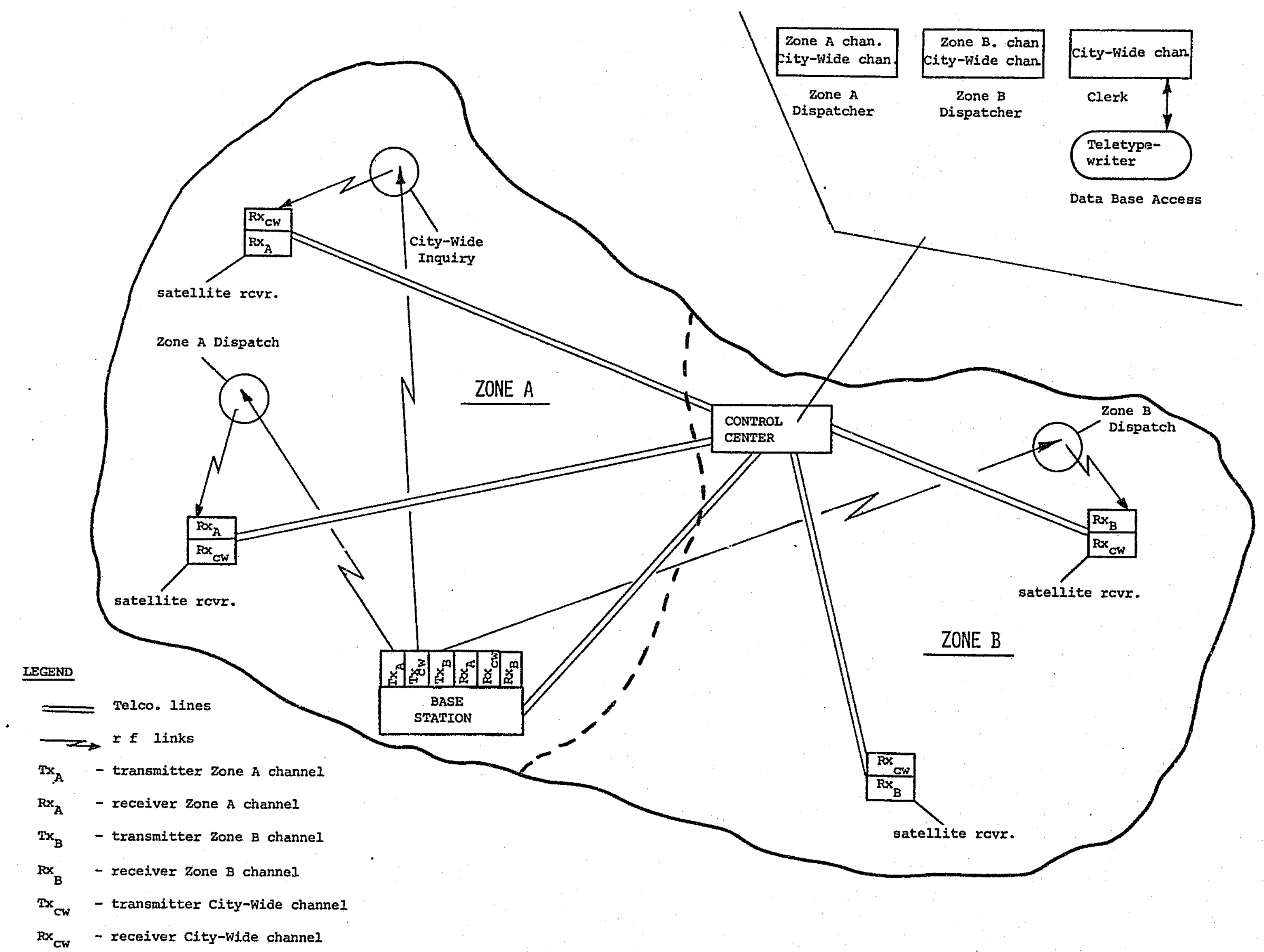


Figure 3. Voice communication system.

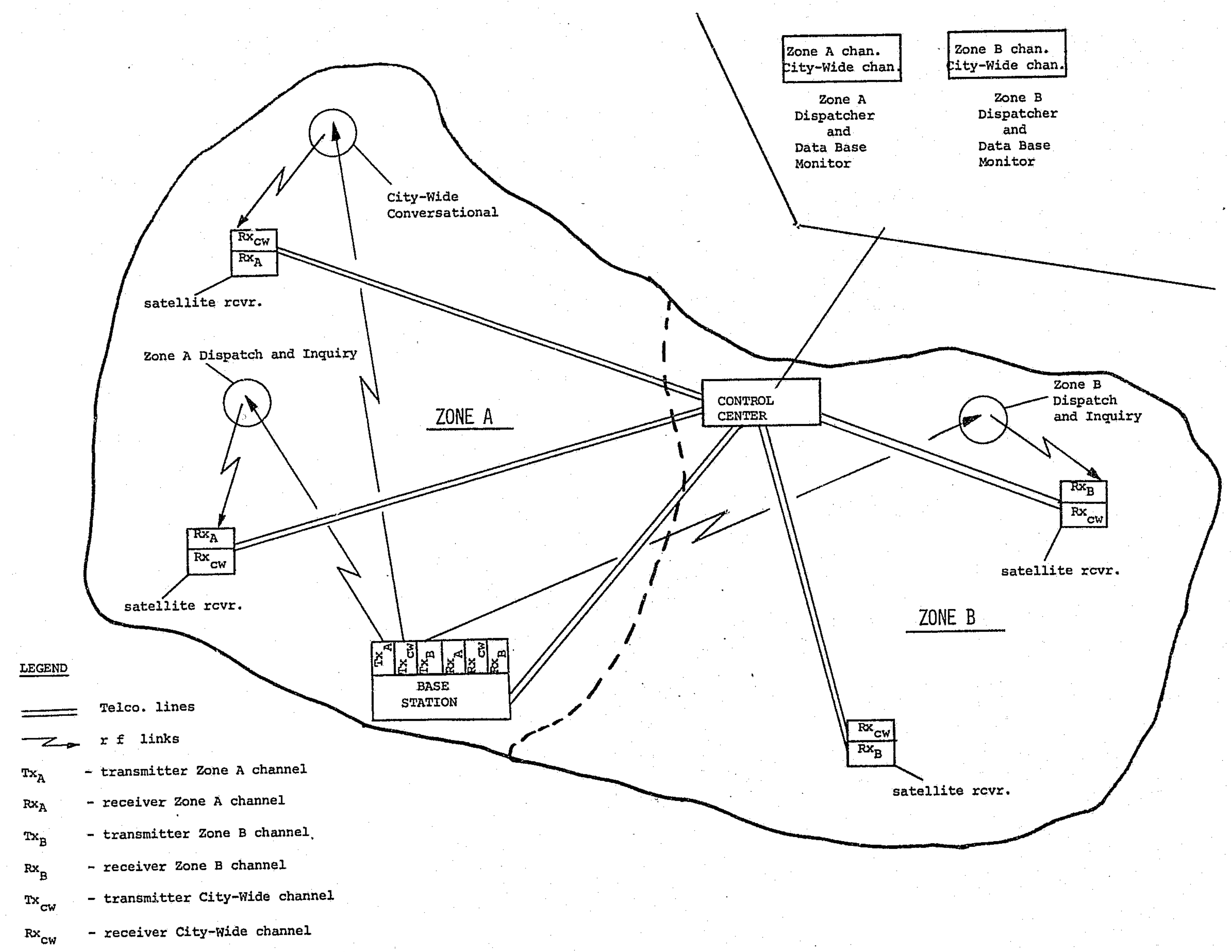


Figure 4. System with digital communication.

are practical ones likely to be encountered when a mobile digital communication capability is added to the communications system of a law enforcement agency.

4.2.5 Digital Data with Existing FM Radios

For applications of mobile digital communications equipment in the law enforcement environment, the equipment must be designed for reliable data transmission through existing voice grade networks. An immediate factor to be recognized is that compensation is needed for the normally longer response and turn on times of older equipment. A suitable technique is to use an adjustable preamble to the data to ensure that the analog communication equipment is ready for data transmission. This compensation results in somewhat longer transmission times than are theoretically necessary for pure digital signaling. The turn-on delay also affects the operation of a digital communication system in that it is one of the more significant drawbacks of a turn-on/turn-off contention system, as it reduces system throughput.

Another condition to be recognized is that while radios are supposed to be designed and maintained to industry standards, this is not always the case. Misaligned or improperly maintained FM radios can introduce severe attenuation and phase vs. frequency distortion into the channels used for digital communications which can adversely affect the performance of data systems. However, present day radios are not designed with digital data quality as a major concern, and some amount of distortion will always be present.

Another condition that affects digital communications is the wide tolerance allowed on the attenuation vs. frequency roll-off characteristics of the limiter filter of existing radios. Frequently the higher frequency components are attenuated to the full tolerance of the specification to achieve better quieting. This technique is normally more acceptable for voice communication, but it degrades the quality of digital communication. However, this design technique is not likely to change as it enhances voice communications.

In order to avoid as much distortion as possible, most digital equipment interfaces with the radio at the discriminator output. In this way the de-emphasis filter and the audio amplifier are bypassed. To compensate for the remaining attenuation and phase vs. frequency distortion present in existing radios, fixed and adjustable equalizers are being developed that can be used with mobile digital terminals. In essence, the equalizers "flatten out" the audio band frequency response. The fixed equalizers compensate for a limited amount of the anticipated distortion. The variable equalizers, on the other hand, can be adjusted to compensate for some of the variations in distortion. With these equalizers some tuning is required to match the individual radio. Adaptive equalizers that automatically compensate for dynamic changes such as those which occur when the physical transmission path is switched, are presently in the research stage. Such techniques may eventually be employed with mobile digital communications equipment.

As in the case of audible tone-coded voting systems and base station keying equipment, the notched audio response of tone-coded squelch used in radios presents a deterrent to achieving high data rates in mobile digital data transmission. However, radios with tone-coded squelch have one convenient advantage in that the audible tones of digital data transmission can be eliminated from the mobile radio speaker by inhibiting the tone control during data transmission. The digital data is unaffected because it is decoded from the discriminator output where a signal is always present whether or not the audio receive stage is turned on. Another advantage to decoding data from the discriminator output is that the audio signal strength into the mobile terminal is not a function of the squelch setting or the volume control setting.

4.2.6 Operational Aspects of Information Systems

It was noted previously that mobile digital terminals that have a direct access for data base inquiries can provide an increased volume of inquiry messages that exceeds the volume of inquiries generated with a voice-only system. This may result in higher channel utilization with a digital system.

There is another important consideration that must be examined in detail, which is a direct result of the use of mobile digital units that can directly access a data base. A major concern is the amount of volume of data base inquiries that can be generated and the subsequent effect on the operations of the data base system. Computer information systems used by police departments have been designed to maintain a certain throughput in response to a level of on-line inquiries. Also these information systems often provide service on a regional basis including state-wide systems. The point of police access to these systems is usually through a terminal device(s) located in the communications center and the interconnection between the terminal and the information system is usually through a hard-wired land line link.

Most present information systems were designed using traffic estimates of the anticipated or expected number of inquiries that would be generated from the police terminals located in the dispatch communications centers. These inquiries, in turn, are generated by mobile units through voice communications. Mobile units when equipped with a digital inquiry capability can access the information system directly, therefore bypassing the dispatcher. The mobile terminals, in effect, become on-line terminals. A minicomputer device can be used for coordinating the flow of information to and from the mobile units.

The types of information files that usually are accessible contain data such as vehicle licenses, vehicle registrations and outstanding want warrants. A patrol officer in a mobile unit is constantly in an environment where such information could be pertinent. It has been shown that personnel in mobile units outfitted with digital terminals will not hesitate to make inquiries given the means to directly access the information system. There will, therefore, be a sharp increase in the number of on-line inquiries that the information system will have to service. This increase could present operational difficulties for the information system that could result in degraded performance, particularly with regard to inquiry response time.

The increase in the number of inquiries can be a factor of over 100. This is the experience of at least one agency with an operational mobile digital communications system. Prior to the installation of the system the average number of data base inquiries averaged approximately 500 per month. Following installation of the system, the monthly average is of the order of 70,000 to 80,000 inquiries.

4.3 Types of Applications

4.3.1 Introduction

The specific types of mobile digital communications that are likely to find application in law enforcement can be divided into a number of categories. These categories form a hierarchy such that each type of application can be considered a subcategory of another. At one extreme, all of the police radio network voice communications could be performed with digital equipment.

The following pages present examples of the different uses of mobile digital communication systems as they apply to law enforcement agencies. In a number of instances, the examples correspond to systems that are presently operational. In most of these cases, visits were made during the study to the respective agencies. These visits provided on-the-spot observations and, wherever possible, participation in live demonstrations. There was no attempt made to conduct a thorough evaluation of any of these systems. However, significant information was obtained as to the advantages and disadvantages of the various types of applications.

The narrative associated with each application considers the various advantages and disadvantages in terms of the problems solved by each application and discusses the other benefits that might be achieved. Wherever alternatives in equipment types can be used in any specific application, comments to this effect are made.

4.3.2 Status Only

The first type of application to be considered is the digital transmission of mobile status exchanges. It has already been shown that approximately 50 percent of all messages belong in this category. The underlying basis for digitizing status exchanges are the codes that are used to represent the various status conditions of the mobile units.

Status only systems can be implemented with one-way mobile-to-base station communications. In this case an add-on device with electronic logic to generate the codes is used with the mobile radios. Whenever a patrol officer wants to indicate his status he selects a corresponding numerical code which causes the appropriate status message to be generated. The means of selecting these status codes can be thumbwheel type switches located on the front panel of the add-on device. The actual transmission of the status is initiated by the officer pushing a transmit button much the same as the push-to-talk button of a voice microphone. The device then causes the appropriate digital signal to be transmitted by the mobile transceiver. The status code is complemented by adding the vehicle identification to complete the message. This feature of status, plus vehicle I.D., can be added to all voice communications as a preamble initiated by the push-to-talk switch.

Variation to this method would provide devices that replace the existing control head provided such devices include a microphone jack, volume and squelch control.

In general practice, a limited number of status codes, such as acknowledgment, in-service and out-of-service, are used more frequently than others. Options exist as to their selection, as special function buttons. The bulk of electronic circuitry required for status units can be located in the vehicle trunk. This mode of digital status transmission, one way only, is unsuitable for law enforcement operations except for those cases where it is used as a preamble to voice messages from the mobile. This lack of suitability is due primarily to reliability of communications in that no guarantee can be made that the messages will be received. Therefore, at least a limited two-way capability has to be provided for reliable digital status communications. This will allow for error detection and automatic acknowledgment.

In two-way systems, the initiation of a mobile-to-base status message is identical to that of a one-way system. However, the two-way capability provides for repeat-request communications and automatic and/or manual acknowledgment of messages received correctly. In some instances, the base to mobile communication link has been used to relay canned messages from the dispatch center and to implement other control functions, such as switch to voice, and dispatcher control of mobile radio channel selection. However, the number of status type messages transmitted over the base-to-mobile link is limited.

The return link can be used to overcome a disadvantage of these systems by verification of the actual status code transmitted from the mobile unit. An officer may inadvertantly select a code that does not pertain to his true status. This message could be transmitted and received error free and the dispatcher would assume an incorrect status of the mobile unit. If, on the other hand, the feedback channel is used to retransmit the receiver status to the mobile and display it, this drawback can be circumvented.

In general, the status only use of mobile digital communications need only use a low data rate as the information content of each message is limited. A number of law enforcement agencies have installed such systems and their operational experience has been relatively trouble free. This may be primarily due to the low data rates employed.

4.3.3 One-Way Inquiry

Another application of mobile digital communication that has been implemented is a one-way digital inquiry capability. In this case the application is designed to relieve channel congestion by using digital techniques for communicating information in response to field generated data base type inquiries. One approach is to implement a one-way base-to-mobile digital communications link. The field generated inquiries (such as license checks) are communicated by voice from mobile to dispatcher. The dispatcher or some other communications center personnel then enters the data base system with the mobile inquiries. The response to this inquiry, once it is determined by the computerized information system, is then communicated directly to the mobile unit using the digital link, by passing the dispatcher. This approach addresses the problem of channel congestion and heavy

dispatcher workload by using digital communication techniques for the base-to-mobile response to inquiries. Therefore it represents a valid application for alleviation of the problems encountered with voice-only radio networks.

Mobile digital equipment most often used for this purpose are mobile printers which are located in the vicinity of the voice radio control head. The positioning of this device is to some extent quite critical to ensure that the officer is not inconvenienced in reading the displayed message. The components of a mobile printer can be functionally divided into three categories: the electronics for processing received digital messages; the printing device; and the media on which the message is printed, usually some form of paper. The electronics are a function of the type of modulation scheme, data rates, and other characteristics of digital signaling. The printing mechanism and the type of paper used is determined by the printing technique. These techniques fall into two general categories - impact and electrostatic printing. These methods of printing are discussed in a subsequent section dealing with equipment operational characteristics. Although mobile printers can be designed to have high reliability, they do contain mechanical components which may be prone to failures in a law enforcement mobile operating environment.

Although the discussion has focused on using one-way mobile printers for data base inquiry operations, this method of digital communications is not limited solely to this application. The dispatching center equipped with a capability of accessing the data link can communicate all base-to-mobile communications using digital signaling. All mobile dispatching can be performed digitally using this mode of operation. This can significantly enhance the capabilities of the one-way inquiry system.

One of the disadvantages of the one-way communications link is the uncertainty of reliability of message exchanges. A feature that has been employed to circumvent this disadvantage is to use dot-matrix type printing techniques. Dot-matrix type techniques have been developed that employ high redundancy characteristics which provide bit-by-bit control for the individual dots of the dot-matrix character. In these cases, when an error does occur that affects the digital communications, there exists sufficient redundancy in the character structure so it is most unlikely that a character would be completely unintelligible. Alternatively, in those cases where the mechanisms use individual hammers for printing the displayed characters, it is possible that the displayed message could contain erroneous characters. This could be particularly disastrous where the officer receives the wrong information. With these types of equipment characteristics, the more suitable method of overcoming this disadvantage is to use a feedback channel. As with status units, this feedback link can be used for repeat transmission requests and acknowledgment. However, in this case the feedback link is used for mobile-to-base communication.

It was noted earlier that the printing medium is usually some form of paper. There are both advantages and disadvantages where paper is used for recording and displaying messages in mobile units. Among the advantages is that a record of received messages can be maintained by the mobile units. For those agencies requiring documentary evidence of previous violations in apprehending suspicious persons, a printer is an ideal means of providing such evidence. In some instances compact printers have been designed that are suitable for meeting the available space requirements in the front of the patrol vehicles. The disadvantages of mobile printers are due primarily to mobile police operational considerations. The output medium is paper, which is not the most durable material for message storage. Also, mobile printer outputs provide yet another piece of paper that police officers will have to track. Furthermore, the officer must assess his paper supply to ensure that he can display messages throughout his tour of duty. Although the mobile operating environment is not particularly quiet, impact printers generate sufficient noise to create a nuisance effect. In the case of electrostatic printers, toner chemicals can be a supply problem. To a large extent, these disadvantages are not of a technical nature. Instead, they are, in the main, dependent on the prevailing attitudes of individual law enforcement users.

4.3.4 One-Way Inquiry - Plus Status

The use of both one-way inquiry and status in the same system is a natural development when a feedback channel is used for error control and acknowledgment. The two modes of operation complement each other when time-multiplexed.

The specific advantages of this type of application are the same as the advantages identified for status-only applications and the one-way inquiry application. The same is true for the disadvantages. However, an important aspect to consider when combining these features into a single system is that, ideally, the printer and status equipment should be sufficiently compatible to operate as one system. Another possibility with this application type is that a status code can be assigned to identify the condition that exists when the mobile unit is about to make an inquiry. This can be transmitted digitally and be displayed at the dispatch-communications center so that the dispatcher is alerted as to the type of inquiry he will receive by voice communications.

4.3.5 Full Two-Way Capability

The most common type of application of mobile digital communications in law enforcement is the one that allows for a two-way communication capability providing message exchanges of text type messages. This type of message includes both status and inquiry-oriented communications.

Implementation of this type of application provides the best means of solving the problems that have been identified in present voice radio networks. The two-way capability is usually implemented using mobile digital terminals that allow the officers to structure a message to be transmitted whether it is a status update or an inquiry requesting information from the control center. In the latter case the information could be contained in the data base of an on-line computerized information system. The two-way capability allows the mobile unit to directly access these data base files from the mobile via appropriate processing hardware and software in the base station. Response to the information request is transmitted directly to the mobile digital terminal and displayed for the officers attention. In this kind of operation the dispatcher is effectively bypassed although he is still able to monitor the digital transactions. Mobile terminal devices that are used to structure text messages generally require a keyboard component.

The equipments for displaying messages of a full two-way text application have been either mobile printer units or CRT-type screen devices. In either case the display and keyboard form a single unit.

Mobile digital communication systems of this type may typically operate as follows. In the case where a field officer wishes to make an inquiry, such as an automobile license check, he formats the message containing the required information. Typically for an automobile license check the character L indicates the type of inquiry, followed by the characters and State of the license plate in question. When he is satisfied that he has the correct contents of the message he initiates the transmission. The digital terminal unit generates an encoded digital message and activates the mobile radio for its transmission to the communications center. The center decodes the message and verifies the absence of errors. If no errors are present, the message is then passed on for appropriate action. If errors are detected, a retransmit request can be sent to the mobile terminal to initiate a repeat transmission. Alternatively, an automatic acknowledgment from the base station is transmitted when the received message is error free. When the message does contain errors the mobile digital terminal will not receive an acknowledgment and it is designed to continue transmission repeats of the same message until an acknowledgment is received or a predetermined number of retransmissions has been reached. The officer in the car is generally made aware of these conditions through status indicators.

Once the response to the received message has been determined (e.g., automobile information for requested license check), the reply message is likewise encoded and transmitted digitally to the mobile unit. The mobile digital terminal equipment decodes the reply and examines it for the presence of errors. If no errors are present, the message is displayed for the officers attention on the display medium of the terminal unit. The operations for error controls on the return channel are

similar to mobile to base communications. However, as indicated in the section dealing with operational requirements, an acknowledgment to a received message should be generated manually by the officer.

With the case of status type exchanges the officer can use the numeric keys of the keyboards where numerical codes are used to describe status. On the other hand, the alphabetical keys of the keyboard can be used to describe status when codes exist requiring their use (e.g., AP16). To distinguish the status messages from other text messages, an appropriately marked function key could be used to indicate a status transmission. Similarly, other keys can be designated for special functions so they can represent frequently used status codes. An important member of this latter category is one that can be used to designate emergency conditions.

It should be noted that in all transmissions from the mobile terminal unit a code corresponding to the vehicle I.D. forms an integral part of each message. Likewise, communications to mobile units will contain the vehicle I.D. which allows for selective addressing.

With this type of application, mobile-to-mobile digital communication is also possible. This mode of operation has been implemented by using the base station to automatically decode a received mobile message and re-encode the message and relay it to the other mobile units. Mobile-to-mobile communication can be enhanced by using these regenerative techniques.

From applications consideration the advantage of using this means of mobile digital communication for law enforcement operations is that it represents a technique for alleviating most of the problems associated with voice-only communication networks. A disadvantage is that this application requires yet another device to be located in the front of the vehicle where space is a premium. This was regarded with great concern by most police agencies contacted during the course of the study. Also, as previously noted, mobile terminals for direct access to on-line information files can result in very heavy data traffic conditions.

Other advantages and disadvantages stem from the use of two-way mobile printers and CRT-type mobile digital terminals, which affects the application and operation. While printers do have the capability for maintaining a record of messages, their printing speeds are considerably slower than CRT-type display rates. This could result in a mismatch between medium to high speed data rates and printing speed. On the other hand, printers are not limited by the length of messages to be displayed at any one time. In the case of CRT-type, the size of the screen is the limiting factor as it determines the amount of information that can be displayed at any one time. This is particularly restrictive in lengthy type exchanges, and screen size should be chosen so as to enable the majority of messages to be entirely displayed. The CRT-type units are not constrained by material supply type factors as are mobile printers (e.g., printing paper), and they have no noise problem. However, the optical characteristics of the screen present difficulties of reading the message in direct sunlight. This latter problem was also observed to exist with some mobile printers.

One advantage of mobile printers over some display units in the application of two-way mobile digital communication is that messages can be communicated to an officer when he has left his vehicle. On his return to the vehicle a record of the messages communicated to him during the period he was away from the car will be available for his inspection. This feature may be of importance for critical type messages. There is, however, some question on whether this is an advantage. For instance, any urgency associated with messages communicated during the time the officer is away from the vehicle will have been lost when such time is of substantial length. Also, the messages that are printed out during this period are not guarded or protected by a law enforcement officer and could be accessed by a third party. This could have serious implications where messages of a sensitive nature are communicated to the mobile unit when the officer is not present in the car.

Other important differences between the types of mobile terminal units are discussed in the next subsection.

4.4 Equipment Characteristics

4.4.1 General

An objective of the study was to identify the features and characteristics of the equipment that is presently available for mobile digital communications in law enforcement applications. There are at least 10 vendors engaged in the manufacture of equipment that offer a wide range of unit costs and technical characteristics. The technical characteristics relate to differences in functional, operational and physical features.

Information of the equipments was mainly obtained as a result of discussions with representatives of each of the vendor firms. In order to present the information in this report, so as to avoid any indications of bias, or preferences, charts have been developed which outline the pertinent features of the equipments available from each vendor. The listing of the vendors named follows an alphabetical order. Details on some of the characteristics of the equipments are of a general nature and do not refer to any specific design methodology that has been used by any manufacturer.

The listed units discussed in this section have not been tested as part of this study. Also, no attempt was made to physically evaluate or validate any of the data supplied by the manufacturers.

4.4.2 Details of Available Equipment

The major details of the presently available mobile digital communications equipment for law enforcement application are outlined in table 7. In the interest of completeness, information is included for equipment manufactured by E. F. Johnson, RCA, and Xerox, although the units are not currently being produced by these companies.

The equipment falls into three basic categories: status units, mobile (one-way) printers and two-way keyboard display units. Although the structure of the chart is almost self explanatory, there is a need to comment on some of the contents. Blank entries (-) are used to identify information that is not published for proprietary reasons, or is unavailable. Features that are not applicable to a particular device are listed as N/A. Although "add-on" printers have not been designated for all manufacturers of CRT-type keyboard devices, all manufacturers listed have considered this option and have indicated that such a capability will be provided if needed. The add-on features involve additional costs.

An examination of the table shows a wide range in a number of the designated categories. Among the types of equipment indicated two types of electronic displays, CTR and plasma, are available. Also, two different printing techniques, electrostatic and impact type, have been separately categorized in the charts. These features are discussed in the following subsection.

A few of the vendors have subdivided the mobile system into two physical components. This approach helps reduce the bulk of the equipment in the front of the patrol car and also facilitates modular construction allowing for possible redesign of the equipments without changing the most costly of the packages, the terminal unit. The respective sizes and weights of the individual units are given in the table.

The modulation techniques used in the various units are binary, except for six cases, and a wide variation in data rates exists. This range is from 75 to 2400 b/s for status units; 800 to 2000 b/s for one-way mobile printers, which are not add-ons; and 150 to 4800 b/s in the case of a two-way keyboard display device.

The input power, specified voltage range, current drain, and ground polarities of the various devices also have considerable variance. The variation in power drain is of significance when the application requires the system to operate with the vehicle ignition turned off.

The variations and the lack of definition of an operating environment are readily apparent from an examination of the data in the table. Environmental

Table 7. Characteristics of available mobile digital equipments.

Manufacturer	Applied Research & Dev.	Atlantic Research	Burroughs	Cincinnati Elect. Corp.	Coded Communications Corp.	E. F. Johnson/ Rydax	E. F. Johnson/ Rydax
Model	MDT240/256	Arcom	HHT	DMED-100	Reporter 111	PDH-2A	MDH-10
Type	Keyboard	Keyboard	Keyboard	Keyboard	Status, canned message only	Status, canned message only	Status, canned message only
Display/Printer	Plasma	LED	Plasma	LED	N/A	N/A	Plasma
Mobile components	1	2	1 (Hand-held)	1 (Hand-held)	1	2 (Replaces control head)	3 (Replaces control head)
Size of terminal unit HxWxD (in)	7x11.5x12 Sloping front	3.8x4.8x10. Sloping front	9x5.5x3.5	2.0x7.0x3.3	3.x8.2x10.5	7.2x4.6x5	7.2x4.6x5.5 9.2x3.2x7[a]
Size of add'l. unit HxWxD (in)	N/A	4.x15.x12.	N/A	N/A	N/A	7.3x8.2x2.5	7.3x8.2x2.5
Weight of terminal unit (lbs)	5	4	5	2	Less than 4	2.8	3.25 4[a]
Weight of add'l. unit (lbs)	N/A	10	N/A	N/A	N/A	2.5	2.5
Modulation technique	DPSK APSK	FSK	FSK	PSK or FSK	PSK	PSK	PSK
Data rate bits/sec.	1950 1300	600	300	150,300,600 or 1200 selectable	400	300	450
Input power (watts/dc)	80	37.5	3 standby 9 display	0.1 standby 2 display	11	17.7	24.5
Input voltage (volts-dc)	13.7±20%	12.5±20%	6	6 or 12 V	13.8±20%	13.6±20%	13.6±20%
Input current (amps-dc)	6	3. max	-	ext. source 0.3 max	0.5 1.5 max	1.3	1.8
Ground polarity	neg.	neg.	neg.	neg.	neg.	neg.	neg.
Output impedance (ohms)	600	600	-	50	50 when transmitting	Standby 22K Transmit 50	Standby 22K Transmit 50
Input impedance (ohms)	100 K	high	-	high	100 K	47 K	47 K
Points of connection	disc., ch. act., DC, mic., p.t.t.	disc., ch. act., DC, mic., p.t.t.	sp./mic. jack	p.t.t., mic., DC, ch. act.	ch. busy/ clear, p.t.t., A-, mic. vol. sq. low, A+, vol. sq. high	V.C. audio, DC sq., ch. act.,	V.C. audio, DC sq., ch. act., mic., CTCSS p.t.t., sp.
No. of function keys	16	10	5	17	8 status 5 message	9[b]	10
Source code	6 bit ASCII	7 bit ASCII	7 bit ASCII	6 bit ASCII	Binary	Hexa-decimal	Hexa-decimal 7 bit ASCII
No. char. displayed / prnt. spd.	256	16	32	16 presented 510 scrolled	None	-	64
Temp. (°C)	-30 to +65	-30 to +65	-	-40 to +85	-30 to +60	-30 to +60	0 to 50
Humidity	0-35% @ 65°C	0-85% @ 66°C	-	0-85% at 85°C	0-90% non-cond.	0-80% non-cond.	0-85% non-cond.
Shock	18 g	-	-	Mil Spec.	EIA	EIA[c]	EIA[c]
Vibration	EIA	-	-	Mil Spec.	EIA	EIA[c]	EIA[c]
Unit price	$2500	$2500	Quotation only	Quotation only	$785	Quotation only	Quotation only

[a]Optional alpha-numeric display.

[b]Does not include messages afforded by the thumb-wheel device.

[c]Meets environmental requirements of the Forest Service, U.S. Department of Agriculture.

Table 7. Characteristics of available mobile digital equipments (continued).

Manufacturer	E-Systems	E-Systems	General Electric	International Mobile Data Inc.	International Mobile Data Inc.	Kustom	Kustom
Model	MST-30	MDT-800	GE-Star	UMCT	TMDT	MCT-10	Printer MP-10
Type	Status, canned message only	Keyboard	I.D./help	Keyboard	Keyboard	Keyboard	Mobile printer (add on)
Display/printer	N/A	CRT	N/A	CRT	LED	Plasma	Electrostatic
Mobile Components	2	3	1	1	1	1	1
Size of terminal unit HxWxD (in)	5x8x10	12.8x10x10 Sloping front	7.4x1.1x1.9	10.6x9.9x7.8 Sloping front	7.2x9x2.5	10.2x13.5x9.8 Sloping front	6x5x10
Size of add'l. unit HxWxD (in)	1.3x8.3x5.3	3.3x15.8 x10.5 & 1.5x5.2x9	N/A	N/A	N/A	N/A	N/A
Weight of terminal unit (lbs)	6	11	0.8	14.3	3.8	17	5
Weight of add'l. unit (lbs)	1	13.5	N/A	N/A	N/A	N/A	N/A
Modulation technique	DPSK	DPSK	PSK	Baseband on FM	Baseband on FM	PSK	PSK
Data rate bits/s	2400	2400	400	4800	4800	1300	1300
Input power (watts-dc)	5	23	1.5	27.6 max	20.7 max	43.8 max	Standby 13.8 max Print 43.8 max
Input voltage (volts-dc)	13.5±20%	13.5±25%	13.8±20%	13.8±25%	13.8±20%	12.5±20%	12.5±20%
Input current (amps-dc)	2.7	1.7	0.1	2.0 max	1.5 max	3.5 max	Standby 1.1 max Print 3.5 max
Ground polarity	pos. or neg.	neg.	neg.	pos. or neg.	pos. or neg.	neg.	neg.
Output impedance (ohms)	51	51	600	600	600	-	N/A
Input impedance (ohms)	51 K	51 K	-	High	High	-	N/A
Points of connection	vol., sp., mic., p.t.t.	vol., sp., mic., p.t.t.	mic., p.t.t., DC	disc., p.t.t., ch. act., DC, mic.	disc., p.t.t., ch. act., DC, mic.	disc., ch. act., mic., DC, p.t.t.	N/A
No. of function keys	16	16	Switch for help	10	Numeric coding 0-9	13	None
Source code	6 bit ASCII	6 bit ASCII	N/A	7 bit ASCII	7 bit ASCII	6 bit ASCII	6 bit ASCII
No. char. displayed / prnt. spd.	256 char. with MP	256	None	315	32	256	50 char./s
Temp. (°C)	-40 to +85	-40 to +85	-30 to +60	-30 to +60	-30 to +60	-30 to +65	-30 to +65
Humidity	0-95% @ 49°C	0-95% @ 49°C	0-90% (EIA)	0-99% RH	0-95% RH	0-85% @ 66°C	0-85% @ 66°C
Shock	EIA	EIA	EIA	EIA	EIA	18 g	18 g
Vibration	EIA	EIA	EIA	EIA	EIA	-	-
Unit price	Quotation only	Quotation only	Quotation only	$3750	$2500	$3820	$1800

Table 7. Characteristics of available mobile digital equipments (continued).

Manufacturer	Motorola	Motorola	Motorola	RCA	Speedcall	Teletype	Xerox
Model	'MODAT'	MODAT MIMDT	VP-100	PSR-1	912	Model 40	Mobile Printer
Type	Status, canned message only	Keyboard	Mobile printer	Status, canned message only	Status, canned message only	Mobile printer	Mobile printer
Display/printer	N/A	Plasma	Electrostatic	N/A	N/A	Impact	Electrostatic
Mobile Components	2	2	1	1	1	2	1
Size of terminal unit HxWxD (in)	2.2x6.2x4.8	4.5x10x7 sloping front	4.1x10.1x9.5	3.5x5.5x2.5	3.25x12.25x7.88	5.5x10x10	9.5x8.5x15.4
Size of add'l. unit HxWxD (in)	2.2x10x12	5.8x1.8x11	N/A	N/A	N/A	5.5x10x10	N/A
Weight of terminal unit (lbs)	3	7	11	4	7	20	16
Weight of add'l. unit (lbs)	10	10	N/A	N/A	N/A	20	N/A
Modulation technique	Decimal FSK	APSK	PSK	PSK	2 of 8 Touchtone	PSK	FSK
Data rate bits/s	75 (estimate)	900/2400	800	300	12-20 digits/s	1200	2000
Input power (watts-dc)	8.3	48	Standby 4 Print. 19	9.6	3.6 max	Standby 6.9 Operate 62.1	Standby 2.6 Print 30
Input voltage (volts-dc)	13.8±20%	13.8±20%	13.8±20%	9-16.5	13.8±20%	13.8±20%	13.9±20%
Input current (amps-dc)	0.6	3.5	Standby 0.3 Print 1.4	0.3	0.3 mA max.	Standby 0.5 Operate 4.5	Standby 0.22 Print 2.5 ave. 10. peak
Ground polarity	pos. or neg.	pos. or neg.	neg.	neg.	pos. or neg.	N/A	Pos. or neg.
Output impedance (ohms)	N/A	N/A	-	N/A	200	low	-
Input impedance (ohms)	high	high	high	N/A	27 K	1 M	100 K to 1 M
Points of connection	disc., ch. act., mic., DC, p.t.t.	disc., ch. act., mic., DC, p.t.t.	disc., ch. act., mic., DC, p.t.t.	disc., DC, mic., p.t.t.	V.C. audio, DC, p.t.t., disc., mic.	disc., ch. act., mic., DC, p.t.t.	disc. or sp., DC
No. of function keys	8 to 16	6	Switch for help	8	9	N/A	N/A
Source code	Decimal code	N/A	5x7 dot matrix	8 decimal digits	-	7 bit ASCII	5x7 dot matrix
No. char. displayed / prnt. spd.	None	240	12 char./s	None	None	120 char./s	28 char./s
Temp. (°C)	-30 to +60	-30 to +60	-30 to +60	-30 to +65	-35 to +85	-30 to +60	-30 to +60
Humidity	EIA	0 to 95%	EIA	N/A	0-95% noncond.	95% @ 50°C	5-95% rel. hum.
Shock	EIA	EIA	EIA	EIA[a]	-	20 g (EIA)	-
Vibration	EIA	EIA	EIA	EIA[a]	-	EIA	RS-204
Unit price	Quotation only	$3200	$1470	$915	Quotation only	$2300	$1100

[a]Meets environmental requirements of the Forest Service, U.S. Department of Agriculture.

conditions are one of the most severe constraints on the operational use of the equipment. Environmental testing of these equipments should be well defined and should take into account the law enforcement environment.

Table 7 also identifies some of the characteristics of the interface between the mobile terminal and the mobile radio. For most modern radios, except for special cases where unusual test points are brought to the control head, the interface connection between the mobile digital unit and the mobile radio is made in the trunk. A separate dc supply cable is installed from the battery terminals to the mounted mobile digital terminal. The output impedance of the mobile digital terminal is generally the same as a microphone bridging network, while the input impedance is generally high. However in some cases, the addition of equipment has been known to reduce the area coverage of the base to mobile link by loading of the mobile radio discriminators and thereby reducing audio output. In addition to the discrimination (disc.), microphone (mic.), and dc power connections, there are special outputs such as channel activity (ch. act.) that allow monitoring of squelch, quieting, etc. and transmitter keying which are connected to the mobile radio. In some cases the data receive point is made at the speaker leads (sp.), however, this is not desirable because of additional data distortion due to the de-emphasis and audio amplifier circuits, which results in the data capability being affected by the volume and squelch controls. Other features include continuous tone-controlled squelch systems (CTCSS) and push to talk input (p.t.t.) to key the transmitter and to initiate a digital identification that accompanies the voice.

Some of the other items listed in the table are the number of special functions (i.e., canned message or status) keys, the source code used to format the digital message and the number of characters displayed in the case of CRT-type units or the printing speed, in characters per second, in the case of mobile printer units. If the source code, the data rate, and the level of redundancy of transmission and printing speed are known, the incompatability between high data rates and lower printing speed is readily recognized. This will require some form of buffering in the unit.

4.4.3 General Functional Characteristics of Available Equipment

The object of this section of the report is to provide a general description outlining the relative advantages and disadvantages of the various design techniques used in some of the functional areas of mobile digital communication equipment for law enforcement applications. The discussion includes printing techniques, such as impact printing with the use of segmented, whole or dot-matrix representations of characters and electrostatic dot-matrix printing. Comparisons of cathode-ray tube and plasma electronic displays are included along with a discussion of the presently available sizes of plasma displays. Keyboard characteristics and packaging techniques are also reviewed.

Functional comparisons between CRT-type and plasma displays and printed paper displays as they apply in the law enforcement environment are included in a previous section of this report. However, a significant comparative point is the size of the characters displayed. Typically, the printed characters are approximately .10 by .15 in, while an electronic display character is at least 50 percent larger. The printers in use presently in the law enforcement mobile terminal environment can be divided into two basic categories, impact type and electrostatic type. In the case of an impact printer, a mechanically moving hammer or series of hammers strikes the paper in such a manner as to form the selected character. The character may be constructed by a single impact or multiple impacts which form a segmental character or a dot-matrix array character. Although in most cases a standard set of characters will be required in the law enforcement application, the individual or bit-by-bit method of addressing dot-matrix hammers provides a relatively easy method of changing the character font and also provides the capability for a limited facsimile device (i.e., outlines or maps could be drawn using a series of dots with base station software control). Individual bit control of the dots of a dot-matrix printer is a high redundant transmission scheme (i.e., typically greater than 50 bits/character) and the chance of having a character interpreted in error is low. Dot-matrix printers can also be controlled by a standard source code such as ASCII, as in the case of single stroke and segmented character printers. The appropriate redundancy can be inserted by standard techniques of error control coding. The paper used to display the printed matter does not have to be of a special type, as

in the case of electrostatic printing, provided there exists an inking mechanism internal to the machine. However, some impact printers do not make use of an inking ribbon but use a layered carbon paper in order to form the permanent characters.

The disadvantages of impact printers are, many moving parts, low limit on printing speed, a high aural noise level and, in the case of standard source code addressed dot-matrix printers, a limited character font and graphic presentation capability. There is no printer available that eliminates all of these drawbacks without introducing some of its own. The electrostatic printer is an attempt at solving some of the problems associated with impact printers. A special paper along with some form of toner, powered in the mobile application, is generally used with electrostatic printers. The printing is usually done in a dot-matrix format with bit-by-bit addressing as discussed in the multiple impact case. Small dot-like electrostatic chargers are placed on the paper. These dots are developed when put in contact with the toner and heat is applied to provide toner fusing. The electrostatic printer is less subject to the problems of high ambient noise level and reliability but introduces the disadvantages associated with relatively expensive paper, lack of simultaneous multiple copy capability, and a time delay between message reception and readability.

As with printers, there are two general classes of electronic displays presently in use for mobile digital terminals for law enforcement applications. These are cathode-ray tube and plasma displays. Both displays use standard source code addressed dot-matrix characters and have comparable brightness and reliability. The CRT devices used in other applications have been known to implode. Cathode-ray tube displays generally exhibit higher contrast ratio than plasma displays due to the display addressing techniques, CRTs are electron beam addressed and plasma displays are circuit matrix addressed. Electron beam addressing allows for more "on element vs. off element" drive isolation than matrix addressing techniques that depend on the isolation between electronic circuit elements to provide contrast. On the other hand, one advantage of plasma displays is that they are of the "flat panel" type and do not require as high a power supply voltage as a CRT display.

As evidenced by the perforations on some equipments that use large plasma displays, another disadvantage is that plasmas are inefficient and generate heat. The plasma display sizes available for this application are 16, 32, 80, and 256 characters although the 80 character display has to be ruled out because of its physical length (i.e., approximately 2 ft). The cost of these displays when acquired on an "other existing manufacturer basis" is about $4 per character. One problem that exists with most of the displays applied to the law enforcement environment, including some printers, is that they are unreadable in direct sunlight. Many display units have a cursor control for editing messages and a buffering capability for input and output messages. These features are usually controlled by the operator by function keys associated with the keyboard.

The keyboard is an integral part of two-way mobile digital terminals and as such is a critical feature as in the case for status keys associated with status units. The arrangement and type of keys should be given some consideration in the selection of a mobile digital device. The arrangement of the status keys on a status-type mobile unit are generally arranged in linear rows. The type of keys used vary in size, configuration, and operational characteristics. Some keys lock in place when depressed and options exist whereby they could be individually illuminated from behind when selected. The future user should be aware of the drawbacks to some of the types of keys, such as dust entry into the voids between keys and along the side of keys, especially when they are of the thumb-wheel type. In most cases the alphabetical keys of the keyboards associated with terminals with full alphanumeric capability have a format similar to that of a standard typewriter. The numeric keys sometimes are located in the standard typewriter positions but are often located elsewhere to also serve as special function keys. In some cases the control and special function keys are color and size encoded. In the case where the various categories of keys are functionally separated, the physical separation of the functional arrangement is not discernible to sight or by touch. One of the frequently noted comments from law enforcement personnel was this need for physical separation of the keys by function.

Another critical area concerning the application of mobile digital terminal equipment in the law enforcement environment is the packaging and location of the terminal equipment. The terminal should be small enough so as not to obstruct an officer's movement in the vehicle, but also be large enough to have readable display characters and easily accessible alphanumeric keys. It should be mounted to facilitate usage in the case of two-man patrols and also not to present a safety hazard when a human impact occurs as in the case of a traffic accident.

Another general concern of law enforcement personnel is the complexity of the equipment and its impact on maintenance. This is where the requirement for future monitoring of operational systems is needed in order to determine the maintainability costs of mobile digital equipment.

4.5 Future Applications

Most of the content of this section of the report has considered the present applications of mobile digital equipment in law enforcement use. In conclusion, this latter subsection outlines some relatively subjective views about future application of such equipment. However, in most cases, these views are shared by many law enforcement personnel and manufacturer's representatives. The general consensus of opinion is that more of a total integration of digital mobile and associated control hardware and software into the police system will be evident in the near future. The piecewise implementation of many presently operating mobile digital systems does not achieve the ultimate goal of a fluid interaction of all the aspects of the police command and control network.

Probably the first step toward this end is the application of computer-aided dispatch in conjunction with a mobile digital environment. Presently implemented computer-aided dispatch systems suffer a restriction in the smooth flow of information from the computer files to the actual reception of the dispatch message in the patrol car. This restriction is the conversion of the digital dispatching information into the actual voice dispatch message. In the case of a totally compatible computer dispatch and mobile digital terminal system, the dispatching operation would achieve smoother implementation.

At present, a digital system cannot be used for communicating all voice communications. For this condition to exist, it would be necessary to employ sampling and quantizing of voice messages. This application is not at the state of the art level and is certainly not economically feasible when one considers the transmission bandwidth allocated to land mobile frequencies. However, future systems should consider central base station control of both digital and voice messages by the use of purely digital signaling. Some basic concepts have already been developed in that some vendor's equipment can relay digital voice requests from the mobile to the dispatcher. However, a truly coordinated voice and digital data compatible system would probably be implemented with a base station computer controlled polling system which would allocate voice slots on a separate voice channel. In general, when central control of a fleet of units is a requirement, a polling sequence of some kind is needed even though some sacrifice of immediate channel acquisition time is made. Another benefit of a polling system is that this can service more vehicles on a fixed time slot allocation basis and becomes the ideal mobile digital communications scheme when data has to be collected from the vehicles in a specified time frame, as in an automatic vehicle monitoring system.

In addition to varied future application of the presently available equipment, some new equipments are also being considered for the law enforcement application. These are a hand-held portable digital communications device and a truly digital radio. The first application for a digital hand-held portable will probably be used for status update for the police force that presently use portable radios for all voice communication. The extension of the capability for a portable device to facilitate data base inquiries will probably follow this development.

A significant increase in data rate is possible when one considers the possibilities of using the total transmission bandwidth (i.e., 20 kHz) of an allocated land-mobile channel to accommodate digital modulation. Direct digital modulation of the rf carrier could result in the achievement of reliable data rates of 10,000 b/s, as opposed to those of approximately 1500 b/s using the present technique of digital submodulation. Development of mobile radios of this type are being considered for future high speed mobile data applications. However, it is

unlikely that this application will be available for law enforcement use for some time.

5. TECHNICAL DISCUSSION OF MOBILE DIGITAL COMMUNICATIONS

5.1 General

The purpose of this section is to describe some of the technical aspects of mobile digital communications. The underlying objective being that a person familiar only with analog communications could study the following discussion and derive enough information to make a reasonable assessment of the types of technical information usually presented in vendor's literature. If more detailed information is required, an extensive list of technical references is cited in appendix A. However, detailed examination of theoretical developments will usually not allow anyone to make sound judgments about digital equipments without being supplemented by extensive field experience.

This text will begin by delineating some reasons for the advent of digital communications along with some basic introductory material. Next, a limited number of the different types of modulation techniques will be discussed. These modulation techniques have been studied in the presence of various types of noise and also under the condition of signal fading. The results of such studies are usually presented in graph form, relating digital performance in terms of a familiar analog communication quantity (i.e., probability of bit error vs. the received signal-to-noise ratio).

It is also common to find relationship between other analog and digital quantities. This will become evident when the maximum signaling speed is presented in terms of bandwidth, a familiar analog quantity.

A formula devised by Shannon [10] will be cited which incorporates the power and bandwidth limitations of digital communications in a definition of channel capacity (a measure of the information carrying capacity of an analog network that will be used to carry digital information). The theoretical information rate determined from this formula is generally impossible to achieve in practice, but varied attempts to transmit data at rates approaching the channel capacity have resulted in the development of many error control coding schemes. Parallel attempts to achieve higher information rates have resulted in the use of M-ary signaling as opposed to binary. M-ary signaling has been used with great success over telephone lines and its applications to mobile digital communications will be discussed. The effects of "imperfect channels" such as those characterized by attenuation or phase vs. frequency distortion will be included.

During the course of this study, discussions of a technical nature were held with the various vendors. The highlights of these discussions are presented in the final subsection.

5.2 Introduction

Until the early 1950's, analog transmission was the primary method of transmitting information. Today, with the widespread use of computers, immense quantities of information data are being generated. One major advantage of digital data transmission is that when the human voice is encrypted properly into digital data, the speed of information transmission can be increased without sacrificing reliability of communication. Another advantage of digital data transmission is extremely long distance communication using regenerative repeaters. Also, because the information is discrete in nature, error control coding techniques may be used effectively. Digital signaling also takes advantage of the cost effectiveness of the new solid state technology available in digital integrated circuits.

Many of these advantages are realized when digital data is transmitted over the police radio network.

o Most mobile digital communications equipment provide an information rate at least five times the speed of the spoken voice with higher reliability of correct communication.

o Modern CRT-type or light panel status displays in use in the dispatching rooms of many police departments lend themselves to remote change of status instantly with digital signaling.

o The advent of large data bases with criminal justice and vehicle information files have their effectiveness increased immensely when the officer in the field is allowed to query them directly.

o Digital signaling is easily encrypted so that security of transmission is enhanced.

In general, digital data transmission systems will provide the modern day police operation with a chance to move forward in the area of command and control with reliable, efficient, and secure communications.

Digital communications transmit information as a discrete sequence. Each member of the sequence is selected from a fixed number of symbols or waveforms. It should be clear that digital signaling is not necessarily binary. Binary digital communications occurs when the symbols selected for transmission can only be one of two possible choices. Generally, when nonbinary signaling is used, each of the symbols transmitted represents more than one binary digit. However, since most transmission schemes in use today are basically binary, the channel characteristics are usually seen defined on the basis of a "binary performance index."

According to Shannon's Law of Information Theory, virtually error-less transmission is theoretically achievable at extremely high data rates. The reason the upper bound of Shannon's channel capacity has not been achieved in practice is the lack of technology to develop ultra high speed data transmission within reasonable cost and complexity.

A block diagram of a digital communications system is shown in figure 5. Two parameters which dictate the design of the communications system are quite evident as the input and output of the diagrammed system. For a given source information rate the design must strive to achieve a "reasonable error rate" when the received symbols are decoded. A "reasonable error rate" is usually determined through a consideration of many factors depending on the system design. The upper bound on acceptable error rate for a police communications system should be at least equal that error rate achieved by normal voice communications.

The components indicated in figure 5 are identified as follows. The source symbols are discrete in nature and generally arrive in sequence (i.e., letters of the alphabet). The source encoder, by the means of a source code, converts the original sequence to a new (generally binary) sequence (i.e., conversion of the letters of the alphabet to ASCII code). The channel encoder prepares the binary data for transmission over the channel (i.e., error control bits are inserted). The transmitter modulates an analog waveform with the binary data, transmits it over the channel so that it can be received by the receiver. The analog waveform is then demodulated. The channel decoder performs error correction and detection and removes the error control bits. The source decoder then converts the received code word back to a source symbol.

The noise power and the channel bandwidth limitations are the most probable causes of errors in the received data. If the characteristics of the channel are known, usually the designer can effectively combat these problems with good channel encoding and proper choice of modulation schemes at the transmitter. Optimum detection schemes are also extremely effective in the reconstruction of data. Sometimes a feedback channel is used to request a repeat of data detected as being in error. As mentioned previously, two digital quantities, signaling speed and the probability of bit error, are generally related to two analog quantities, bandwidth and signal-to-noise ratio. The power and bandwidth characteristics of a channel allow the digital designer two degrees of freedom. In a power limited case where insufficient signal-to-noise ratio is responsible for high error rates, it is possible to spread the signaling characteristics in frequency space (i.e., multitone

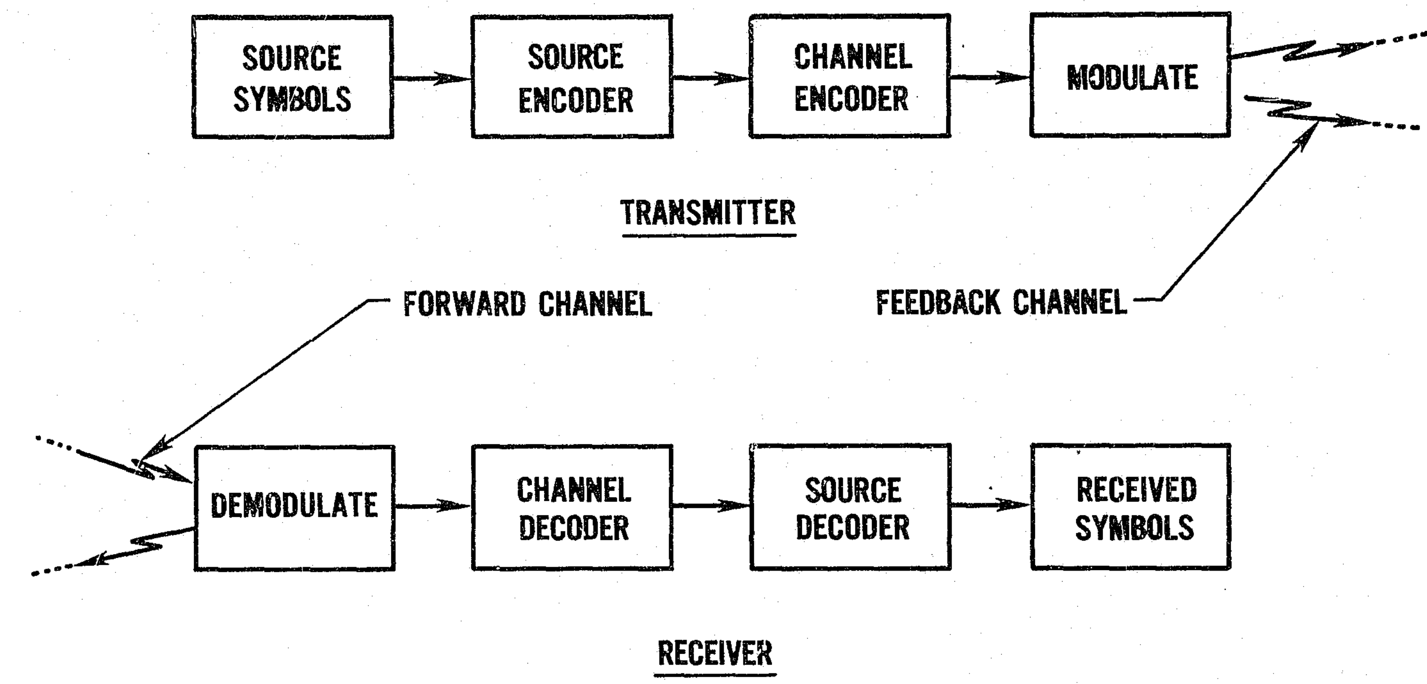


Figure 5. Block diagram of digital communications system.

FSK). On the other hand, a bandwidth limited case would require a modulation scheme which would take advantage of signal-to-noise ratio, if available (i.e., multiphase PSK). These types of trade-offs will be discussed later in this report.

The next subsection of this report, section 5.3, presents information on the expected error rates of various binary modulation schemes with respect to signal-to-noise ratio. The types discussed are: frequency shift keying (noncoherent), phase shift keying (coherent) and differential phase shift keying. These modulation techniques are all used for digital transmission over mobile radio channels by present day manufacturers.

5.3 Binary Frequency Shift and Phase Shift Signaling

In this section, the performance of the binary (i.e., two-state) signaling techniques presently in use for mobile digital communications will be examined. Most of the information presented here can be obtained from many standard texts devoted to communication theory [22,25,29,30] with the exception of the performance of binary signaling in impulse noise with Raleigh fading [11].

Digital signaling techniques in use today in mobile digital communications include the following:

1) noncoherent frequency shift keying (FSK)
2) coherent phase shift keying (PSK)
3) differential phase shift keying (DPSK)

5.3.1 Binary Signaling in Gaussian Noise

A FSK waveform as applied to mobile digital communication consists of constant amplitude audio frequency pulses of different frequency, each frequency representing one of the message symbols. In the binary case only two FSK tones are used, one representing a "one," the other representing a "zero." The selection of the two frequencies depends upon the signaling speed and the channel characteristics, however they are usually somewhat central to the audio pass band allowed the "FCC filter." In the case of mobile digital communication this digital audio signal is then frequency modulated by the radio and transmitted just as a normal voice communication would be. Upon reception, the FM signal is passed through the conventional discriminator and then recovered audio is processed digitally. In the case of noncoherent FSK detection, the conventional detection scheme consists of two band pass filters, centered on the respective signaling frequencies, and a pair of envelope detectors. The outputs of the envelope detectors are then compared, to determine the binary output. This detection scheme is shown in figure 6. The logical decision scheme is to decide f_1 when the output [illegible] is greater than zero.

The actual determination of the probability of making an incorrect decision is derived from the results of statistical decision theory. Assuming that frequency f_1 is transmitted and the channel is corrupted by some additive noise, the distribution of the values of the output of the two envelope detectors, one with a sinusoidal signal at f_1 plus noise, the other with just noise can be determined from probability theory (assuming the noise is well-defined, e.g., Gaussian). Once a good probabilistic definition of the two signal inputs is found, the following is asked. What chance is there that output Y_0 exceeds output Y. when f_1 is transmitted at a certain signal level? That is, what is the probability of an incorrect decision or probability of error? Similar arguments are applied to all types of digital signaling in many different types of noise, and as long as all parameters (detection circuitry, signaling method, type of noise) are well defined, a unique solution can be found for the probability of error.

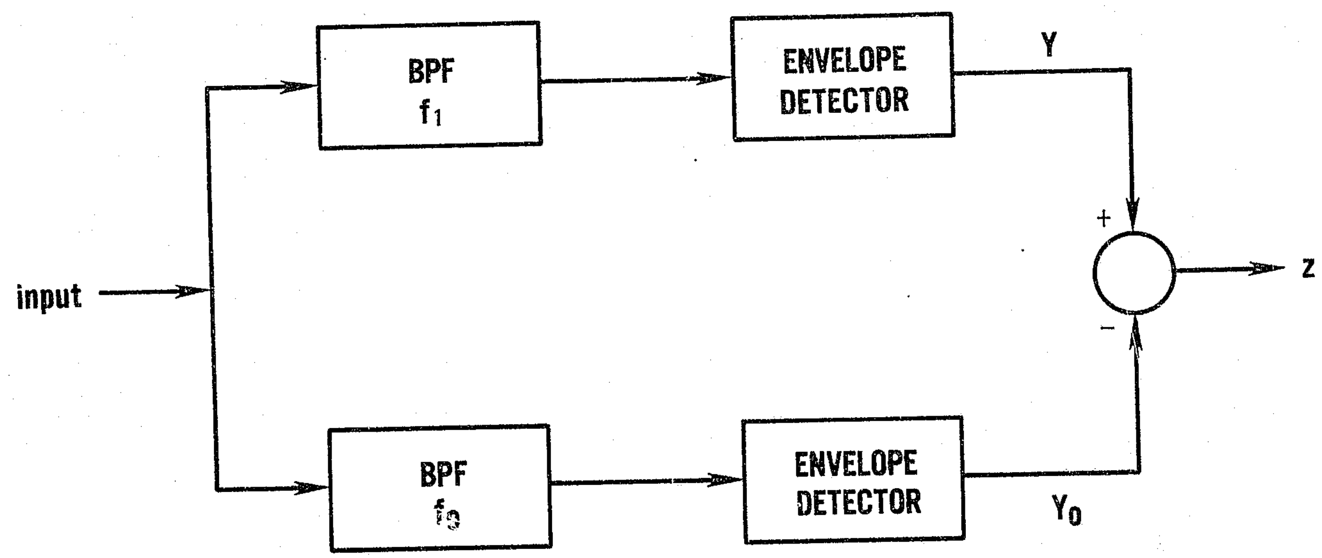


Figure 6. FSK detection scheme.

Graphs of the probability of error vs. signal-to-noise power ratio per received bit for FSK, PSK, and DPSK modulation in additive Gaussian noise are presented in figure 7. Gaussian "noise" is frequently used to describe channel behavior in the presence of noise and its amplitude characteristics are represented by a normal type distribution. The Gaussian distribution is typified by the fact that it represents the limiting situation when a large number of independent fluctuations add together, such as thermal noise.

Besides FSK, coherent phase shift keying is also used in mobile digital communication. In this case, one "audio carrier" is selected, usually at the geometric center of the audio pass band and its phase is shifted between two states, in order to represent binary ones and zeros. Just as in the case of FSK, this digital audio signal is modulated, the same as voice, by the FM radio and upon reception, the recovered audio undergoes statistical detection.

One very basic difference between FSK and PSK signaling as applied to mobile communications is that usually FSK is incoherent, while PSK is coherent. FSK can be detected both incoherently and coherently, while PSK cannot. In coherent detection, a facsimile (in frequency and phase) of the incoming signals has to be generated at the receiver, through the use of additional circuitry. The recovered replicas are then mixed with their counterparts, so that the components of noise in quadrature (90° out of phase) with the transmitted signal are "subtracted out" of the detection process. In the case of FSK, coherent detection reduces the probability of error somewhat, but usually when the cost and complexity of coherent detection is to be incorporated into a system, PSK modulation (which has to be detected coherently) is usually employed because it offers further advantages of even lower probabilities of error. It must be kept in mind that the advantage of lowest probability of error (fig. 7) is gained at the expense of coherent detection, insofar as envelope detection cannot be used because the transmitted information lies in the phase reversals.

There is still another type of phase shift modulation in use which does not require coherent detection which has lower error rates than FSK but not quite as good as PSK (see fig. 7). It is known as differential phase shift keying, and, as the name implies, the phase difference between each succeeding bit position is detected and converted to a binary output. The detection system delays the previously received digit and uses it as the phase reference. The differential encoding scheme works by starting with an arbitrary first digit and if a transition in phase occurs in the next digit the result is a zero. On the other hand, if no transition in phase occurs, the decoded output is a one. The Gaussian noise performance is also indicated in figure 7.

If figure 7 is studied, the difference in error performance between the modulation schemes can be determined with respect to power requirements. Compared to coherent phase shift keying, differential phase shift keying requires only 1 dB more signal power to achieve equal error rates of one in ten thousand. This is why DPSK is becoming increasingly popular as a binary modulation scheme and coherent phase keyed systems are usually expanded to multiphase systems in order to afford the expense of coherent detection. Noncoherent FSK requires 3 dB more power than DPSK to achieve the same error rate of 1 in 10,000. The only disadvantages of DPSK of any importance are the restriction of constant signaling speed (because of the one-bit delayed reference) and the fact that errors occur in bursts of two bits.

5.3.2 Binary Signaling with Rayleigh Fading in Gaussian Noise

Multipath propagation characterizes police radio frequency bands in many urban areas. Multipath is a term used to describe the phenomena that occurs when many components of the same signal arrive at the same receiver with different time delays between them, due to multiple reflections of the signal off obstructions such as buildings.

The results presented in section 5.3.1 assume a constant signal amplitude for the recovered audio signal that will enter the digital detector. In a multipath situation, the received signal will tend to follow a statistical distribution of signal values known as the Rayleigh distribution. Analyses of the probability of error with fading signal components in Gaussian noise are quite common in the

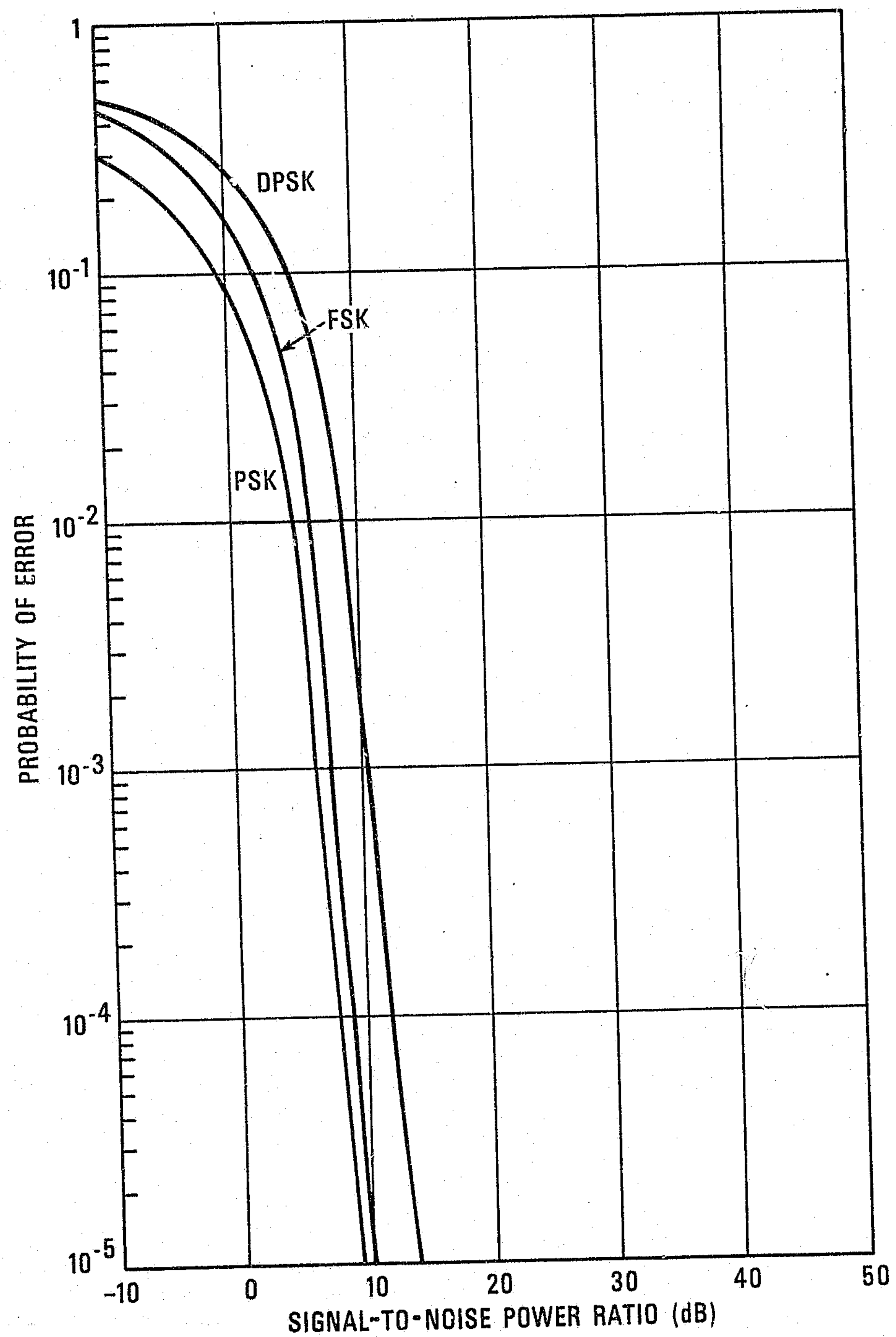


Figure 7. Binary signaling nonfading Gaussian noise.

literature and a typical graph of bit error vs. mean signal-to-noise power ratio is shown in figure 8 for FSK, PSK, and DPSK.

If this figure is compared with that of a nonfading channel, it can be seen that an increase in signal level of 25 dB is needed to achieve error rates of 10^{-4} for any modulation scheme. Coherent PSK still achieves the lowest error rates and its advantage over DPSK is increased to 3 dB. The relative difference between DPSK and noncoherent FSK remains the same as in the nonfading case. The most apparent difference between the fading and the nonfading case is the slope of the relationship between the error rate and signal to noise ratio. In the nonfading case, the relationship is exponential, whereas in the Rayleigh fading case the relationship is linear.

5.3.3 Binary Signaling in Impulsive Noise

Another form of noise present in a mobile communication system is impulsive noise. Impulsive noise (generated by man-made phenomena such as vehicle ignitions and switching transients) is sufficiently different from Gaussian noise to warrant additional calculations of the probability of bit error in such an environment. Two models of impulsive noise have been developed, namely the "Telephone" model and the "Atmospheric" model. However the results obtained with both models are similar and therefore, only the "atmospheric" model, developed at the National Bureau of Standards, is presented here. The probability of error in impulsive noise is much greater than in Gaussian noise, as shown in figure 9. The parameter V_d is a measure of the degree of impulsiveness of the noise, and is explained in detail elsewhere [11]. Figure 10 is a comparison of FSK and PSK with V_d = 16 dB, while in figure 9 V_d=6 dB. These graphs do not include results for DPSK. However, as it is generally true, the curve for DPSK lies somewhere between those for FSK and PSK. Two general conclusions can be made from these curves in comparison with figure 7. The impulsive noise model indicates much higher error rates than the Gaussian noise model and the degree of impulsiveness (i.e., higher or lower V_d) does not seem to affect the curves drastically.

5.3.4 Binary Signaling in Impulsive Noise with Rayleigh Fading

Figures 11 and 12 provide information on the bit error probability vs. mean signal-to-noise power ratio for both FSK and PSK modulation in the presence of impulsive noise and Rayleigh fading. It can be seen that the impulsive noise error probability curves are only slightly effected by the addition of Rayleigh fading. This is unlike the Gaussian noise case, where the curves were drastically shifted to higher error probabilities by the addition of fading considerations. A comparison of the curves in figures 8 and 11 yields the result that if the radio channel is characterized by fading, the type of noise, whether Gaussian or impulsive, is immaterial. In fact, of the two noise considerations, Gaussian noise causes a higher error rate than impulsive noise on a fading channel.

5.4 Binary Signaling Speed and Bandwidth

The audio bandwidth that a digitally modulated signal is allowed to occupy in a mobile FM radio is limited by the FCC low pass filter installed by all radio manufacturers. In practice, the usable audio bandwidth is approximately 3000 Hz. In the case of binary signaling, Shannon's law of channel capacity reduces to C = W b/s, where C is the channel capacity of a system with an allowable audio bandwidth of W Hz. The maximum binary signaling rate is then found to be 3000 b/s. A rather intuitive statement should clarify the implications of this law. Suppose the usable bandwidth extended to W Hz and an attempt was made to send a digital signal at a signaling rate of W + w b/s; Fourier analysis of the signal shows that the fundamental components will appear at W + w Hz, which is outside the range of the channel bandwidth.

Nyquist's First Theorem also states a relationship between signaling speed and bandwidth with respect to intersymbol interference. Intersymbol interference is a phenomena which occurs when the effect of a subsequent bit(s) is not allowed to rescind before the transmission of a succeeding bit(s). This occurs when the impulse response of the channel is longer than the interval between signaling pulses.

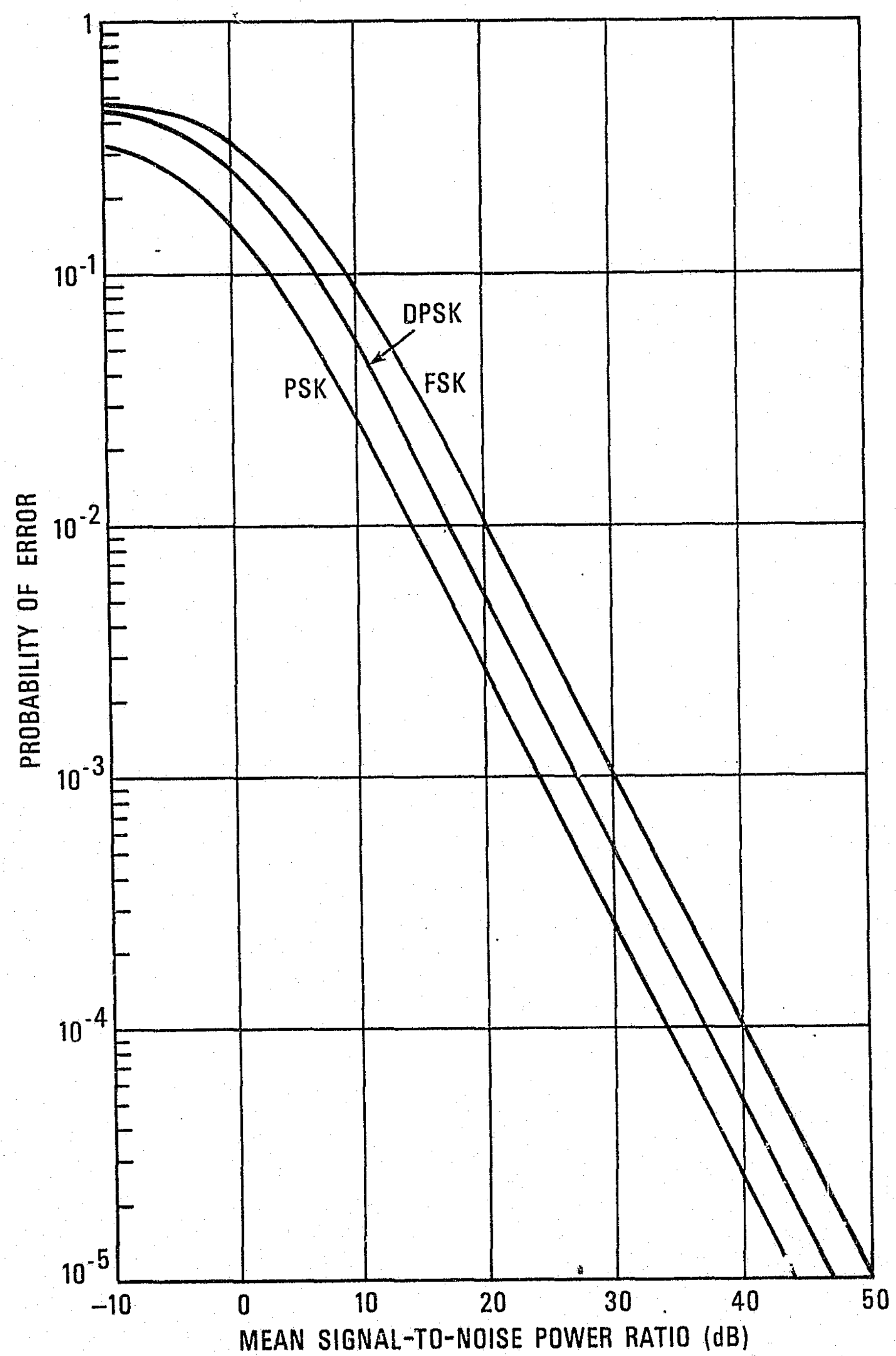


Figure 8. Binary signaling fading Gaussian noise.

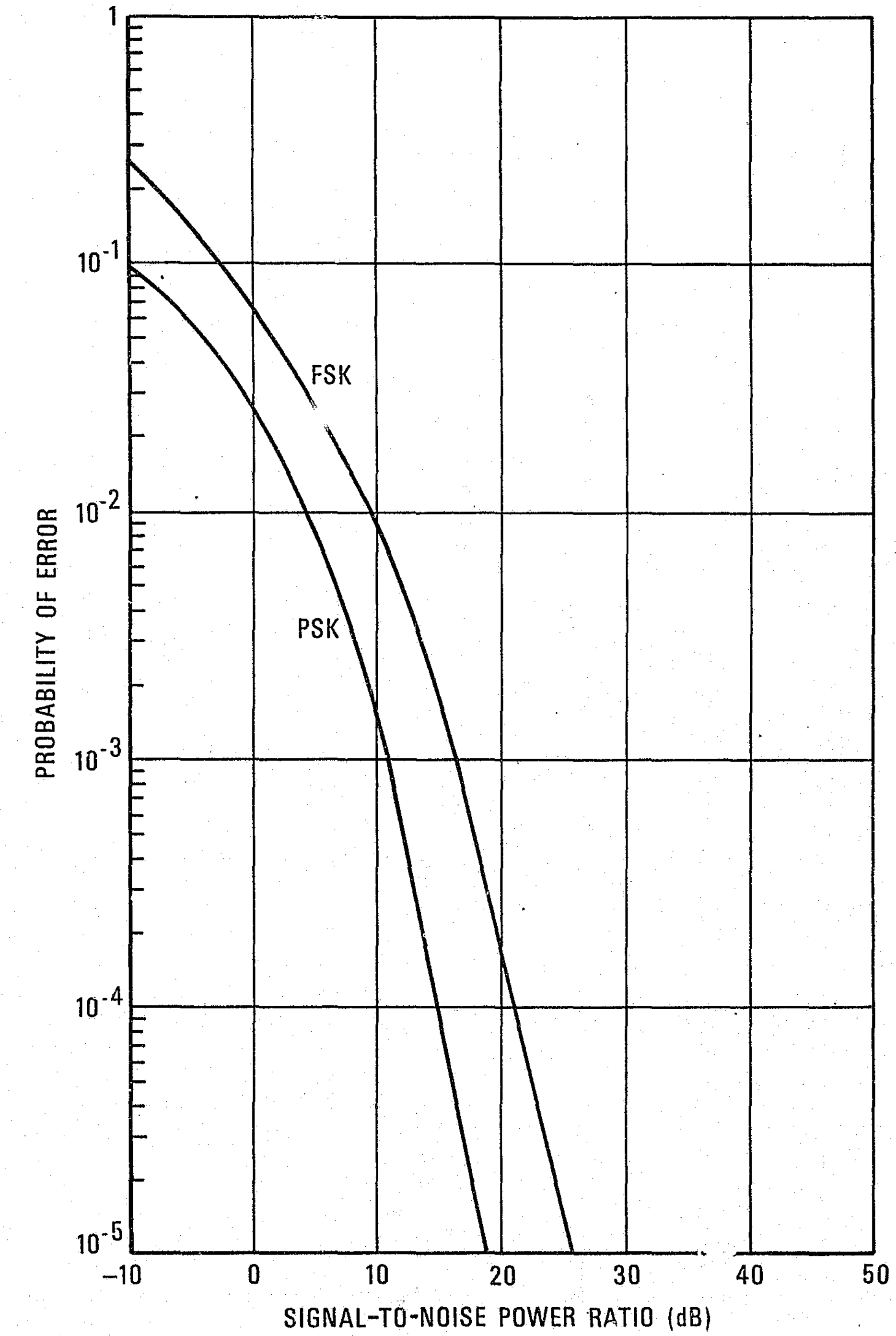


Figure 9. Binary signaling nonfading impulsive noise, V_D = 6 dB.

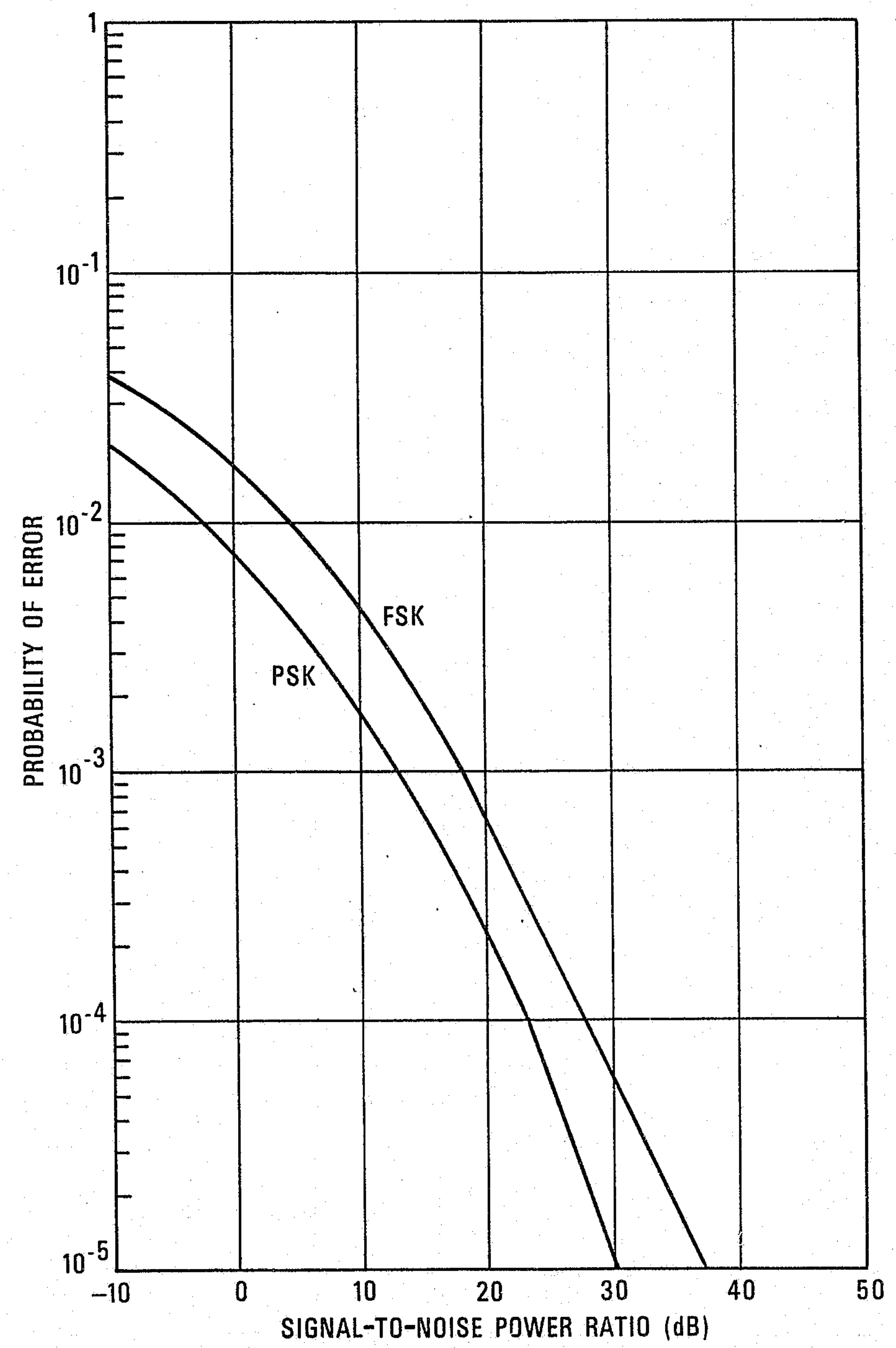


Figure 10. Binary signaling nonfading impulsive noise, V_D = 16 dB.

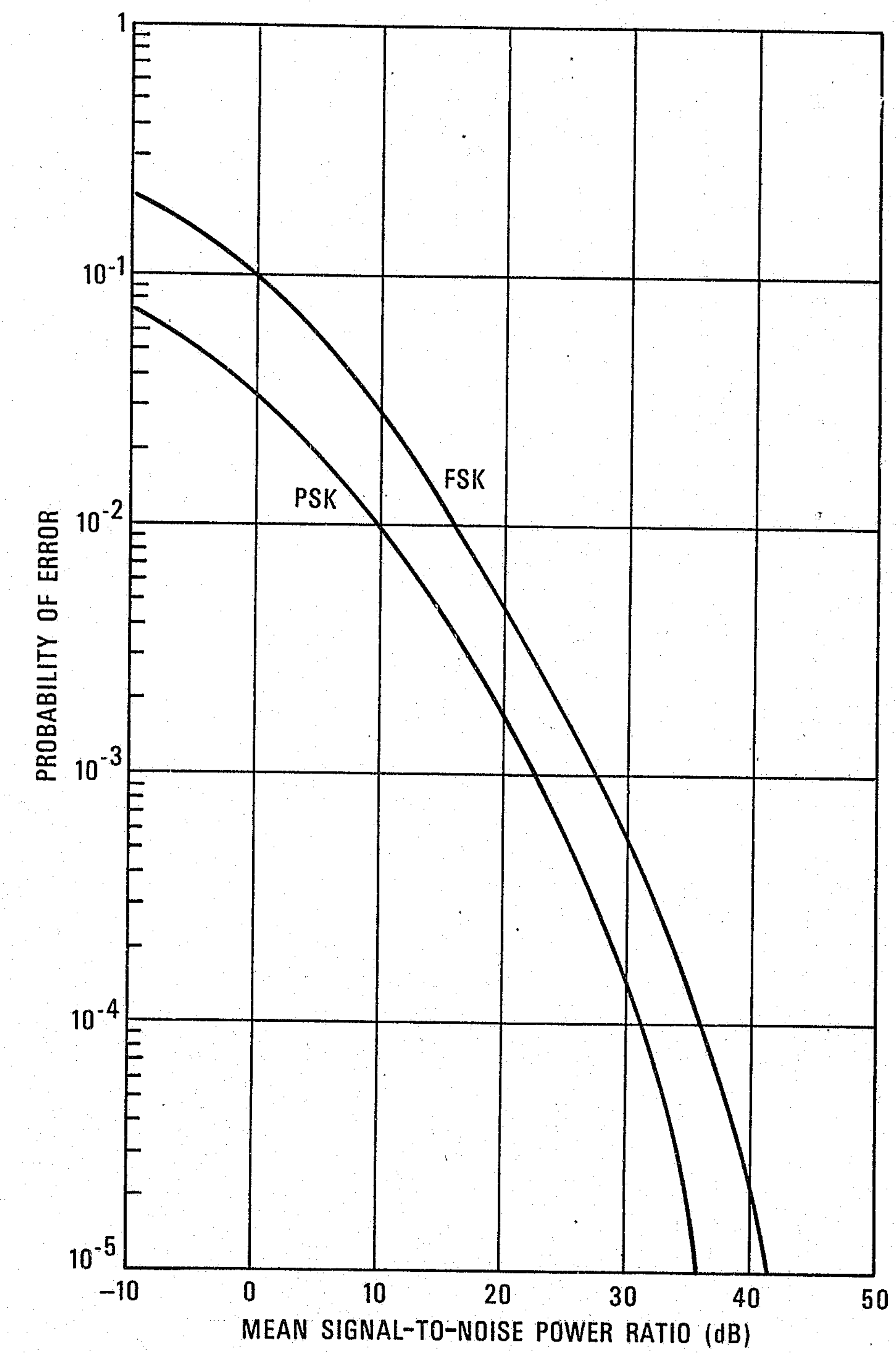


Figure 11. Binary signaling fading impulsive noise, V_D = 6 dB.

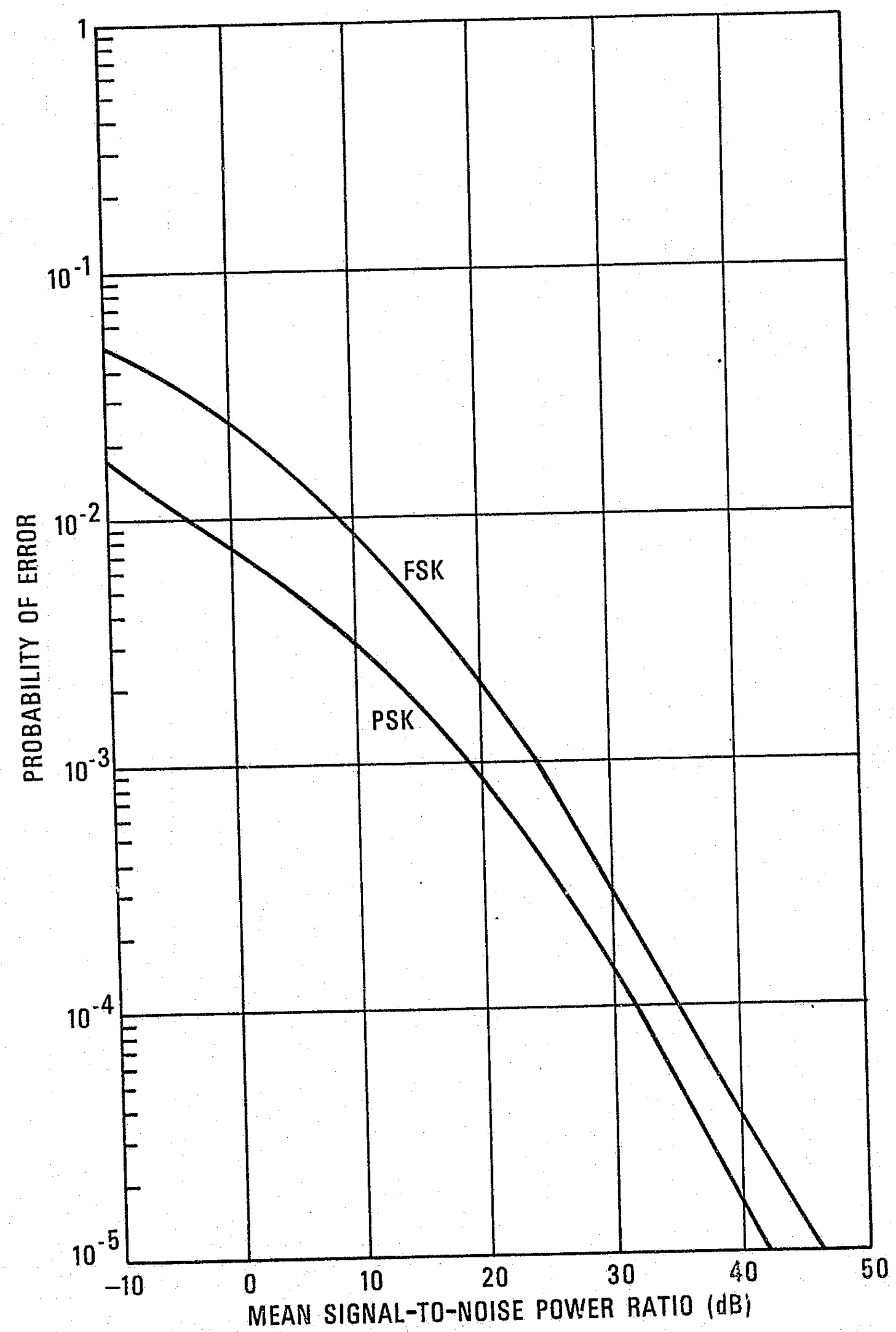


Figure 12. Binary signaling fading impulsive noise, V_D = 16 dB.

Nyquist's First Theorem states that it is impossible to signal at a rate s > W without observing intersymbol interference. In order to implement a system with standard waveforms, they would have to be strictly time-limited in order to be nonexistant at t = s. However, intersymbol interference is a phenomena that occurs at the receiver and any time limited transmitted signal is going to have a decaying tail after passing through the distortion introduced in the channel. Therefore in practice, signaling speeds of typically .5 W to .75 W are achieved, unless advanced signal shaping and channel equalization techniques are employed.

The bandwidth-signaling speed limitations apply directly to single audio carrier modulation techniques such as PSK and DPSK. In the case of FSK signaling, the spectrum is spread because of the separation of the two signaling tones. Generally, the separation between the two tones for most of these systems is approximately equal to one half the signaling rate.

Table 8 [56] can be used to make an assessment of the relationship between bandwidth and signaling speed for the listed modulation schemes where S is the maximum signaling speed, B is the transmission bandwidth, and K is the pulse shape factor (between one and two, closer to one with presently available systems).

Table 8. Relationship between modulation schemes and signaling speed.

Type	$\frac{S_{max}}{(K/2)B}$
FSK	1/2 - 2/3 (depends on tone spacing)
DPSK	1
PSK	1

5.5 Channel Capacity

The law of channel capacity for discrete signals state that the maximum information rate that can be employed over any channel is directly proportional to the signaling speed and the logarithm to the base 2 of the number of electrical states. That is:

$$C = s \log m \text{ (baud or symbols per second)},$$

where s is the signaling speed (baud), and m is the number of existing usable electrical states.

In the case of the binary channel (two distinguishable states)

$$C = S \log_2 2 = S \text{ b/s}$$

and

$$S_{max} = W \text{ b/s}$$

$$\therefore C = W \text{ b/s},$$

where W is channel bandwidth.

This formula implies two degrees of freedom for increasing the data rate with discrete signaling. They are:

1) Increase the signaling speed.

2) Increase the number of distinguishable signal levels (i.e., voltage levels, number of phases, etc.).

If m is defined as the number of voltage levels used to signal over a channel, the channel capacity equation can be reduced to include signal-to-noise ratio as the independent variable (the results apply to any type of signaling, i.e., multiphase, etc.). The value of m is related to signal-to-noise ratio on a noisy channel in the following way. The total received power is S+N and the received rms voltage is therefore $\sqrt{S+N}$. The number of distinguishable voltage levels have to be separated by a value equal to the rms noise as a minimum. That is

$$m = \frac{\sqrt{S+N}}{\sqrt{N}}$$

For example if N = 2 V, then in order to have two distinguishable signals $\sqrt{S+N} = m\sqrt{N} = 2x2$ V = 4 V. This would perhaps be an on-off keying system with a decision threshold set at 2 V.

Now

$$m = \frac{\sqrt{S+N}}{\sqrt{N}} \quad \left(1 + \frac{S}{N}\right)^{\frac{1}{2}}$$

and

$$C = S \log_2 m$$

$$C = S \log_2 \left(1 + \frac{S}{N}\right)^{\frac{1}{2}}$$

$$C = S \log_2 \left(1 + \frac{S}{N}\right)$$

at the maximum signaling speed of S=W:

$$C = \frac{W}{2} \log_2 \left(1 + \frac{S}{N}\right) \text{ b/s}$$

It can be shown that this general m - state formulation reduces to C = W b/s in the binary case. For the binary case:

$$m = 2 = \left(1 + \frac{S}{N}\right)^{\frac{1}{2}}$$

$$1 + \frac{S}{N} = 4$$

$$C = \frac{W}{2} \log_2 \left(1 + \frac{S}{N}\right)$$

$$C = \frac{W}{2} \log_2 (4)$$

$$C = W \text{ b/s}$$

Although there are two degrees of freedom for achieving data rates which approach channel capacity, there is another parameter available to the system designer that enables him to approach this condition. This parameter is the algebraic distance between code words, which forms the basis for error control coding. This will be examined in a later section.

5.6 M-ary Signaling

The technical discussion to this point has been limited primarily to binary signaling schemes. As indicated in the discussion of channel capacity, it is possible to increase the data rate by increasing the number of distinguishable signal states. In the area of mobile data communications binary PSK and FSK modulation schemes can be readily expanded to multilevel or M-ary modulation schemes with some added cost and complexity. This discussion will be limited to M-ary PSK and FSK, although other M-ary modulation schemes exist.

As the information output from the source encoder or channel encoder is generally binary in nature, this binary information has to be encoded into M-ary symbols before transmission. For example, in the case of four-phase signaling, the binary 4-ary encoding might be as follows:

Binary information	M-ary phase (degrees)
00	0
01	90
10	180
11	270

In general, the M-ary encoder accepts blocks of k source bits and converts them to $M = 2^k$ different source symbols. In the four-phase example, k = 2 b and $M = 2^2$ = four phases or symbols. The opposite or decoding procedure is implemented at the receiver. The graphs in figures 13 and 14 indicate the probability of symbol error vs. normalized signal-to-noise power ratio per bit. Direct comparison of the ordinate of these curves with that of the binary case is not possible. However, for reasonable values of k, the probability of bit error is approximately equal to half the symbol error rate.

In the study of multiphase PSK systems, increased signaling speed can be achieved at the expense of increased signal power while maintaining the same bandwidth requirements. The details will not be discussed here, but it is possible to show that by maintaining a fixed bandwidth and converting the signaling scheme from two-phase to four-phase modulation, the information rate can be doubled and

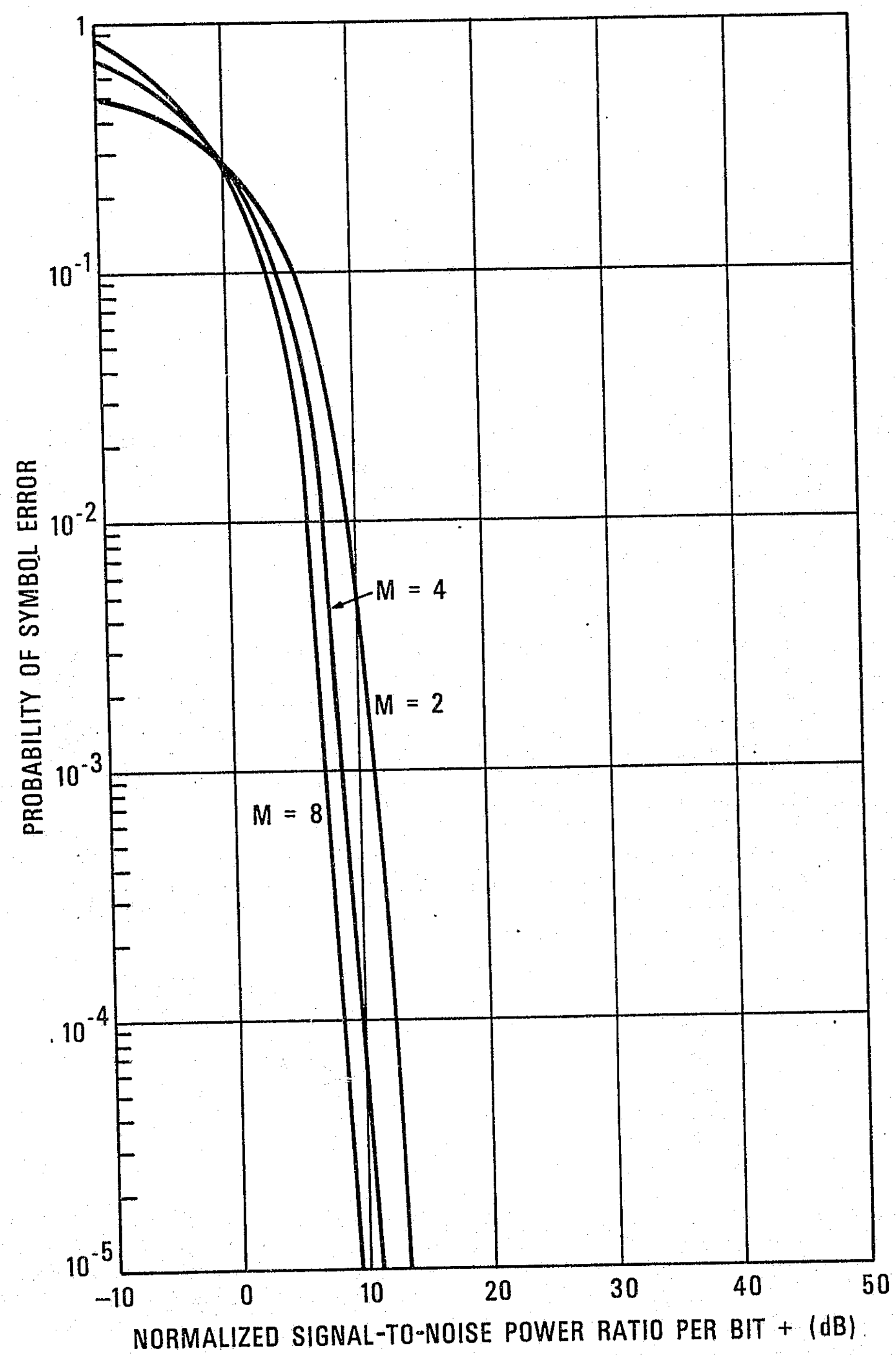


Figure 13. M-ary FSK nonfading Gaussian noise.

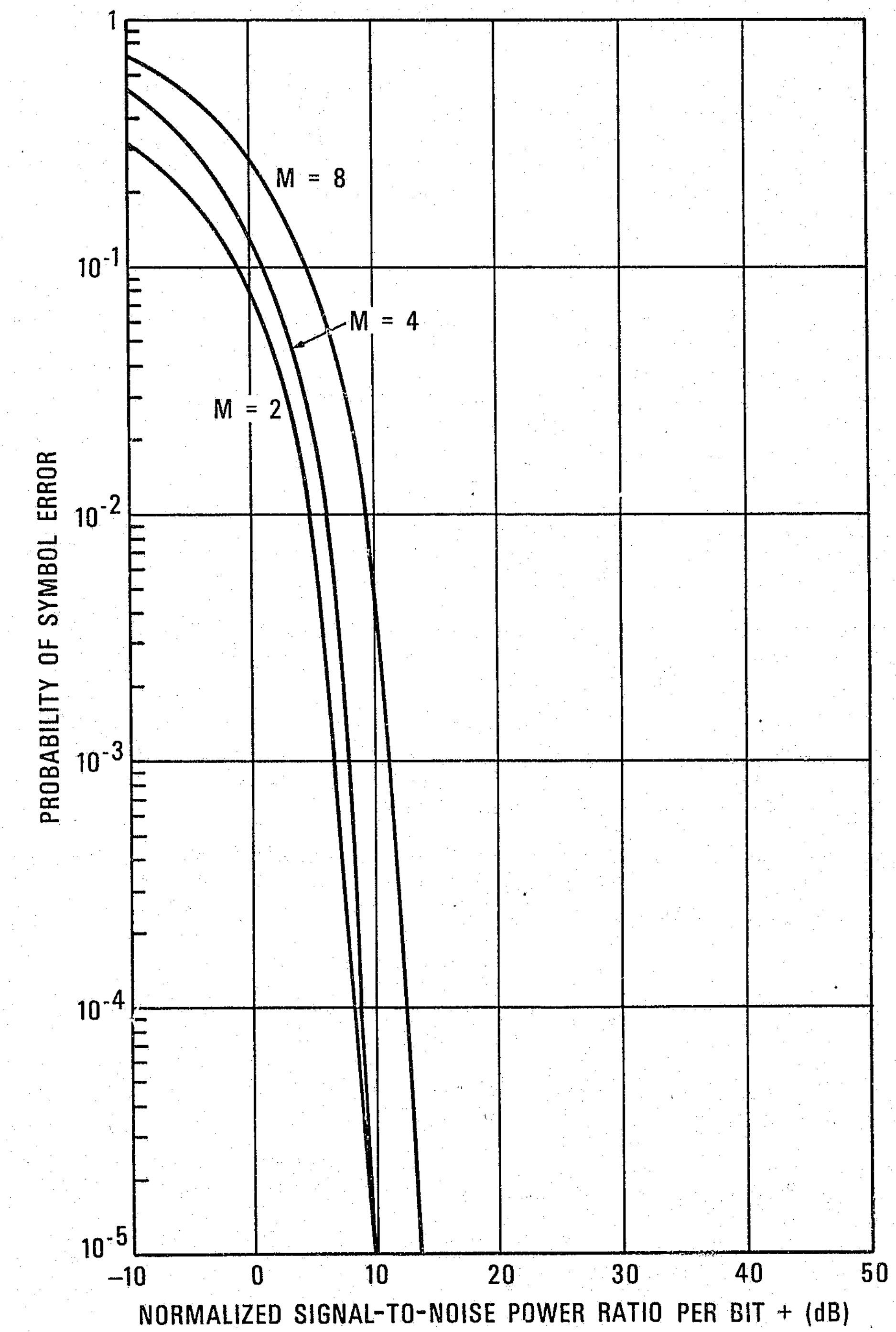


Figure 14. M-ary PSK nonfading Gaussian noise.

still maintain the same bit error rate. The penality paid is a four-fold increase in required transmission power. Such trade-off advantages diminish as M is increased further.

In the case of multi-tone FSK a somewhat inverted trade-off study can be cited. If the operating system is considered power limited and if enough bandwidth exists to accommodate multi-tone signaling, the error rate can be made to approach zero very fast. However, for fixed bandwidth systems the information rate must be decreased to achieve this result.

Therefore, in general, if the system designer considers the channel power limited and wishes to operate at an essentially error free low information rate, a multitone FSK can be used. This type of data transmission scheme is already in use in one status-only mobile communication system. However, in a saturated signal environment, the system designer might consider M-ary PSK as an alternative modulation scheme.

5.7 Error Control Coding

As in M-ary signaling where an encoder accepts blocks of source bits and produces one of $M = 2^k$ distinct waveforms, algebraic error control coding accepts blocks of the same source bits and encodes them into one of $M = 2^k$ code words. Each code word contains a binary digit, n being greater than k in order to insert redundancy. Because of this, error control coding may be considered to be a technique which utilizes a third degree of freedom in order to approach channel capacity.

As previously discussed, error probability in digital transmission is a function of signal-to-noise ratio. In power limited systems, error control coding is often used to provide reliable communication.

Error control coding is the calculated use of redundancy in the transmitted message and, as such, is better than simple redundancy schemes, like simply retransmitting the same message twice. The additional bits are added to the transmitted sequence based on complex mathematic relationships. The "check digits" so generated are used to detect and sometimes to correct errors in the transmitted message. In the limit, error-free transmission is possible. However, a trade-off between efficiency, cost, reliability, and complexity is usually involved in the decision of which error control scheme to implement.

A reduction in effective bit information rate occurs when error control coding is used. Suppose that for I information digits, C check digits are inserted. If the original signaling rate was S b/s and the new information rate in bits per second is S',

$$S' = \left(\frac{I}{I + C}\right) S \text{ b/s}$$

The term in parenthesis is sometimes called the efficiency of the code. In general, effective codes have small efficiencies.

Parity check is a basic scheme for adding redundancy. In its simplest form one parity bit is added to each message block. This type of coding is not generally very effective but has a high efficiency. A single error or any number of odd errors can be detected in the coded block (including the parity bit). Normally if an error is detected, a retransmission is requested (a two-way channel may be needed).

The availability of a two-way link for communications is very useful because it allows the use of decision feedback or adaptive error control. If the data channel is subject to varying conditions, such as fading and impulse noise, decision feedback techniques are generally very effective. With or without feedback, simple error detection is only effective when the original bit error probability is low and also when the probability of having an undetected error is not too critical. Actually the probability of undetected errors is the resultant error probability in a system that employs coding.

By adding many check bits to an information block, each comprising a parity check over different sections of the other information and parity bits, it becomes possible to structure codes so that the detected errors can be located, making error correction possible. In general, approximately twice as many check bits are needed in order to correct errors rather than only detect them. As an example, if it is required that three out of five information bits must be corrected when they are in error, a block code with an information rate of one third and a total block length of 15 b (five information bits) can be used.

A general class of block codes defined by a definite algebraic structure are known as the Bose-Chaudhuri-Hocquenghem (BCH) codes. This set of codes includes many of the earlier discovered codes, such as the Hamming codes, as special cases. They can be used for both error detection and correction.

In general, all algebraic codes are classed as (n,k) codes, where n is the total number of bits in the code sequence and k is the number of information bearing bits. The number of check digits is n-k. Encoders to implement these cyclic codes consist of single shift register circuits, however, associated decoders are relatively complex and expensive to realize.

There exist some basic principles by which the communication engineer can evaluate the power of certain codes. The degree of error control offered by a certain code is given by its minimum Hamming distance (d). The Hamming distance between two code words is equal to the number of bit positions in which they differ. If there are d-1 errors or less in a received code word, a code with minimum distance d can detect all the errors. The same code can only correct $\frac{d-1}{2}$ errors.

The error detection capability of a code and its relationship to Hamming distance can easily be seen by recognizing the fact that if a code word is changed in d-1 or less bit positions, it cannot be transposed into another legitimate code word. The fact that a greater degree of redundancy is required to correct errors, often requires the system designer to revert to simple error detection and requests for retransmission. However, many references cite the fact that forward error correction with a request for retransmission only when an uncorrectable error is detected maximizes throughput, and is well worth the cost and complexity of implementation.

The performance or error correcting codes in a channel affected by additive Gaussian noise is dependent on the range of values of the signal-to-noise ratio. Longer codes tend to perform better on a higher signal-to-noise ratio, while shorter codes achieve their best performance at lower signal-to-noise conditions. In fact, at extremely low signal-to-noise values, the uncoded case maximizes effective data rate and provides the smallest probability of error. The small gains that one achieves in error control coding over a Gaussian channel is due to the fact that the probability of bit error falls off very rapidly with increasing signal-to-noise ratio.

However, significant gains can be made with error coding over fading and impulsive channels. The fades or periods of noise impulsiveness should be long in comparison to the duration of a bit period. It is then that a high level of correlation exists between adjacent bit errors, and burst error correcting codes achieve their effectiveness. Algebraic codes can be designed especially for combating burst-type errors. One problem in applying these techniques is that sufficient data on the length of the bursts does not exist and an efficient code design is difficult to achieve.

Another approach which is used over fading radio channels is the concept of interleaving. For example, it is required to transmit 10 code words each coded against random occurring errors. Instead of transmitting the bits in the sequence in which they are generated, one alternatively selects bit number one from each successive code word and then the bit number two, and so on. In the case where the bit sequence is long enough so that the bits belonging to each code word feel the effects of statistically independent channel conditions, a burst error problem has been reduced to that of random errors. However, the effectiveness of this type of error control coding is not diminished by the exponential dependence of errors on the signal-to-noise ratio which characterizes the Gaussian channel. The interleaving concept plays a powerful role in new concepts for employing coding over fading radio channels as well as in design for channels characterized by impulsive noise.

Another type of code design is the convolutional or recurrent codes. These codes do not separate the message digits into blocks, but use a continuous coding-decoding procedure (i.e., the check bits are not inserted with reference to a block structure, but on a "running basis"). These codes eliminate the need for storage or buffering and are usually designed for burst error correction, which are interlaced and also have a high degree of redundancy. One example is the Habelburger code with one check digit for each information digit, which can correct a burst of six errors assuming 19 correct preceding digits. Encoding and decoding are accomplished by single shift registers. In applications where terminal complexity is of concern, bit rate reduction can be tolerated, and if the channel is impulsive, convolutional codes are ideal.

5.8 Imperfect Channels

Even if the communications designer has chosen to signal below the Nyquist rate for the available audio bandwidth (i.e., S<W b/s) the problems of proper pulse detection and intersymbol interference may not be totally eliminated. All real channels exhibit some form of time dispersion. In the radio channel the transfer function is sometimes measured in terms of attenuation and delay as a function of frequency.

The envelope delay distortion, sometimes called phase distortion, represents the relative time delay of various frequency components of the signal. These various frequency components of the signal travel through filters, transformers, etc., in the radio and associated communications equipment and arrive at the detection stage dispersed in time. The delay distortion is most severe at the edges of the pass band of the channel, due to the parabolic component of the delay.

Attenuation or amplitude distortion is the variation in signal amplitude from a flat response over a channel bandwidth. Its effect is to produce distortion by emphasizing or attenuating different frequency components of the signal.

Both attenuation and delay distortion can be corrected by the use of "equalizers." A "fixed equalizer" is one that is used in the case of constant channel parameters. These are relatively inexpensive. Manually adjustable equalizers are the next level of sophistication and may be used to "tune" data transmission to various types of radios. However, if dynamic changes in the distortion characteristics of the channel occur, as in the case of voting receiver systems, adaptive or automatic equalizers can be used. The cost effectiveness of adaptive equalizers is presently under study by a number of manufacturers.

5.9 Technical Discussions with Vendors

Throughout this study, a number of technical discussions were held with the various vendors who are currently manufacturing mobile digital communication equipment. In many instances some of the comments arising in these discussions pertain to the technical topics that have been presented in this section. These comments are detailed below and are categorized by reference to a technical area and do not make reference to specific vendors. In general, the technical viewpoints and opinions were varied, which may be evidence to the fact that no two vendors' equipment are identical.

- <u>Data transmission rates</u> - The reasons for data rate selection were many. However, in some cases, it was claimed that simulation of the police radio network was performed in order to arrive at a data rate. Most vendors who operate at above 600 b/s feel that an increase in data rate would be detrimental to system performance. However, those vendors whose systems operate below 600 b/s recognize a need for increasing their data rates and will probably do so in the near future.

  If communications through other transmission media, such as telephone lines, is necessary the majority of the manufacturers said that the same data rate would be maintained throughout the system (no buffering). However, if problems in communicating over telephone arose, the bulk system data rate would have to be reduced.

- <u>Modulation Techniques</u> - No strong feelings existed on which binary modulation technique was best as they are all quite similar in performance. Some vendors are using multilevel signaling and are quite impressed with its performance, although there is some feeling that the higher data rates offered are not necessary for law enforcement applications.

- <u>Error control coding</u> - A wide range of various techniques are in use, from simple parity checks to half-rate convolutional codes. The general consensus of opinion is that some form of algebraic coding will be necessary and the proper codes will be developed as a result of "in the field" experience.

  One vendor has the capability of changing code schemes. They found that a half-rate code with burst error correcting capability was most effective in a metropolitan area. Flexibility in error control coding must be maintained in order to maximize throughput in the various system environments that will be encountered.

- <u>Cause of errors</u> - Three major causes of bit errors were indicated in the discussions. They are listed in order of priority below:

  1) Imperfect channels (i.e., attenuation vs. frequency and envelope delay distribution). Sometimes these problems are more severe on telephone lines than on the mobile radio network.

  2) Impulse noise (automobile, bus ignitions).

  3) Signal fades.

- <u>Minimum quality of radios</u> - The general feeling was that the radios should meet and be maintained to either NIJ or EIA standards.

- <u>Voting systems</u> - Probably the most significant in-the-field system design problem is the various voting systems that the data must flow through. The data is usually received at two or more voting receivers and then relayed to a comparator over telephone lines. The first problem that arises is in establishing the first circuit to the base station, which takes from 30 to 500 ms or even longer, depending on the condition and the type of voting system. In order to solve this problem, the circuit must be "readied" for data by inserting a "front porch delay" in front of the data. This front porch delay is generally somewhat greater than the time needed to establish the first circuit to the base.

  Another problem is the impulse caused by the switching transients when the system votes. One solution that presently exists is to "lock on" to one voting receiver during the data burst and not allow the system to vote. Another solution is to design a "burst error" correcting code to allow that data to ride through a voting transient.

  Still another problem arises in systems that have control tones in the audio pass band. In order to prohibit these tones from being heard, the system audio response is generally severely attenuated in the vicinity of the control frequencies. This results in attenuation vs. frequency distortion of the data. Subaudible control tones generally will not effect the data.

6. CONCLUSIONS

Digital communications have become accepted as a useful mode of mobile communications for law enforcement application. They are primarily being used to supplement voice communications for various categories of voice-only message transactions that can be readily structured for digital representation. The advantages offered by digital signaling including increased speed of communications, the ability to handle a greater volume of communications, and an inherent security against message interception. These factors are fundamental to alleviating the communication problems of congestion that exist with many voice-only law enforcement radio systems. Therefore, digital communications represent one of the most useful means that technology can offer for improving communications operations for law enforcement agencies.

The study has shown that there are several types of applications of digital communications in police operations. These types of applications are structured by the communications that take place within the law enforcement environment. Of these, status-only type transactions can account for over 50 percent of the messages exchanged. Where status is represented by some coding scheme digital communications is particularly applicable. This type of application is the most straightforward in terms of its suitability for police work. At the other end of the application spectrum is a two-way, full text capability, where, in effect, the mobile digital equipment is a computer terminal.

The extent to which digital communication systems impact upon overall police operational procedures depends upon the type of information that is exchanged in digital messages. With status only communications, the impact is least in that status of mobile units can be made automatically available to dispatchers. The full text capability has the most impact as the mobile unit is no longer required to make data base inquiries through a dispatcher. Also, the dispatcher himself is relieved of this task as the mobile terminal permits direct access to the data bases. This latter type application can be used for keeping voice communications to a minimum. It can, however, result in data traffic implications for on-line computer information systems that, if not properly controlled, would create a level of demand exceeding the originally anticipated design levels of such systems.

It has been found that voice and digital communications sharing the same channel in a contention mode is undesirable. This is particularly so when the volume of digital communications is comparable to the amount of voice traffic. In addition, a nuisance factor can be created where the digital tones are not muted from the speaker output. Techniques should always be utilized to eliminate the audible tones.

The types of applications defined in the study can be satisfied with presently available equipments. Furthermore, the needs determined by the users are well within the state of the art of digital communications. The range of equipments offered by manufacturers provide a flexible choice of system configurations.

In a general sense, digital communications are accepted and welcomed by law enforcement agencies. There is a confidence in the capability of these communications to help solve existing problems with present voice-only radio systems. However, it is not possible at this time to make a general assessment of the success of these digital techniques in eliminating communication congestion. Increase in digital traffic, which is experienced due to the ease of operation, tends to load the radio channel to the existing level or greater, experienced prior to the installation of the digital equipment. An indication of possible success exists in individual cases where these systems are now operational. As the application of digital communication grows, it is expected that a reasonable measure of success will be obtained. This should result in greatly improved police communications and at that time, a determination can be made with regard to the effect of new communications technology in providing assistance to the police in its role of combating crime.

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APPENDIX B--HINTS FOR PROSPECTIVE USERS

The following suggestions are offered as a guideline for law enforcement agencies who are considering the purchase and use of mobile digital communications equipment.

1) Evaluate the message structure of present voice-only network.

2) Determine the transactions to be digitized and estimate the impact they will have on solving the problems of channel congestion and dispatcher workload. Decision to be made on mode of digital communication (i.e., one- or two-way, etc.).

3) Identify what, if any, status messages are to be communicated. Specify the code type that will be used to represent these messages.

4) Identify the special messages that the digital equipment should have (e.g., emergency, etc.).

5) Determine the display format of mobile messages. Include special features such as "flashing" of critical messages and the need for hard-copy output.

6) Examine the operational requirements of acknowledgment of messages. This will indicate whether mobile and dispatcher responses should be manual, automatic, or both.

7) Give consideration to frequency allocation. Decide if channels are available for digital data use.

8) If a two-way data base inquiry capability is needed, analyze traffic impact on the information system.

9) Write a functional specification requesting proposals from suppliers. The proposal should contain a detailed explanation on how the system operates and what tests are to be conducted to demonstrate equipment and system performance.

10) Testing should involve a variety of normal and unusual operating conditions.

11) Tests should be made to demonstrate that the digital equipments are compatible with the existing radio network. For example, checks should be made that the equipments work through satellite repeater stations.

12) All tests should be performed with a cross section of user personnel.

13) Determine which aspects of installation and performance for which the supplier must take responsibility.

14) Insist on thorough training program in both operational and maintenance procedures of equipment.

15) Anticipate significant start-up and maintenance problems.

16) If a computer unit is to be used as a central communications controller, specify sufficient level of instruction in the application programs for possible future in-house modification of the software.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report is the result of a study of digital communications equipment for law enforcement use. The primary objective was to determine the suitability of the various types of this equipment for use by law enforcement agencies. The report reviews present voice message traffic on typical police radio networks and discusses operational requirements for digital communications equipment. It further reviews the possible applications of digital communications equipment for law enforcement use, and lists the characteristics of mobile digital terminals being offered at present. A brief technical discussion of mobile digital communications is also provided.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

digital communications equipment; digital techniques; equipment standards; law enforcement; mobile digital terminals; voice message traffic

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