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RELIABILITY OF 2400-BAUD DIGITAL TRANSMISSION OVER VHF MOBILE RADIO LINKS

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ABSTRACT

To relieve the overloading of present voice transmission channels, we recommend a Mobile Terminal System--a computer-controlled communications system in which computer-coded information would be transmitted at much higher speeds than are possible for voice, with a consequent increase in the effective channel capacity. This recommendation is based on a one-year study which attempted to find a simple, low-cost system of transmitting such information at the highest speed practical over available mobile radio channels.

A simple method of phase modulation with synchronous detection was shown to be effective at rates up to 2400 bauds, or 300 characters per second, within the usual voice bandwidth. This method was employed in fairly extensive tests of various transmission paths representing best-worst conditions in the Santa Clara Valley. Results showed that the system tested would be satisfactory in any geographical area where voice transmission is now successfully used. Transmission of coded data would increase channel efficiency at least ten and possibly a hundred times, with many side benefits. Error detection with automatic request for retransmission might be employed to avoid errors caused by poor reception, and voice transmission could be resorted to in emergencies.

LOCATOR TERMS FOR THE IBM SUBJECT INDEX

Communications, land-based mobile
Terminals, portable
05 Computer Application

CONTENTS

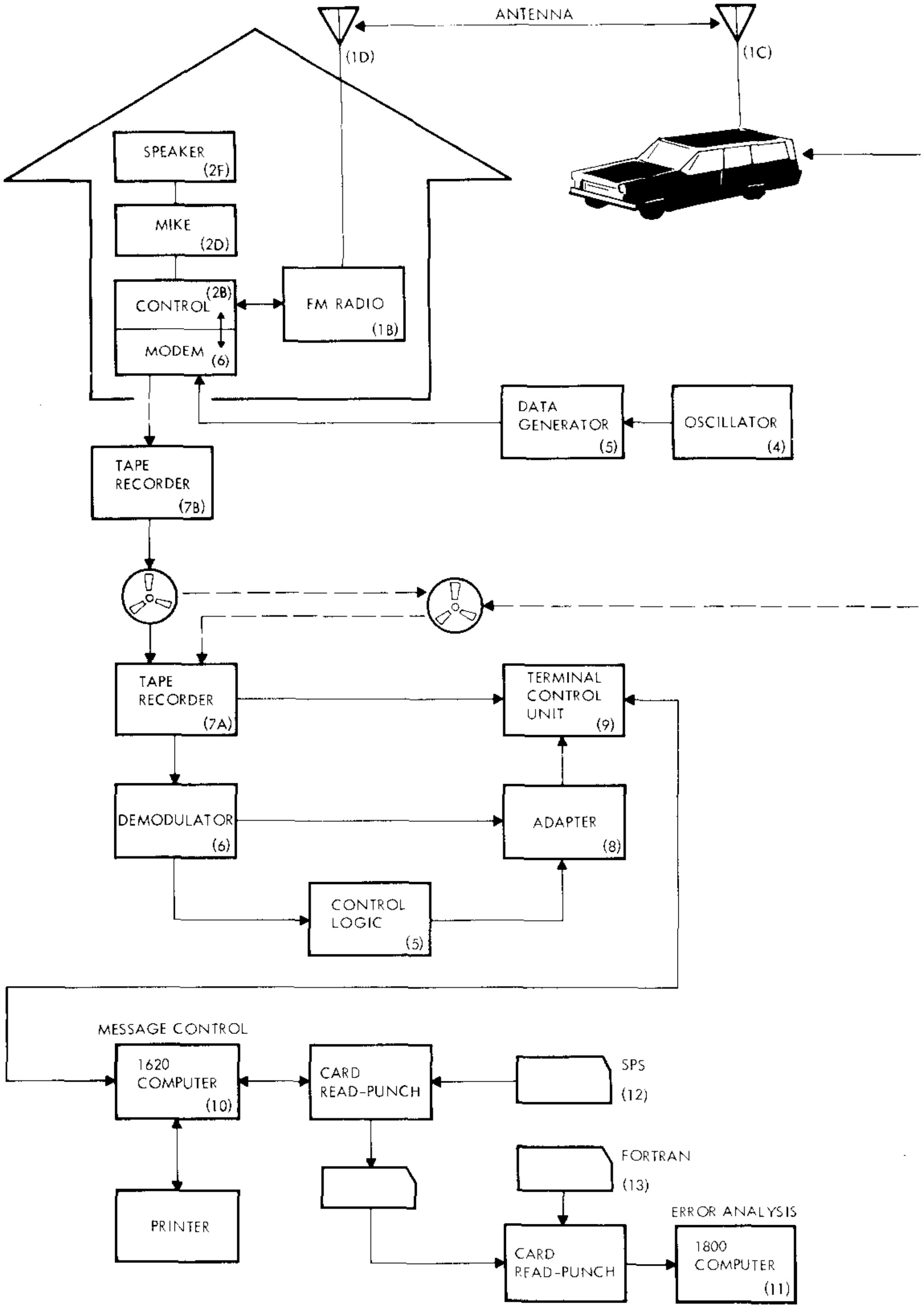
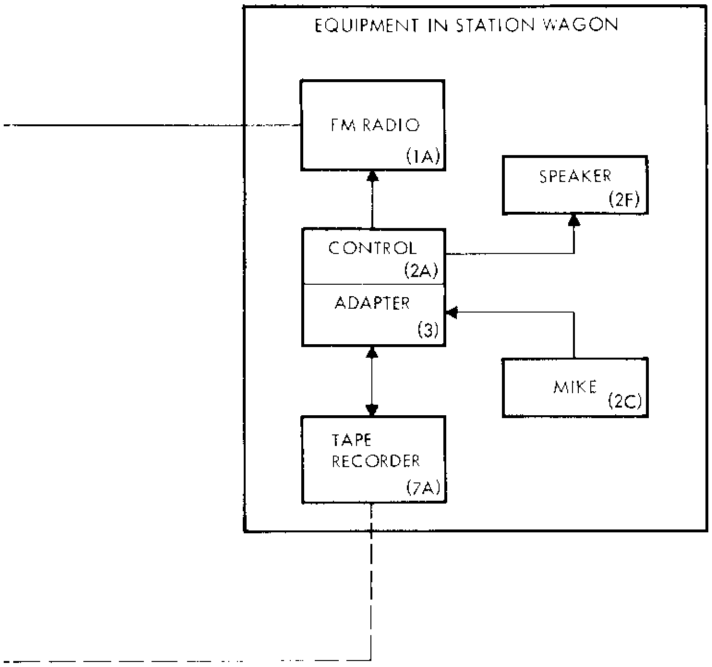


Fig. 1. Test Equipment



I. INTRODUCTION

A. THE PROBLEM: OVERCROWDED RADIO CHANNELS

With present methods of voice communication, even if transmission were steady, the communication rate would be about five characters per second. When we take into account pauses for taking notes and other interruptions, the effective rate declines to something like one to three characters per second. But the broadcast voice mode also requires a certain amount of vocal addressing, acknowledging, and redundant voicing of letters or digits. This redundancy compounds the transmission inefficiency, creating problems in transmission over a relatively small number of channels.

The problem of crowded voice transmission channels, particularly in the public safety and special services, has been well documented. The President's Commission on Law Enforcement and Administration of Justice has called for improvements in police communication.[16] A big part of the delay in getting police to the scene of a crime, according to the Task Force on Science and Technology, is the police communication.[17] The task force recommends a number of ways to shorten this delay: automatic reporting of patrol car locations, computer assistance in dispatching decisions, and giving a police officer direct access to his department's computer.

While law authorities are hoping to speed up and extend police radio communication, the Federal Communications Commission is concerned about the overloading of the present channels. With mobile transceivers in this country now numbering more than five million, and still multiplying rapidly, the channels assigned to safety and special services are seriously overcrowded. One FCC study[13] concludes that the land mobile service has already reached "the bottom of the barrel." The number of mobile units licensed for such service in the United States doubles every five years. Last year, the New York City Police were forced to operate many police cars without radios until they got temporary permission to use Forestry Service frequencies. In New York City, it is said, land-mobile radio communications will reach the saturation point in 1971.

To alleviate the problems in land mobile spectrum allocation, several changes have been proposed:

1. Re-allocation of some of the UHF TV channels for land mobile units.
2. Pooling of present land mobile channels in a sort of public utility, similar to the wireless phone service offered by the Bell System.
3. Allocation of a portion of each speech channel for data transmission to obtain enough narrow-band channels for radio teletype.
4. Alternation of voice and telegraph transmission on the same channels.
5. Assigning of some channels for matrix transmission of messages to printer. (This would still require human check for retransmission in case of error.)

B. OUR APPROACH: DIGITAL COMMUNICATION IN A MOBILE TERMINAL SYSTEM

To get some real relief for the FCC's present jam and at the same time improve the speed of police communications, we recommend a computer-controlled communications system. In this system, a computer central would communicate with buffered input/output terminals in mobile units for police, fire, industrial and other land transportation services. This approach we call the Mobile Terminal System.

The advantage of such a system is that the information transmitted would be in a computer code transmitted at much higher speed than present voice communication. The transmission of binary data, taking much less time than voice communication, would in effect increase the channel capacity. (VHF radio at high speeds of 10,000 bauds would be possible, but probably too expensive.) The modulation system must be simple, low-cost, and capable of operation at the highest practical speeds over available mobile radio channels. Within the usual voice bandwidth, up to 2400 bauds* or 300 characters per second, the modulation system can be a relatively simple method of phase modulation with synchronous detection.

We propose to substitute digital for voice communications in all land mobile applications where this is appropriate, and in this way to eliminate most of the voice communication. Each motor vehicle would have a buffered input/output terminal and modem. The dispatcher at the control center, with a computer to assist him, would not make general broadcasts but would send messages, usually 50 characters or less, to individually selected vehicles at the rate of at least 50 characters per second, with 300 characters per second as an objective. At the vehicle, the messages would be temporarily stored in a buffer and then printed out or displayed at 10 to 30 characters per second on a compatible low-cost device. The buffer allows the human recipient of the message to visually verify it, and stores the message until he depresses a transmit key which starts transmission in the high speed burst mode (on a contention basis).

Initial studies indicate that a Mobile Terminal System would use channel capacity at least ten and possibly a hundred times more efficiently than present voice communications. Many other important benefits are inherent in the system. These include source recording, display or printout, ability to leave messages in an empty car, positive confirmation of message receipt by terminal and human at different times, computer processing, and computer allocation of resources (by linear programming techniques).

C. EXPLORATORY STUDY: SUMMARY OF METHOD AND RESULTS

We have just completed a one-year exploratory study of the communication channel problems which are basic to the development of a reliable mobile terminal system. The first question is what digital transmission speed is practical and what level of error detection or correction is required. The approach we took to this question and the results we obtained, which are discussed in detail in the subsequent sections of this report, are summarized below for the reader's convenience.

1. METHOD

a. We established 300 characters per second as a target transmission rate. This is equal to 2400 bauds--well within the voice channel capacity of present land mobile radio.

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*Baud is the unit of signaling speed equal to the number of code elements per second.

b. We applied for and received an Experimental Developmental Service Status Class license in accordance with Section 5.252 (a) of the FCC rules.

c. We purchased two standard narrow-band FM mobile radios, mounting one in the car and the other in our laboratory.

d. We conducted base-station-to-mobile and mobile-to-base-station transmission at 300 characters per second throughout sections of Santa Clara County selected for geographical characteristics that represent best-worst conditions for this type of transmission.

e. More than 45,000 127-bit messages (equivalent to 17 six-bit characters or 13 eight-bit bytes, plus selective station addressing in a working system) were transmitted. These were processed on a computer, which compared each message as received with a prerecorded copy and compiled the number of bits in error to determine the effectiveness of the transmission technology and the level of results to be expected.

2. FINDINGS

a. In any geographical area where voice transmission is now satisfactory, the percentage of error-free messages ranges, depending upon geographical conditions, from 33% to 95%. In an operating system, automatic error detection and retransmission at the standard rate of 300 characters per second would be a built-in requirement.

b. Within the percentage range stated above, an effective transmission rate of from 100 to 300 characters per second can be achieved. This is an improvement of two orders of magnitude over the 1 to 3 character per second effective rate of voicing.

c. With the elimination of verbal "hand shaking" and redundancy voicing of letters and digits, message transmission time is reduced to the net time required to send the actual message. As a result, an additional order of magnitude of improvement is predictable.

d. Since standard land mobile sets, without modification, were used, the capability of the system to be employed in the voice mode for emergency override is not impaired. This is especially important in public safety transmission.

3. RECOMMENDATION

Two-way digital communication with mobile VHF units can be provided in a way that would conserve radio frequency spectrum: VHF mobile units can transmit and receive at 300 characters per second by using phase modulation, synchronous detection modems and a buffer with automatic error detection logic at 2400 bauds. This basic strategy permits the use of present voice mobile VHF channels* for digital transmission with emergency voice override.

II. TEST EQUIPMENT AND EQUIPMENT MODEM

The equipment used in our tests is shown in Fig. 1, and is listed in Table 1. The equipment consists for the most part of conventional components. Their characteristics and their use in our tests are described in detail in Appendix A. This section will concentrate on the experimental modem (modulation-demodulation unit) used in the tests, since this is a unit that was developed in this laboratory especially for this type of application.

A. PHASE MODULATION, SYNCHRONOUS DETECTION MODEM

This modem is a reliable, low-cost device based on the principle of phase modulation with synchronous detection, which takes advantage of the synchronous characteristics of the VHF-FM radio channel. This system has two advantages:

1. It rejects any noise interference that is effectively ninety degrees out of phase with the signal.
2. It uses a direct binary system which is more immune to noise than multilevel systems.

The principal disadvantage of the simple synchronous phase modulation used is that on typical telephone lines it is not possible to recover the clock, since the telephone channel is nonsynchronous.

At present, if operation over both telephone lines and radio links is required, it is necessary to demodulate at the radio end of the telephone line, and use a different set of modems on the telephone lines.

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*This study does not examine the nature of input/output devices for public safety vehicles. Those are left to a separate study. To determine the characteristics of the communication channels, we used a magnetic tape unit in the vehicle to simulate the buffer storage of an input/output terminal.

Table 1. Test Equipment

Item No. in Fig. 1	Name	Specification
1A, 1B	FM Radio (Motorola, U73MHT-3100A)	151.070 Megahertz, 110 watts output
1C 1D	Antenna on roof of station wagon Antenna, unity gain	
2A, 2B 2C, 2D 2E, 2F	Radio Control Boxes Microphones Speakers	
3	Adapter to switch between microphone, tape recorder or speaker	
4	Oscillator to provide 2400-hertz clock source	Hewlett-Packard Model 200 CD Oscillator
5	Signal Generator & Control Logic	Generates 127-bit pseudo-random sequence
6	Modem consisting of modulator and demodulator for 2400-baud phase modulator with synchronous detection plus data synchronized clock.	
7A	Tape recorder (Sony TC-800) to receive or send audio signal consisting of phase-modulated 2400-hertz sinewave.	
7B	Tape recorder, same as 7A, to receive 2400-baud signals from demodulator.	
8	Adapter to connect demodulator to Terminal Control Unit	
9	Terminal Control Unit-A special unit on the 1620 paper tape channel to receive or send information from 1620 core memory.	
10	1620 Computer 60K core memory 1311 disk file (2 units, one for programs; and one for data). For experimental analyses one radio bit stored as alphabetic character (2 numerics or 8 bits) to avoid adding serial-to-parallel hardware.	127 bits stored as 254 numeric core positions with 46 numeric positions for message numbers and labels 150 messages fill 45K of core 15K for program SPS programming
11	1800 Process Computer for analysis of error messages 2310 disk storage.	Batches of 75 messages stored on Disk 1 working store for analysis under FORTRAN compiled programs.
12	SPS Message Handling Program for 1620 Computer	
13	FORTRAN Error Distribution Analysis Program for 1800 Computer.	

The phase modulation modem used in the reliability tests is shown in Figs. 2 and 4. The modem is constructed of computer logic modules similar to the modulation circuits used in IBM files. The modulating and demodulating waveforms are shown in Figs. 3 and 5.

A sample data input waveform is shown (curve 0) in Fig. 3. The data is converted to transition coding (curve 3) before reaching the modem. A 2400-Hz clock is required (curve 1). The clock and the inverted data signal are ANDed together, as are the inverted clock and time data signal. Each of these outputs is inverted and both are ORed to give the modulated signal (curve 9). The modulated signal is then sent through a low-pass filter giving a signal output waveform like curve 10 in Fig. 3.

The synchronous demodulator is shown in Fig. 4 and the corresponding waveforms in Fig. 5. The input signal (curve 11) is amplified and then is reproduced through an emitter follower. The signal is then sent to a balanced modulator and to a subcarrier recovery section. Full-wave rectification coupling through a 4800-Hz tuned circuit and a phase control unit to a frequency divider (÷2) gives a 2400-Hz sinewave (12). This subcarrier (12) and the input signal are compared by the balanced modulator, giving a positive voltage when they are in phase and a negative voltage when out of phase. This gives a recovered signal waveform (13), which is filtered and squared to give waveform (14). The squared waveform is then differentiated to give short pulses (15), which trigger a single-shot hold circuit to give the original level-coded waveform (17). The clock is recovered by sending the short pulses to a tuned circuit and square to give the clock waveform (16).

B. ALTERNATIVE MODULATION SYSTEMS

The tests of 2400-baud digital transmission over VHF mobile radio were done with the phase modulation, synchronous detection modem described above. Before and during the tests, we tried a number of alternative modulation systems. Some of them were carried only as far as laboratory bench tests and then dropped because of synchronization problems requiring a better clock recovery system. Others were carried as far as preliminary tests on VHF radio and/or telephone lines. Only the phase modulation, synchronous detection modem was fully tested.

Waveforms used in alternative modulation systems considered are shown in Figs. 6 and 7. Curve A in Fig. 6 shows a sample binary sequence that is level coded. A phase modulation waveform is shown in curve 1. Due to the ambiguity in phase modulation from level coding, we used phase modulation from transition coding as shown in curves B and 4 in Fig. 7.

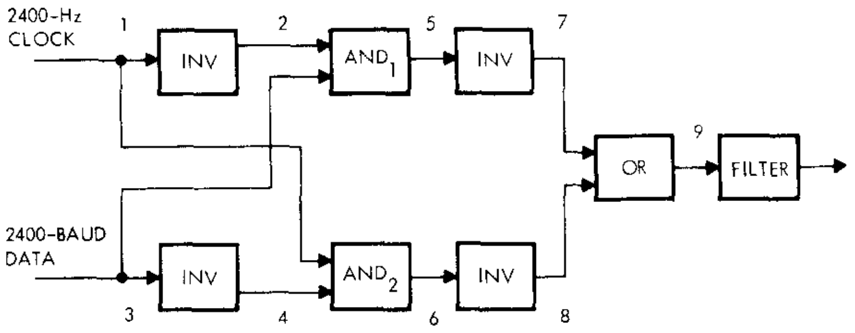

Fig. 2. Modulator Logic of Phase Modulation Modem

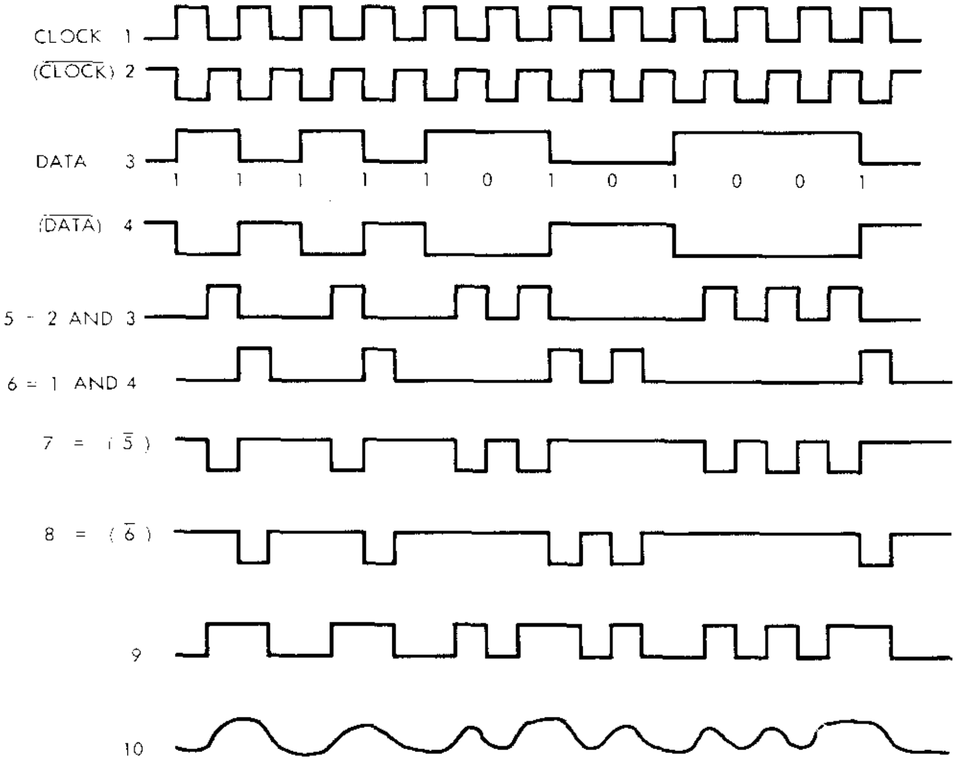

Fig. 3. Waveforms in Modulator at Numbered Points in Fig. 2

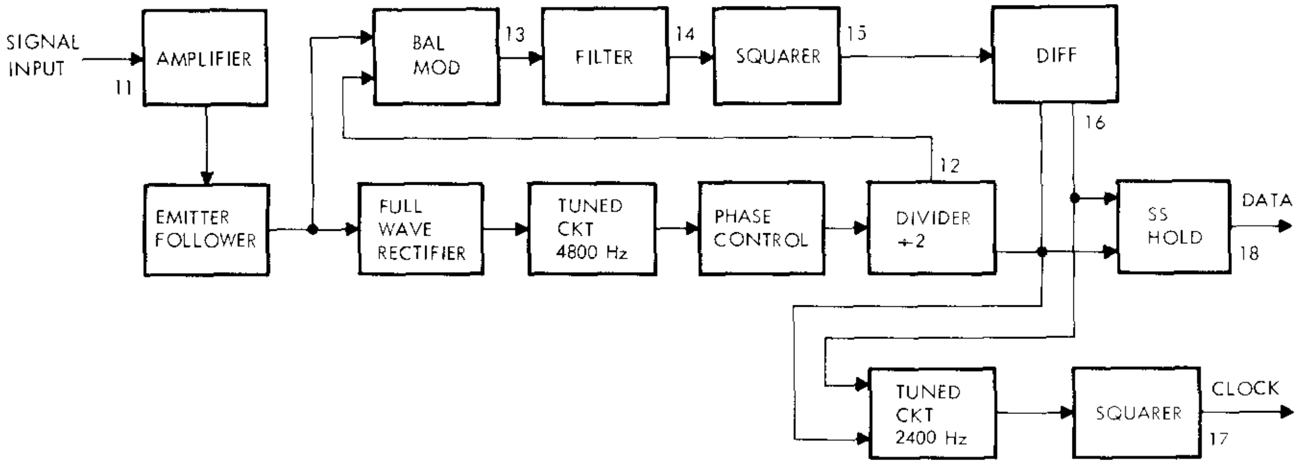

Fig. 4. Demodulator Logic for Phase Modulation Modem

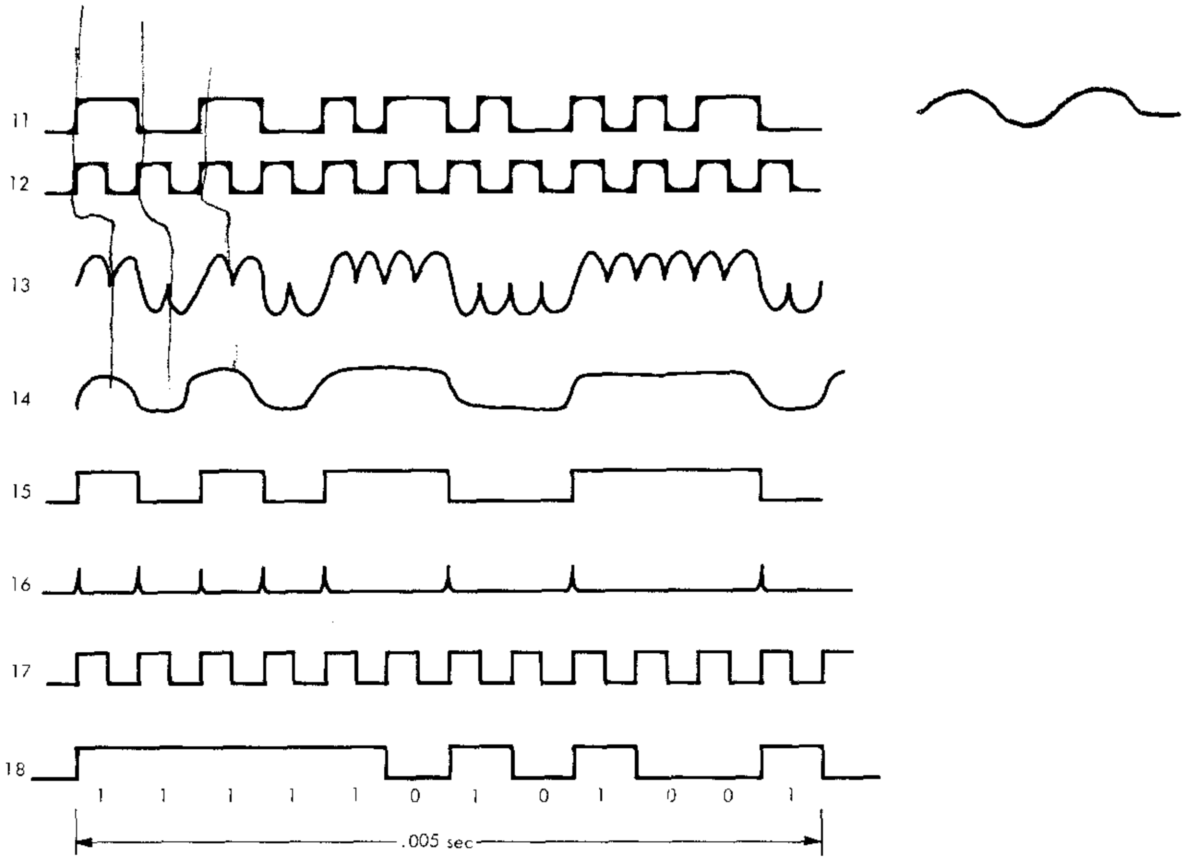

Fig. 5. Waveforms in Demodulator at Numbered Points in Fig. 4

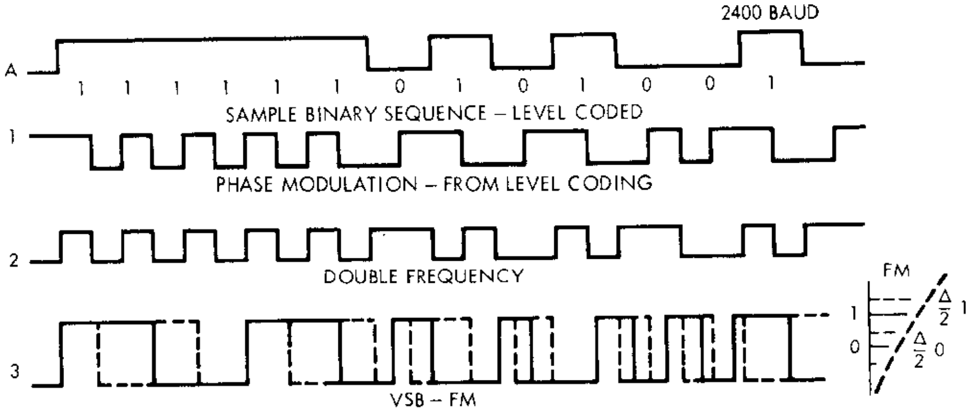

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Fig. 6. Modulation System: Level-Coded Binary Data

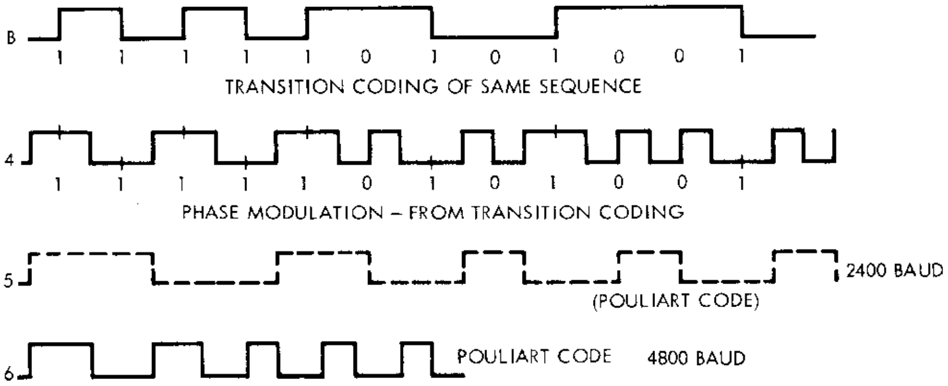

Fig. 7. Modulation System: Transition-Coded Binary Data

Another trial system was the double-frequency modulation shown in curve 2. This double-frequency modulation system is similar to phase modulation, but might not have as good a noise rejection as phase modulation with synchronous detection.

In considering alternative modulation systems, one characteristic to be sought is adaptability to both radio channels and telephone lines. The phase modulation, synchronous detection system of curve 4 works well at 2400 bauds on VHF radio links because of the synchronous nature of the VHF-FM communication system. However, the nonsynchronous nature of dial-up telephone lines precludes use of this modulation system on a switched telephone network at 2400 bauds, connecting state police and local police systems.[8]

Conventional double-sideband frequency modulation systems work both on telephone lines and radio links at 1200 bauds. Due to the bandwidth of the telephone lines, and for minimum adaptation from voice usage of VHF-FM radios, single-sideband, or vestigial-sideband systems, as well as multilevel operation, would have to be used to obtain the 2400-baud transmission. Experiments were done with a vestigial-sideband (VSB) FM system similar to that described by Hopner, Calfee and West.[9] The waveform of this VSB-FM modulation system before filtering is shown in curve 3 in Fig. 6. The logic involved in this modulation system is a type of duobinary coding. The systems considered requiring transition coding to avoid ambiguity are shown in Fig. 7. The transition coding waveform is shown as curve B for the same data as curve A in Fig. 6. Curve 4 can be easily decoded using a clock signal derived from itself. Each transition at the sample time gives a one, and when no transition occurs it corresponds to a zero.

Another system was investigated to see if 4800-baud operation could be easily obtained. W. H. P Pouliart in a U. S. Patent[15] showed a code containing both the binary information and the clocking information. Curve 5 illustrates one implementation of the Pouliart code by putting the phase modulation signal of curve 4 through a binary trigger to obtain the waveform of curve 5. This is then divided by two to give the waveform of curve 6. Some experimental tests were made of this Pouliart code, but this line of investigation was abandoned when initial tests indicated that, at 2400 bauds, best noise rejection can be obtained by using phase modulation.

There is a reliability penalty of 3 db associated with duobinary systems having three detection levels as compared with two-level (binary) detection. Synchronous detection provides 3 db of additional noise rejection. Since the VHF transmission medium is very noisy, the 6-db noise rejection bonus plus simplicity of implementation led to the decision to use synchronous phase modulation for the mobile links.

III. TEST PROCEDURE

In planning our tests, we wanted to make certain that we covered a range of conditions, including worst conditions for VHF transmission. (We did not include telephone line, VHF repeater or UHF link transmission.) Examination of the map of Fig. 8 shows the geography of the Santa Clara Valley, which is at the south end of San Francisco Bay. Most of the valley floor is from 100 to 200 feet above sea level, between two mountain ranges having peaks as high as 4,000 feet--the Diablo Range and the Santa Cruz Mountains.

The width of the valley varies from two miles in the south to twelve miles in the north. The IBM experimental antenna is on the roof of the IBM Los Gatos Laboratory, whose location is on a flat shelf at the opening of a small valley along the edge of the Santa Cruz Mountains. This gives a clear straight line-of-sight path to the center of San Jose, Milpitas, Santa Clara, Alviso and Campbell. The path to Los Gatos, Cupertino, Mountain View, and parts of Sunnyvale is obstructed by a small arm of the Santa Cruz Mountains. This location gives a range of conditions from good to worst case. The Santa Clara County Communication System Center has its main base-station on a hill (elevation: 400 feet) southeast of the center of the valley, marked in Fig. 8. This position gives a straight path to practically all areas on the valley floor.

One of the two FM radios, of a type commonly used in police radio systems, was installed in a station wagon, while the other was mounted on a movable table in the laboratory. The feedback shift register described in Appendix A generated a pseudorandom (PR) sequence of ones and zeros which served as test messages. The output of the sequence generator was phase-modulated by the modem described in the previous section; and the 2400 hertz signal was connected to the audio input of the FM radio. The main tests were transmitted at 151.070 megahertz from the unity gain antenna on the roof of our laboratory and were recorded on an audio tape recorder carried in the station wagon traveling around the county.

The routes around the valley traversed by the station wagon during the tests are shown by the bold black lines in Fig. 8, and further described in Table 2, which also gives the original numbers and computer file numbers of the transmission tests on these routes. Transmission from mobile to base was recorded for two sections of the run. For the mobile-to-base tests, modulated messages were prerecorded on magnetic tape and then played back from a battery-operated tape recorder in the station wagon. The first mobile-to-base tests were unsuccessful, because the radio frequencies disturbed the speed control circuits on the tape recorder. Building of a shielding box for the tape recorder permitted tests to be conducted without this disturbing effect. This experience indicates that there may be a need for similar shielding of the buffer, error detection, and control logic in a Mobile Terminal System.

The stability of the tape recorder in the station wagon was tested by driving the station wagon around the parking lot of the ASDD Los Gatos Laboratory while recording the received signals. This tape was then brought into the computer laboratory and tested. It was found to have all messages 100% correct for base-to-mobile transmission.

A similar test was made for mobile-to-base transmission. For this case, a laboratory recorded tape was used in the moving station wagon to supply the digital messages. The received messages were recorded on a duplicate tape recorder and then compared in the computer laboratory. On these tests, messages transmitted from the parking lot averaged 80.7% perfect messages, and 96.7% having one bit or less in error. This indicated that with two audio tape units in the system for mobile-to-base transmission there could be errors in the system due to instabilities compounded by the use of two audio tape units. Therefore, we made most of our tests (33,378 messages) in base-to-mobile mode, where we could be sure there was no ambiguity due to audio tape instabilities. We ran a smaller number (12,372 messages) mobile-to-base to determine if there were signs of any other problems we might have overlooked.

The tape from the station wagon was brought to the computer room and read into a demodulator controlled by a logic adapter and then into a terminal control unit connected to an IBM 1620 I/O channel modified to accept 2400 bauds through the paper tape I/O channel. The messages received in the 1620 were analyzed for errors and the number of transmitted messages and summary of the number of errors were printed out.

In addition to the count of messages in error, either a copy of each message in error or the error bit pattern was punched into cards for later detailed analyses.

From these error statistics one can simulate the effect on matrix printing or the functions of proposed error detection or correction codes for digitally controlled printers. The problem in matrix printers without error detection logic is that the police officer at the mobile terminal must watch for defective characters and decide whether to guess at the correct character or request a retransmission. If digital transmission is used with logic decoding to the printer, some error detecting logic is needed to request automatic retransmission.

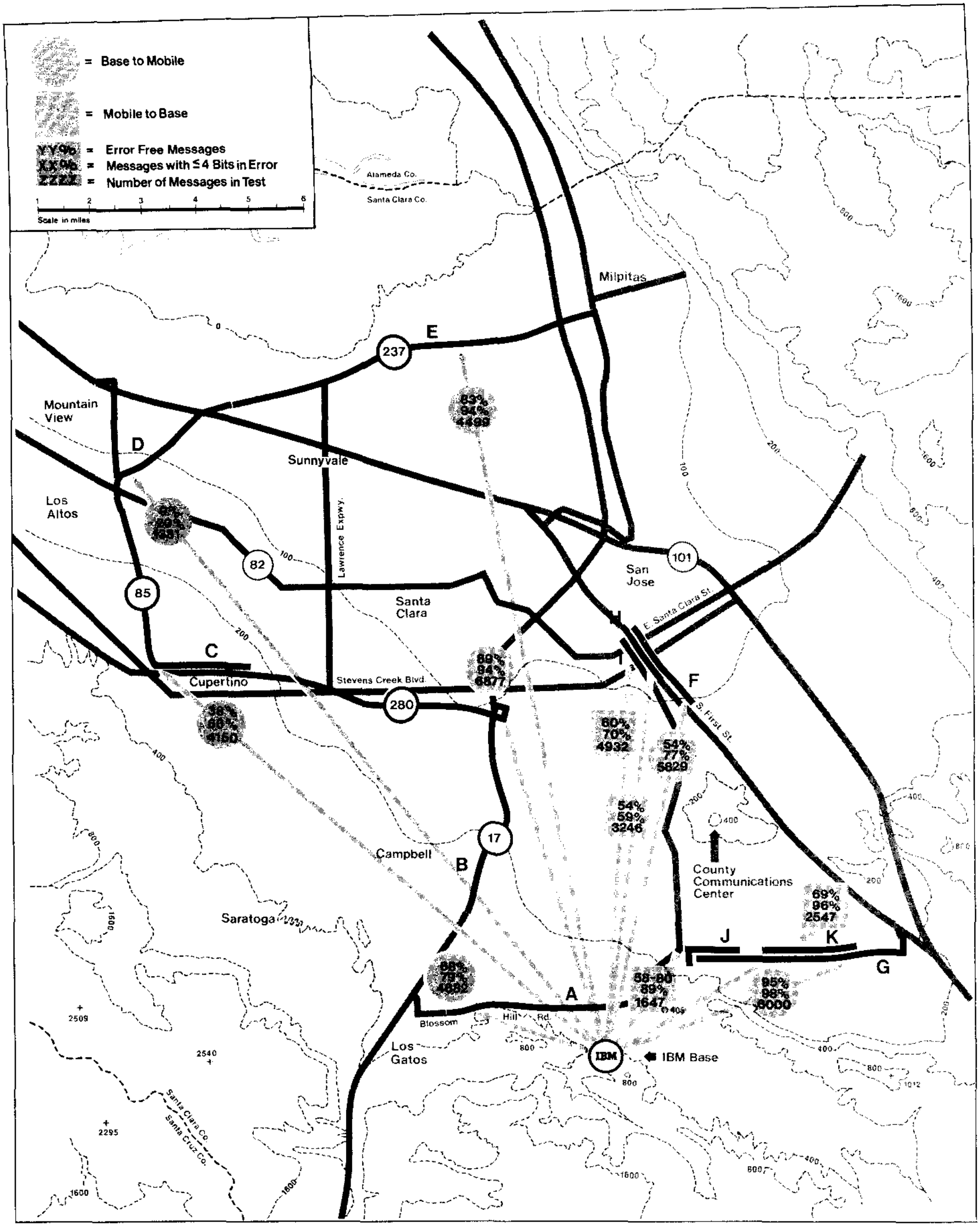

Fig. 8. The Santa Clara Valley, Showing Transmission Paths and Test Results (Bold black lines with letter codes are the test routes followed by the mobile unit. The test routes are further described in Table 2.)

Table 2. Routes Travelled by Mobile Unit in Transmission Tests (see also map of Fig. 8)

Route	1620 Test No.	1800 Test Group
Base-to-Mobile Tests		
A. Country Road (1 to 3 miles) Blossom Hill Road toward Los Gatos	23005-23070	A. S/360 Volume 585872 File 1 (A)
B. Intercity Freeway (4 to 10 miles) Highways 17 and 280 Campbell to Cupertino	23071-23124	D. S/360 Volume 585872 File 4 (D)
C. City Street and Depressed Highway (10 to 13 miles) Homestead Road and Highway 85	23125-22158	F. S/360 Volume 585872 File 6 (F)
D. Industrial Freeway (14 miles) Highway 85 at Highway 82 and Highway 237 near Highway 101	23159-23167	FA. S/360 Volume 585872 File 11 (K)
E. Country Highway (13 miles) Highway 237 Sunnyvale to Milpitas	23176-23218	B. S/360 Volume 585872 File 2 (B)
F. Downtown Street (6 to 7 miles) First Street, San Jose	23219-23263	C. S/360 Volume 585872 File 3 (C)
G. Suburban Through Street (2 to 5 miles) Downer Road, IBM Plant toward Almaden Road	23264-23315	E. S/360 Volume 585872 File 5 (E)
Mobile-to-Base Tests		
H. Downtown Street (6 to 7 miles) First Street, San Jose	Selections from 25476-25522	G. S/360 Volume 585872 File 7 (G)
I. Downtown Street (6 to 7 miles) First Street, San Jose [same raw data as in H but analyzed for different sync-idle period]	25601-25633	H. S/360 Volume 585872 File 8 (H)
J. Suburban Through Street (2 to 5 miles) Downer Road from IBM Plant	25428-25444	I. S/360 Volume 585872 File 9 (I)
K. Suburban Through Street (2 to 5 miles) Downer Road near Almaden Road	25574-25585	K. S/360 Volume 585872 File 10 (J)

Table 3. Summary of Test Results

TEST	NUMBER OF MESSAGES	% ERROR FREE	% ≤ 4 ERRORS
BASE TO MOBILE			
A Country Road, 1 to 3 miles	4682	69	80
B Intercity Freeway, 4 to 10 miles	6877	89	94
C City Street and Depressed Highway, 10 to 13 miles	4150	38	66
D Industrial Freeway, 14 miles (Intermodulation Noise)	1331	9	20
E Country Highway, 13 miles	4499	83	94
F Downtown Street, 6 to 7 miles	5829	54	77
G Suburban Through Street, 2 to 5 miles	6000	95	98
MOBILE TO BASE			
H Downtown Street, 6 to 7 miles (14-Bit Sync Idle)	3246	54	59
I Downtown Street, 6 to 7 miles (15-Bit Sync Idle)	4932	60	70
J Suburban Through Street, 2 to 5 miles (14-Bit Sync Idle)	2547	69	96
K Suburban Through Street, 2 to 5 miles (15-Bit Sync Idle)	1647	58-80	89

IV. RESULTS

The average percentage of error-free messages recorded as our station wagon travelled the main freeways of the county and downtown streets of San Jose ranged from 30 to 100%. With error detection and automatically requesting repeat of messages in error, we would have an effective transmission rate of 100 to 300 characters per second. The error patterns and their message numbers were saved in punched cards so that future analyses could be made as to the relative efficiency for different block lengths. The results obtained for the different test routes are summarized in Fig. 8. The top number in the circles represents the percentage of error-free messages; the next number is the percentage of messages with four or less bits in error out of a 13-character message (104 bits plus 14-bit sync-idle and 9-bit EOM); and the third number is the total number of messages transmitted.

The reliability of transmission on the different test routes is also summarized in Table 3. The correspondence between the error rate and the interference of the hills can be seen by examining the percentages of error-free messages and the contours marked on the map.

Full details of the method of error analyses and the error distribution for different routes are given in Appendix B.

The summary of the reliability tests in Table 3 is arranged to show the effect that error detection with automatic request of error checking would have on the message transmission, in comparison with the effect of human error detection by using a matrix printout. If we take Set No. C to the downtown area with tall buildings with 54% error-free and 77% of messages with less than five bits in error, we see that half the messages would have to be repeated with electronic detection and request. If we assume up to four bits in error in a matrix printout normally could be corrected at sight by the person reading the printout, the matrix format would still require about one out of four messages to be repeated on operator request. This indicates that error detection with automatic request for retransmission is likely to be more practical.

V. CONCLUSIONS

In the geographical area where voice transmission is satisfactory, the percentage of error-free messages at 300 characters a second ranges from 33% to 95%. Simple error detection with automatic request for retransmission is recommended to permit automatic printing of a message when the vehicle is unattended and when the vehicle is passing through tunnels, overpasses, etc.

With this range of error rates, the effective transmission rate is 100 to 300 characters per second, which is two orders of magnitude times the voice operation effective rate 1 to 3 characters per second. (Switching time, note writing time, etc., reduce the voice transmission rate 5 characters per second to the range of 1 to 3 characters per second.)

These reliability tests indicate that the present problems in VHF frequency transmission, especially by public safety services, might be relieved by converting land mobile communications in the major metropolitan areas to 2400-baud digital communications using the present voice VHF-FM radio equipment. This service could be provided for both terminal-to-terminal and computer-to-terminal systems, so that repeating of messages in error can be handled automatically. This reduction of channel use by two orders of magnitude might allow free channel capacity for voice override in emergency and for future growth of digital land mobile communication.

ACKNOWLEDGMENT

This work is the first of a series of studies organized by Dr. E. Hopner to determine how best to implement a Mobile Terminal System originally proposed by R. E. Kaufmann. Dr. Hopner, with O. F. Meyer and L. P. West, also did many preliminary experiments with different types of modulation systems. The Phase Modulation, Synchronous Detection Modem chosen for these tests was designed and built by O. F. Meyer. R. L. Cloke optimized the adapter logic between the Modem and the Terminal Control Unit of the 1620 Computer and built and debugged the adapter unit. F. B. Wood wrote the error analysis and message control programs and collaborated with R. L. Cloke and O. F. Meyer on the field tests.

APPENDIX A: TEST EQUIPMENT

A. FM RADIO AND ACCESSORIES

Items 1A and 1B in Table 1 are Motorola MOTRAC Mobile FM Two-Way Radios covering the range from 136 to 174 Megahertz, model U73MHT-3100A, 110 watts radio frequency power output. These sets have crystals for 151.070 Megahertz, a frequency allocated for highway maintenance service. The equipment has been assigned Federal Communications Commission Type No. CC3042, and the FCC has granted IBM permission to operate an Experimental (Developmental) service (Class Experimental XD MO) with call sign KB2XAF, in accordance with Section 5.252(a) of the Commission's rules.

The block diagram of the transmitter is shown in Fig. 9. For these reliability tests, the private line tone oscillator was removed, but no other changes were made in the transmitter. The phase modulation signals at 2400 bauds were connected into the audio amplifier through the microphone jack.

The receiver block diagram is shown in Fig. 10. The received signal to be recorded for later analysis is taken off between the discriminator and the first audio amplifier. The private line switch is left off. The amplifier did not require any internal changes to receive phase-modulated signals. The connection was made from the output of the discriminator through the test jack on the radio control head, and then through the adapter control box to the tape recorder.

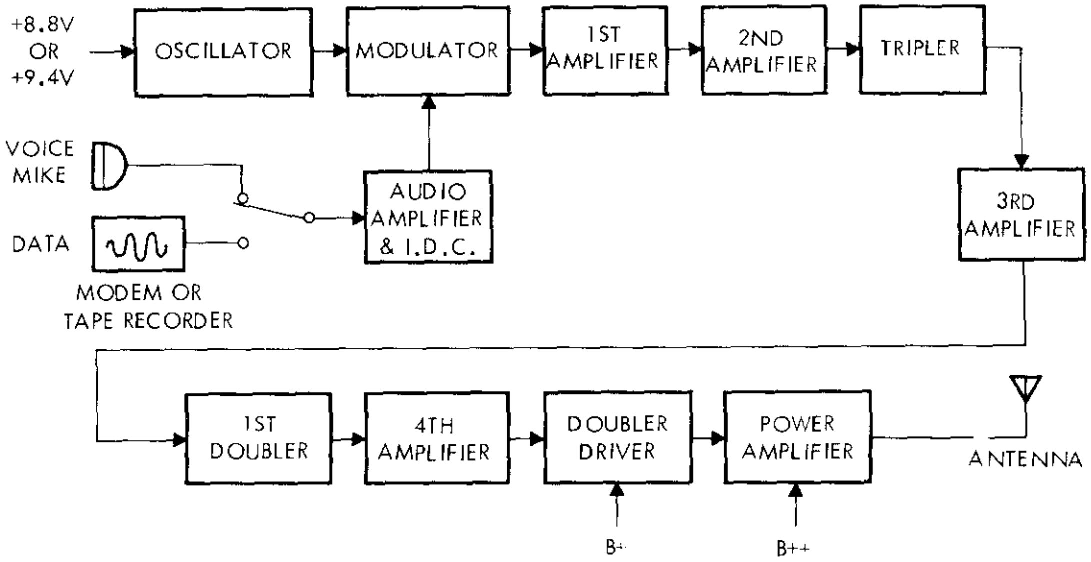

Fig. 9. Transmitter (Block Diagram)

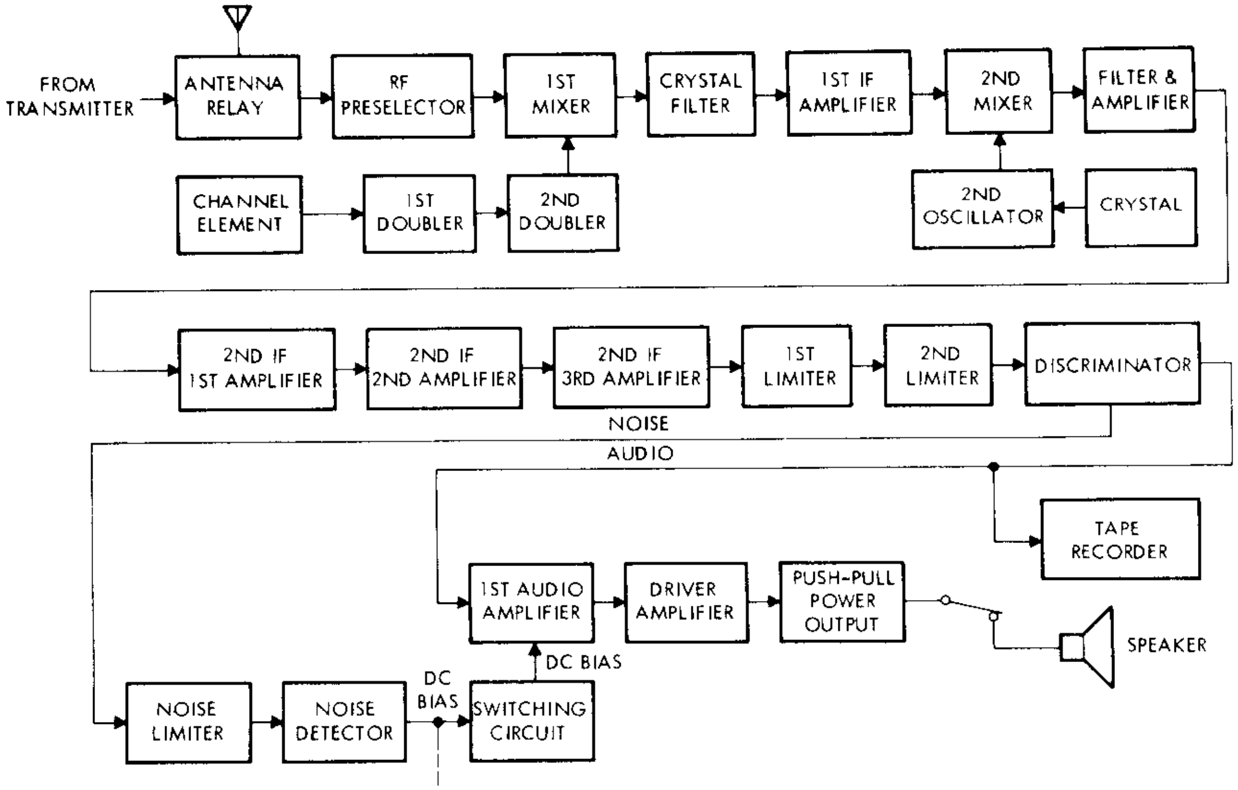

Fig. 10. Receiver (Block Diagram)

B. ADAPTER CONTROL BOX

The adapter control box which is inserted between the microphone and the control head of the mobile radio is shown in Fig. 11. It is designed so that no internal changes in the mobile radios are required. All connections are made to regular leads or test points available at the standard control head. The mobile unit is set to receive by putting SW 2 in the off position, connecting the cable from the adapter to the control head, connecting the jumper from the adapter to the discriminator output test jack on the back of the control head, and connecting the tape recorder to the receiver output jack on the adapter.

For transmission from the mobile unit to the base station, we set the connection on SW 1 to the data position, connect the tape recorder output to the data input jack, turn SW 2 on, and adjust potentiometer P1 for normal FM deviation.

A Hewlett-Packard Model 200 CD Oscillator provided the basic 2400-hertz sinewave clock signal for generating the test messages. The

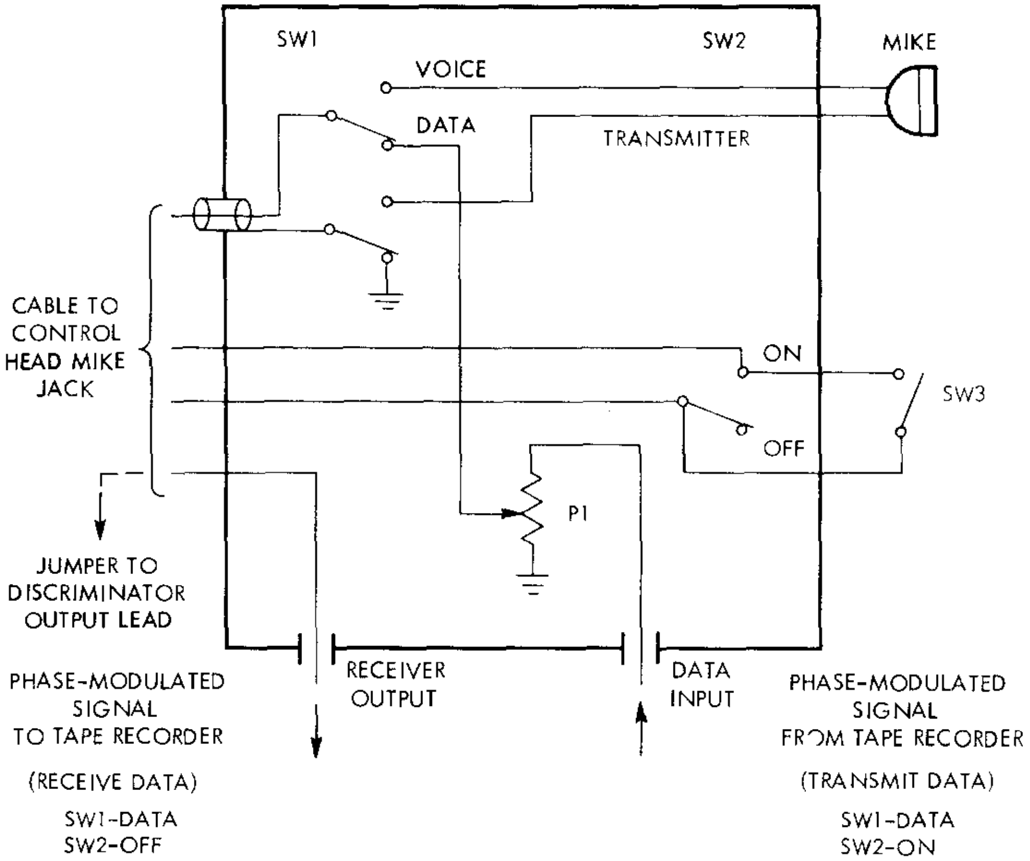

Fig. 11. Radio Control Adapter Circuits

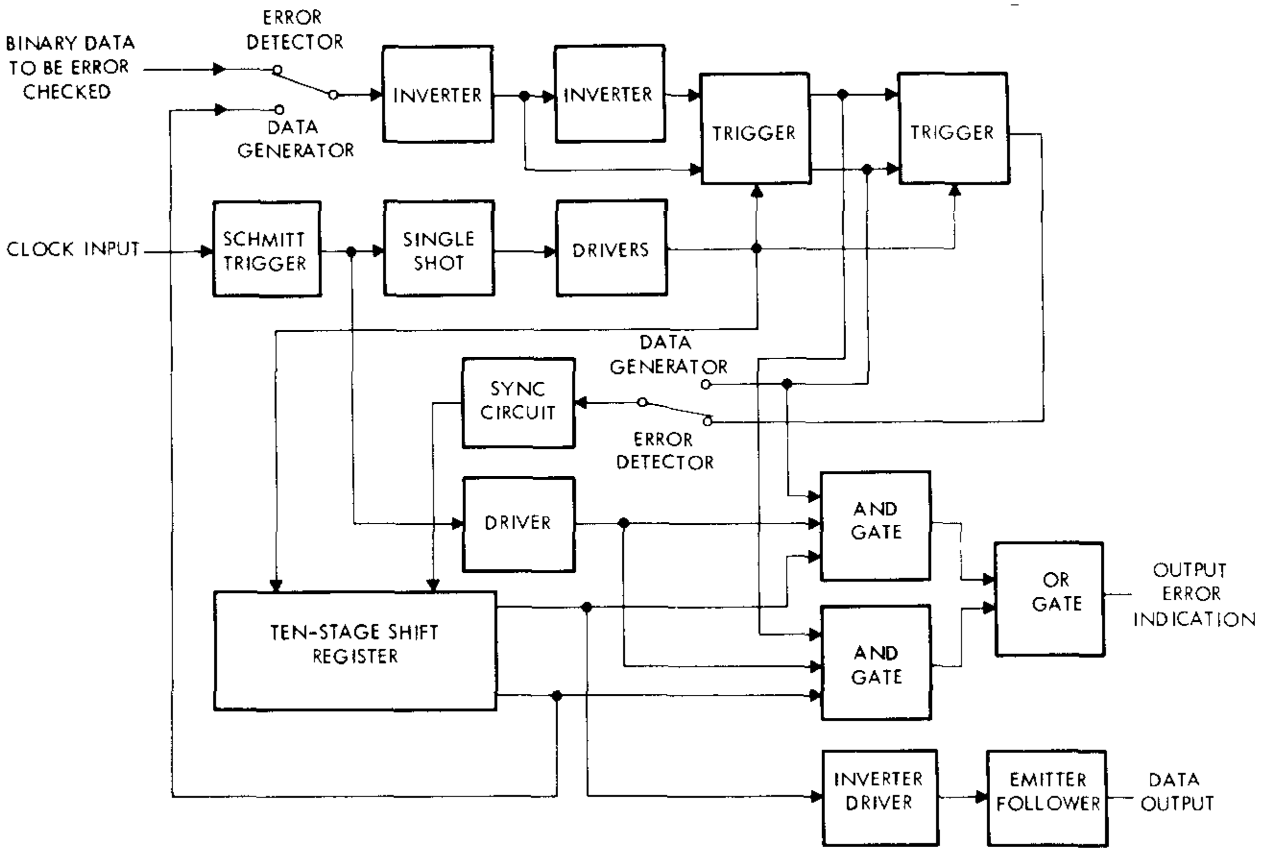

Fig. 12. Binary Data Generator and Error Detector (Block Diagram)

2400-hertz sine wave is used as input to a Binary Data Generator and Error Detector developed earlier by L. Provazek* and O. Meyer of our laboratory, using a type of feedback shift register conceived by Dr. C. M. Melas.

C. BINARY DATA GENERATOR

The Binary Data Generator and Error Detector has the capability of producing binary data at speeds to two million bauds.* The unit also has the capability of checking for errors in binary data which has been transmitted from a similar unit. For each binary data bit in error, the unit produces a pulse which can be recorded on a counter to determine the error rate.

As shown in the block diagram of Fig. 12, the major component of the data generator is a ten-stage shift register which produces NRZ data. An up level (ground potential) is considered a binary one and a down level (negative 6 volts) is taken as a binary zero. When connected in a ring, the shift register produces a ten-bit repetitive pattern. Ten character switches are included with the shift register to allow an operator to choose any desired ten-bit pattern. To place the desired character into the shift register, the operator presses a push button switch, which initiates a dc reset. When the dc reset switch is released, the ten-bit character will circulate in the register.

The sync circuit is primarily a one-transistor single-shot which is driven by the data, plus an AND gate which gates the data input to the single-shot and the single-shot output. With the single-shot set for a duration of one bit time less than the longest string of consecutive ones in the data sampled, the AND gate output will consist of a single pulse coincident with the last one of the string. A pulse is derived from the output of the AND gate and can be used to synchronize an oscilloscope with the data as well as to reset the shift register.

The sync circuit is designed so that a synchronous pulse can be extracted from data sources regardless of bit rate, provided the data is repetitive and has during its period one string of consecutive ones which is longer than any other such string. The character generator is designed to produce repetitive pseudorandom sequences of two basic lengths: a 127-bit sequence, which always has a string of seven ones as the longest string of ones, and a 889-bit sequence which has a longest string of ten ones. This method provides for only one sync pulse during

---

*The description of the data generator and error detector is adapted from an unpublished memorandum by L. Provazek.

BIT TIME		10-STAGE SHIFT REGISTER	
	D	1098765432	A
0000	0	011111110	0
0001	0	111111100	0
0002	1	111111000	1
0003	1	111110001	0
0004	1	111100010	1
0005	1	111000101	0
0006	1	110001010	1
0007	1	100010101	0
0008	1	000101010	1
0009	0	001010101	1
0010	0	010101011	1
0011	0	101010111	1
0012	1	010101111	0
0013	0	101011110	0
0014	1	010111100	1
0015	0	101111001	1
0016	1	011110011	0
0017	0	111100110	0
0018	1	111001100	1
0019	1	110011001	0
0020	1	100110010	1
0021	1	001100101	0
0022	0	011001010	0
0023	0	110010100	0
0024	1	100101000	1
0025	1	001010001	0
0026	0	010100010	0
0027	0	101000100	0
0028	1	010001000	1
0029	0	100010001	1
0030	1	000100011	0
0031	0	001000110	0
0032	0	010001100	0
0033	0	100011000	0
0034	1	000110000	1
0035	0	001100001	1
0036	0	011000011	1
0037	0	110000111	1
0038	1	100001111	0
0039	1	000011110	1
0040	0	000111101	1
0041	0	001111011	1
0042	0	011110111	1
0043	0	111101111	1
0044	1	111011111	0
0045	1	110111110	1
0046	1	101111101	0
0047	1	011111010	1
0048	0	111110101	1
0049	1	111101011	0
0050	1	111010110	1
0051	1	110101101	0
0052	1	101011010	1
0053	1	010110101	0
0054	0	101101010	0
0055	1	011010100	1
0056	0	110101001	1
0057	1	101010011	0
0058	1	010100110	1
0059	0	101001101	1
0060	1	010011011	0
0061	0	100110110	0
0062	1	001101100	1
0063	0	011011001	1
0064	0	110110011	1
0065	1	101100111	0
0066	1	011001110	1
0067	0	110011101	1
0068	1	100111011	0
0069	1	001110110	1
0070	0	011101101	1
0071	0	111011011	1
0072	1	110110111	0
0073	1	101101110	1
0074	1	011011101	0
0075	0	110111010	0
0076	1	101110100	1
0077	1	011101001	0
0078	0	111010010	0
0079	1	110100100	1
0080	1	101001001	0
0081	1	010010010	1
0082	0	100100101	1
0083	1	001001011	0
0084	0	010010110	0
0085	0	100101100	0
0086	1	001011000	1
0087	0	010110001	1
0088	0	101100011	1
0089	1	011000111	0
0090	0	110001110	0
0091	1	100011100	1
0092	1	000111001	0
0093	0	001110010	0
0094	0	011100100	0
0095	0	111001000	0
0096	1	110010000	1
0097	1	100100001	0
0098	1	001000010	1
0099	0	010000101	1
0100	0	100001011	1
0101	1	000010111	0
0102	0	000101110	0
0103	0	001011100	0
0104	0	010111000	0
0105	0	101110000	0
0106	1	011100000	1
0107	0	111000001	1
0108	1	110000011	0
0109	1	100000110	1
0110	1	000001101	0
0111	0	000011010	0
0112	0	000110100	0
0113	0	001101000	0
0114	0	011010000	0
0115	0	110100000	0
0116	1	101000000	1
0117	1	010000001	0
0118	0	100000010	0
0119	1	000000100	1
0120	0	000001001	1
0121	0	000010011	1
0122	0	000100111	1
0123	0	001001111	1
0124	0	010011111	1
0125	0	100111111	1
0126	1	001111111	0
0127	0	011111110	0

Fig. 13. Complete Set of Shift Register Stages in Generation of 127-Bit Pseudorandom Sequence

a period of either sequence. Once the sync pulse is adjusted for the bit rate of operation and the sequence desired, the sequence can be shortened to any desired length by first placing the correct character (corresponding to the sequence length desired) in the ten-character switches and setting the Binary Data Generator and Error Detector for automatic reset operation. The positions of the ten-character switches to obtain a shortened sequence of the 127-bit and 889-bit sequences have been determined. Therefore, a sequence of any desired length under 889 is quite simple to obtain.

The unit can also be used to check for errors in binary data (including the shortened sequences) produced by a similar unit. The only condition placed on the pattern to be checked is the requirement for a unique longest span of ones needed to obtain one sync pulse for each sequence period. When the unit is operating as an error detector, a clock (synchronized with the data) is required to drive the error detector. The incoming data is sampled with the clock and is delayed one bit time before entering the sync circuit. The one-bit delay is required so that the shortened sequences can be error-checked. The sync pulse is derived from the delayed incoming data and is used to set the shift register to the proper character through the ten character switches. The ten character switches on the error detector must be in the same position as the ones on the binary data generator producing the data. Once the error detector is synchronized with the incoming data and is producing data identical to the data being sent, the job of detecting errors is quite simple. The incoming data is compared with the generated data and a pulse is produced each bit time a difference exists.

The pseudorandom patterns appear very much random during one period, thus approaching the nonperiodicity of actual binary data. In our tests we used as our test message the 127-bit pseudorandom sequence. To obtain the 127-bit sequence, a ten-bit character of the sequence is placed in the character switches and the dc reset is pressed.

Figure 13 shows the complete set of shift register stages which generate the 127-bit sequence. Column D is the output bit from the sequence generator. The nine stages of the shift register are labelled from right to left as A, 2, 3, ..., 10. The first stage of the shift register, labelled A, is a flip-flop. The sequence of operation is this: the output bit is read from stage 10 to register D. The bits in stages 2 through 9 are shifted to stages 3 through 10. The state of flip-flop A is transferred to SR 2, and then the output bit stored in D is sent to flip-flop which changes its state, if D = 1 and does nothing if D = 0.

The salient features of the unit are the circuit for obtaining the synchronous pulse and the method of resetting the shift register with the ten character switches.

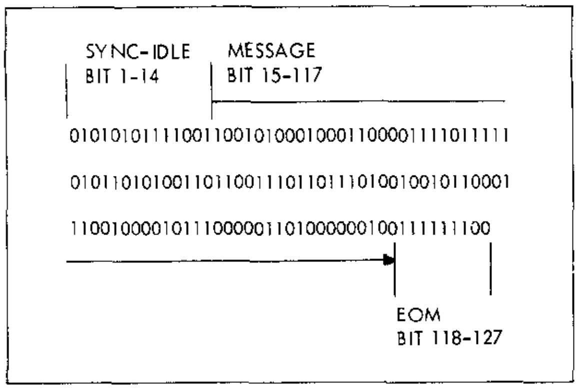

Fig. 14. 127-Bit Standard Message Used in Tests

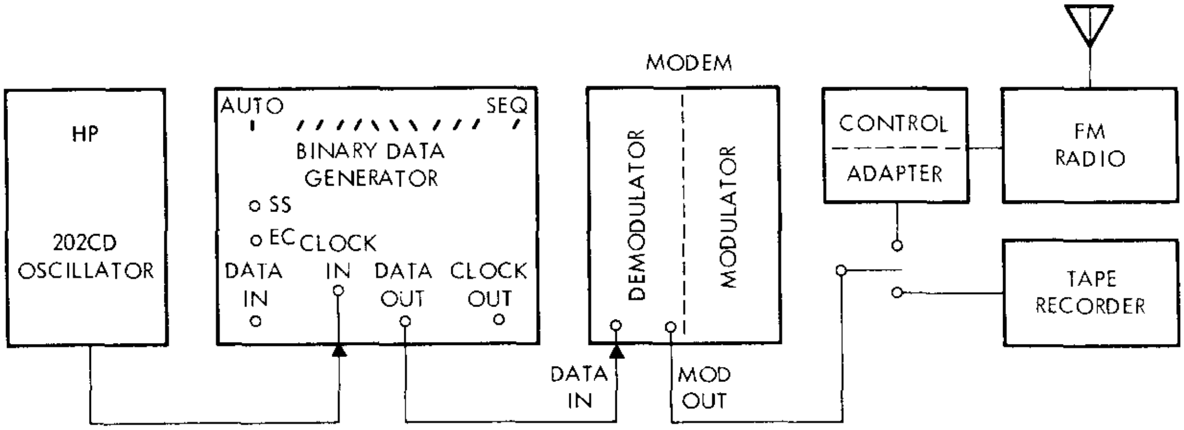

Fig. 15. Equipment Setup for Transmitting Test Messages

The 127-bit test message shown in Fig. 14 can also be read from the columns showing the tenth stage of the shift register in Fig. 13. The string of seven ones at the end of the previous message provides a sync pulse during the next bit time, which initiates the start of a message. When transmitting from the base station to the mobile units, the received messages are recorded on a tape recorder. The full 127-bit sequences are transmitted and recorded. When replaying the recorded data into the 1620 Computer for analysis, the first 14 bits are treated as a sync-idle time, and the reading into the computer starts with the 15th bit. The 14 bits or 5.7 milliseconds is the time needed by the 1620 computer and terminal control unit to perform logical checking and update message counter registers between messages.

During the reading of the recorded messages from the tape recorder into the 1620 terminal control unit, the sync circuit of the Binary Data Generator is used to detect the end-of-message. A delay in the 1620 TCU-to-Modem Interface is adjusted for the 14-bit delay (15 bits on some tests).

Figure 15 shows how the equipment is connected for transmission of digital test messages or for recording messages on tape for later transmission.

In the reliability tests we wanted to have data on the distribution of numbers of errors per message in error and to save data on the error patterns to help determine what codes would be useful. Since the hardware logic in the Binary Data Generator only signals whether a message is in error or correct, we developed a program in the Symbolic Programming System (SPS) language for the 1620 computer to detect and count errors, and to punch out cards for message in error, so that the punched card error message could be re-run later for error distribution analysis.

D. INTERFACE BETWEEN 1620 TCU AND MODEM

The principal function of the Interface Unit is shown in Fig. 16. To read recorded messages into the 1620 computer, the output from the tape recorder is first read into the demodulator section of the Phase Modulation-Synchronous Detection Modem. The demodulated signal and a clock signal derived from the input signal in the modem are both sent to the Binary Data Generator and the interface. The Binary Data Generator sync circuit detects the combination of seven ones in a row and sends the scope sync (SS) pulse to the interface which generates the End of Line signal to stop the writing into the 1620 through the TCU.

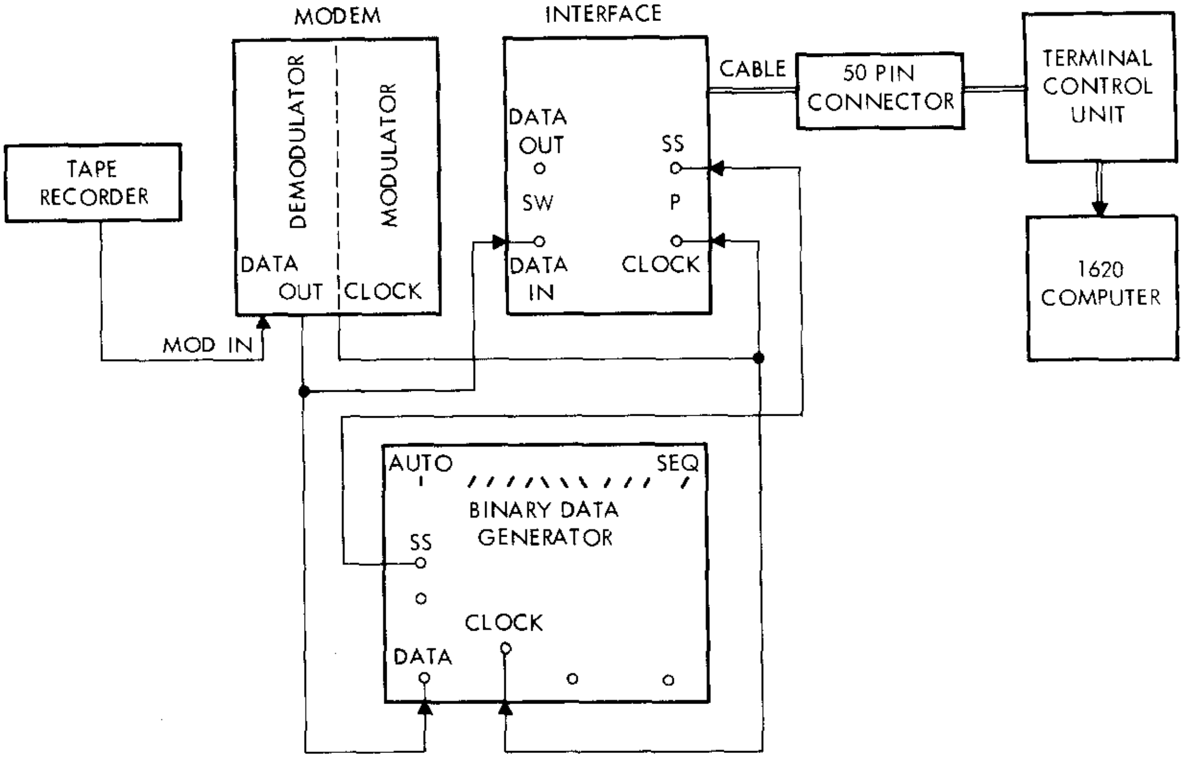

Fig. 16. Equipment Setup for Analyzing Test Messages

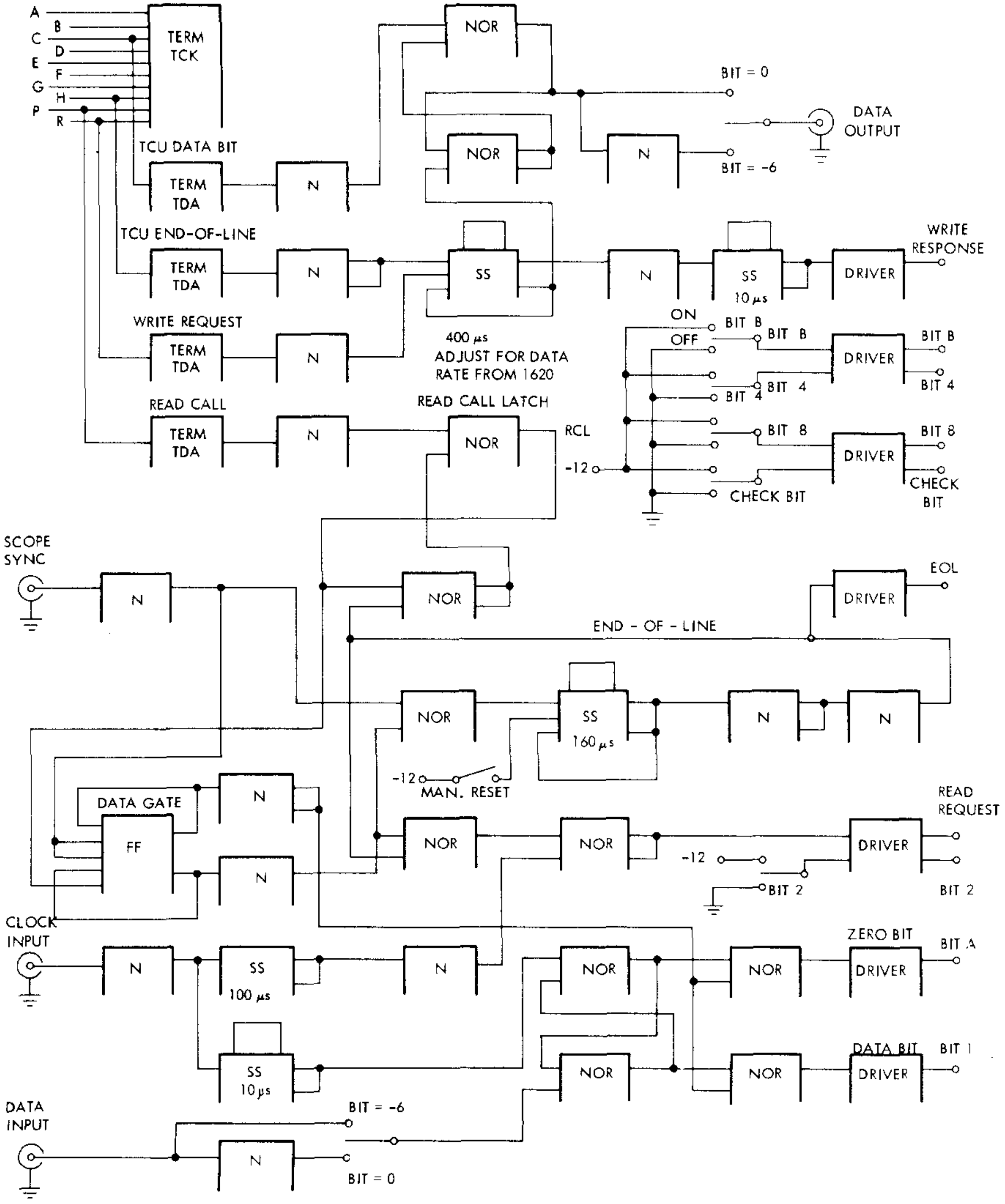

Fig. 17. 1620 TCU-to-Modem Interface (2400 Bauds)

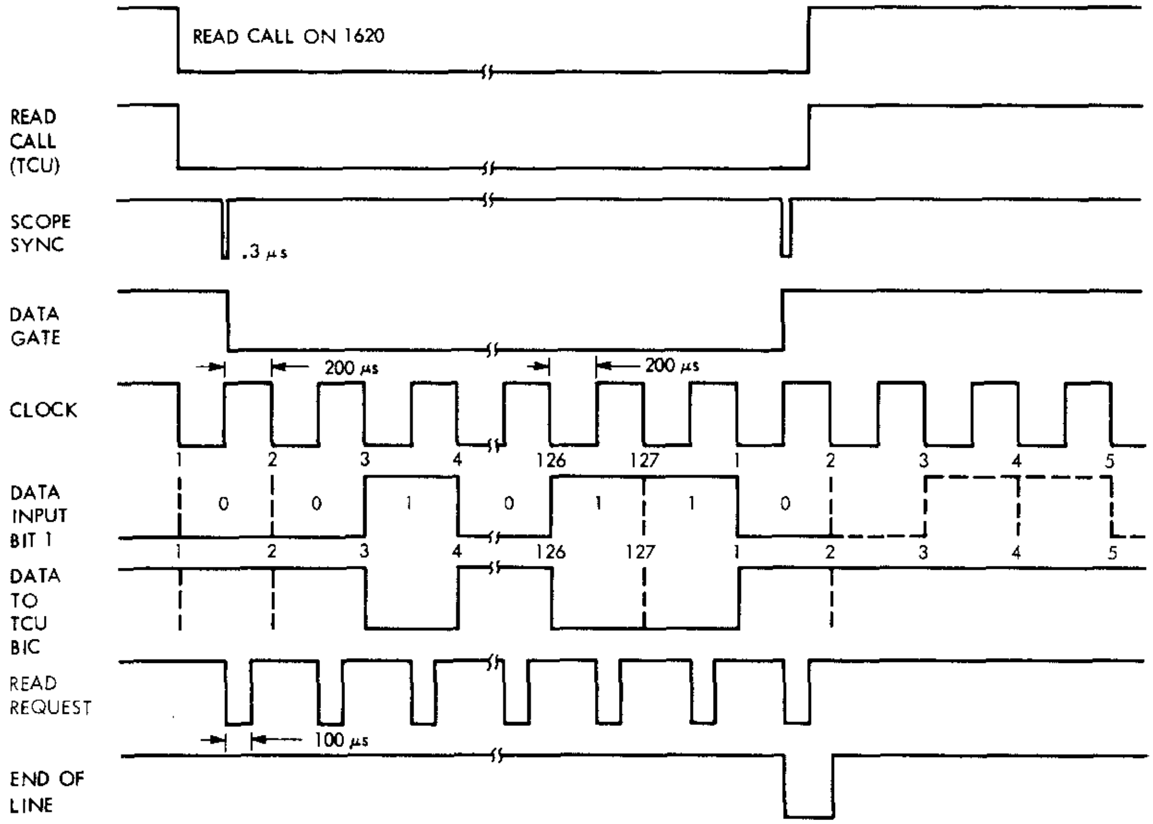

Fig. 18. Waveforms in TCU-to-Modem Interface

After a delay of 14 bit times, the interface generates the Write-Respond signal to actuate the TCU to read the next message into the 1620.

The interface unit has alternative logic elements for use in sending messages from the computer to the radio or to the tape unit.

The interface unit between the modem and the TCU was constructed by R. L. Cloke in the summer of 1967. The circuit logic diagram is shown in Fig. 17. The waveforms are shown in Fig. 18. The original data gate waveform in Fig. 14 was on for 127-bit times, then off for 127-bit times. This meant that the data gate allowed alternate 127-bit messages to enter the 1620 computer, keeping the 127-bit off period for the 1620 processing of the message.

In the Fall of 1967, the test format was changed so that the off-time was cut to 14 bit times (called the sync-idle period), with a 104-bit message (equivalent to 13 characters of 8 bits each) followed by a 9-bit EOM control signal. In this mode of operation, messages were received in the 1620 core until the core was full, and the core was then dumped into a disk file. After a number of core loads of messages were collected in the disk file, batches of ten messages at a time were read back to core storage for processing to determine the number of errors per message. The first, 140th, and last message of each batch of 150 messages, plus all messages containing errors, were punched into cards for detailed analysis later.

The message control program on the 1620 computer was written in the Symbolic Programming System language to minimize the processing time required for message control.

The error distribution was analyzed with FORTRAN programs on the 1800 computer to reduce the amount of machine language programming required.

E. LIST OF COMPUTER PROGRAMS

The following computer programs were developed for the reliability tests:

MTS4 VERSION B8 7.178 Simulation of Sequence Generator--Generates 127-bit or 889-bit pseudorandom sequences of 1's and 0's.

MTS164 VERSION M2 7.347 Message Control Program--Receives up to 150 messages (127-bit max) with labels identifying test number, date, tape recorder counter number, etc. Stores blocks of 150 messages in disk pack for later analysis.

MTS105 VERSION M0 7.343 Message Analysis Program--Receives batches of ten messages from disk pack, then compares with standard pseudorandom message, adds number of errors to message label, counts number of messages in error, punches card copy of messages in error, and prints error patterns. This program has alternative subroutines to introduce artificial errors for debugging and to substitute alphanumeric messages in place of pseudorandom sequences.

MT210/MT310 VERSION A3 8.053 Error Message Data Editor--The program receives batches of up to 75 error messages on punched cards from the 1620 computer for analysis on the 1800 computer. This program checks each error message for correct format. If format errors exist, it calls for operator intervention to accept or reject the message. This enables the operator to correct for format errors, missing cards, etc., before the error distribution analysis run is started.

MT203/MT303 VERSION J7 8.057 Error Message Data Reduction--The program receives batches of up to 75 error messages that have been screened for format errors and missing cards in a previous run in the 1800 under program MT 210. Batches of up to 75 messages are stored on Disk 1. Then each message is read from the disk and compared with the standard pseudorandom sequence. Statistics are collected on the number of short messages which are greater than half-length, quarter-length, and zero-length, in that order. Then statistics are collected on messages with less than 2^n errors, where $n = 0, 1, 2, 3, 4, 5, 6, 7$, in that order. If more than 20 errors occur, the message is run through a correlation routine which shifts the message plus or minus one bit and rechecks to catch messages which have the correct text, but were out of sync. This program prints cumulative summary statistics of the error distributions after each test group of up to 150 messages.

APPENDIX B: ERROR ANALYSIS

Reliability as a function of the route of travel of the station wagon is plotted in Fig. 19A through 19K. In each plot, the x-axis is the dial reading on the tape recorder, which corresponds to time and distance travelled along the test route. (Note that, with higher dial readings, the diameter of the tape reel increases, and the scale of the x-axis expands proportionately.) The second scale on the x-axis translates the dial readings into time.

The ordinate has a scale of percentage of error-free messages. Each individual test consists of a batch of 150 messages. On some of the earlier computer analyses, certain errors stopped the processing in the 1620 computer, and not all 150 messages could be analyzed. In each case, the width of the bar represents the transmission time actually analyzed, and the height of the bar gives the percentage of analyzed messages that were error-free. That is, when not all 150 messages could be analyzed, the width of the bar is made proportionally narrower, and the percentage ordinate remains the correct scale.

Plots A through K correspond to the routes shown on the map of Fig. 8 and further defined in Table 2 (reproduced here for convenience in interpreting the error data). For example, Fig. 19A gives the results for Test Route A. The interference of the hills between Blossom Hill Road and the IBM Laboratory can be seen by following the plot in Fig. 19A while examining the contour lines affecting the transmission path for Test Route A in Fig. 8.

The next set of tests (Route B) goes from Campbell on Highway 17 to Cupertino on Highway 280. The average percentage of error-free messages is 89%. Each dip in the percentage of error-free messages corresponds (Fig. 19B) to an overpass, underpass, or other more complex freeway interchange.

The Homestead Road-Highway 85 set of tests (Route C) starts with a 10-mile transmission path. Blossom Hill (elevation: 800 feet) is in this path, and the section of Highway 85 in Sunnyvale is depressed below ground level for the first section. Here, we have an average of 38 percent error-free messages (Fig. 19C).

As the station wagon got near Moffett Field (Naval Air Station), we had intermodulation problems, in that we could hear voices from other VHF transmitters. We defined this section as a separate test (Route D). These results are plotted in Fig. 19D. These tests confirm that the reliability of VHF 2400-baud digital transmission is approximately the same as voice transmission between the same points; i.e., if voice transmission is bad to a given point, the digital transmission can also be expected to be poor.

Mobile Unit Routes in Tests (also see map of Fig. 8)

Route	1620 Test No.	1800 Test Group
Base-to-Mobile Tests		
A. Country Road (1 to 3 miles) Blossom Hill Road toward Los Gatos	23005-23070	A. S/360 Volume 585872 File 1 (A)
B. Intercity Freeway (4 to 10 miles) Highways 17 and 280 Campbell to Cupertino	23071-23124	D. S/360 Volume 585872 File 4 (D)
C. City Street and Depressed Highway (10 to 13 miles) Homestead Road and Highway 85	23125-22158	F. S/360 Volume 585872 File 6 (F)
D. Industrial Freeway (14 miles) Highway 85 at Highway 82 and Highway 237 near Highway 101	23159-23167	FA. S/360 Volume 585872 File 11 (K)
E. Country Highway (13 miles) Highway 237 Sunnyvale to Milpitas	23176-23218	B. S/360 Volume 585872 File 2 (B)
F. Downtown Street (6 to 7 miles) First Street, San Jose	23219-23263	C. S/360 Volume 585872 File 3 (C)
G. Suburban Through Street (2 to 5 miles) Downer Road, IBM Plant toward Almaden Road	23264-23315	E. S/360 Volume 585872 File 5 (E)
Mobile-to-Base Tests		
H. Downtown Street (6 to 7 miles) First Street, San Jose	Selections from 25476-25522	G. S/360 Volume 585872 File 7 (G)
I. Downtown Street (6 to 7 miles) First Street, San Jose [same raw data as in H but analyzed for different sync-idle period]	25601-25633	H. S/360 Volume 585872 File 8 (H)
J. Suburban Through Street (2 to 5 miles) Downer Road from IBM Plant	25428-25444	I. S/360 Volume 585872 File 9 (I)
K. Suburban Through Street (2 to 5 miles) Downer Road near Almaden Road	25574-25585	K. S/360 Volume 585872 File 10 (J)

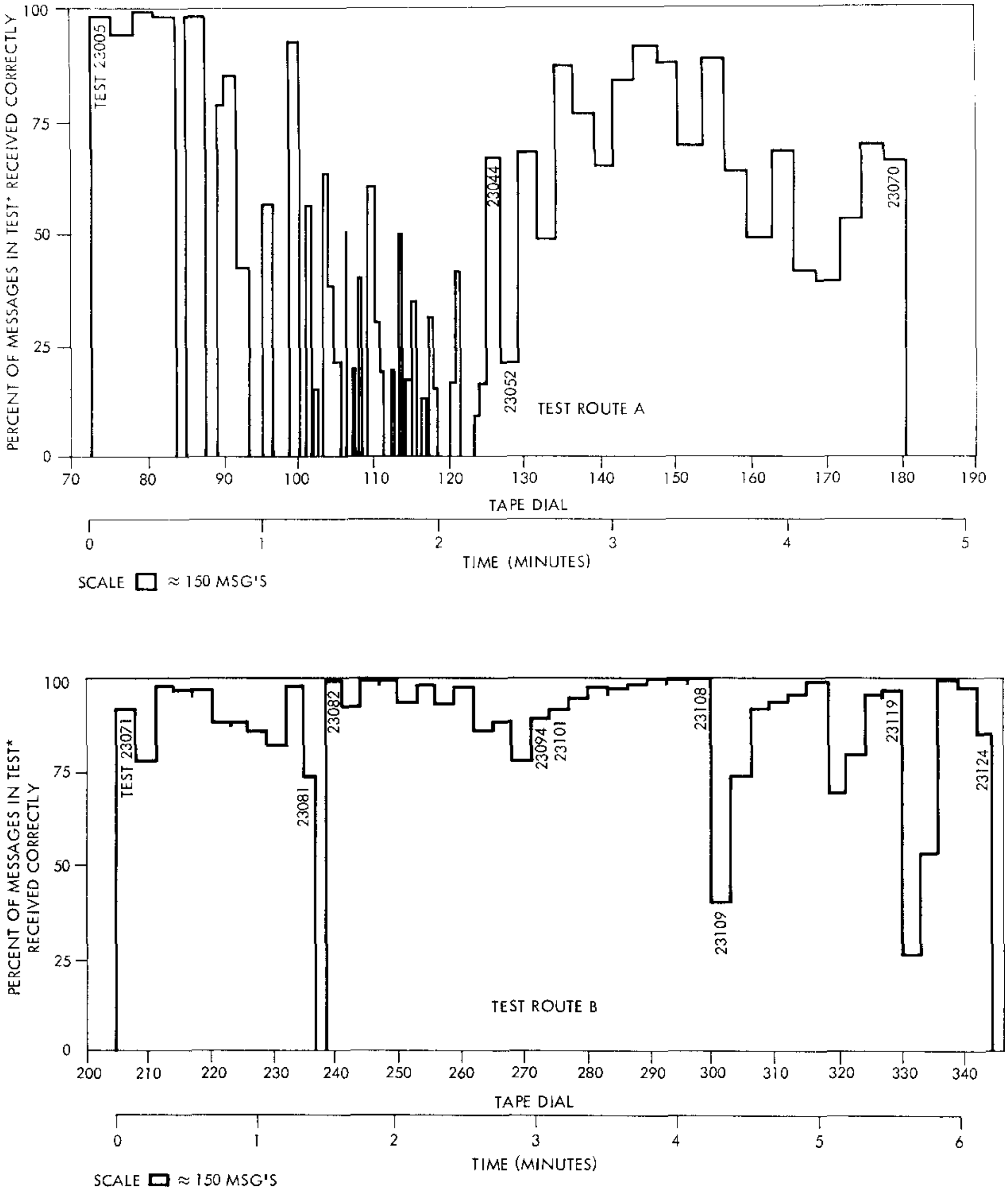

Fig. 19. Reliability as a Function of Distance Traveled on Test Route

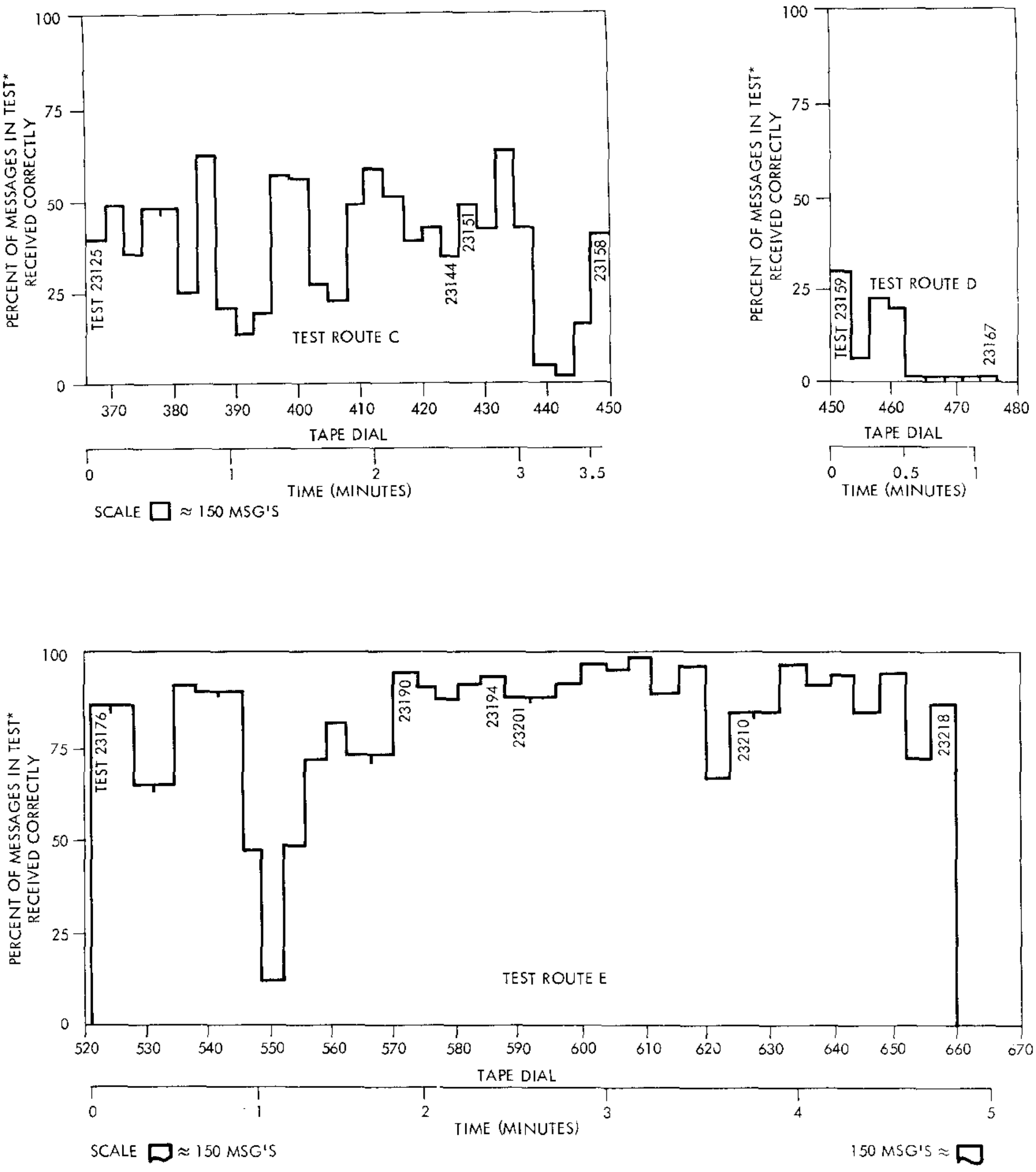

Fig. 19. Reliability as a Function of Distance Traveled on Test Route (continued)

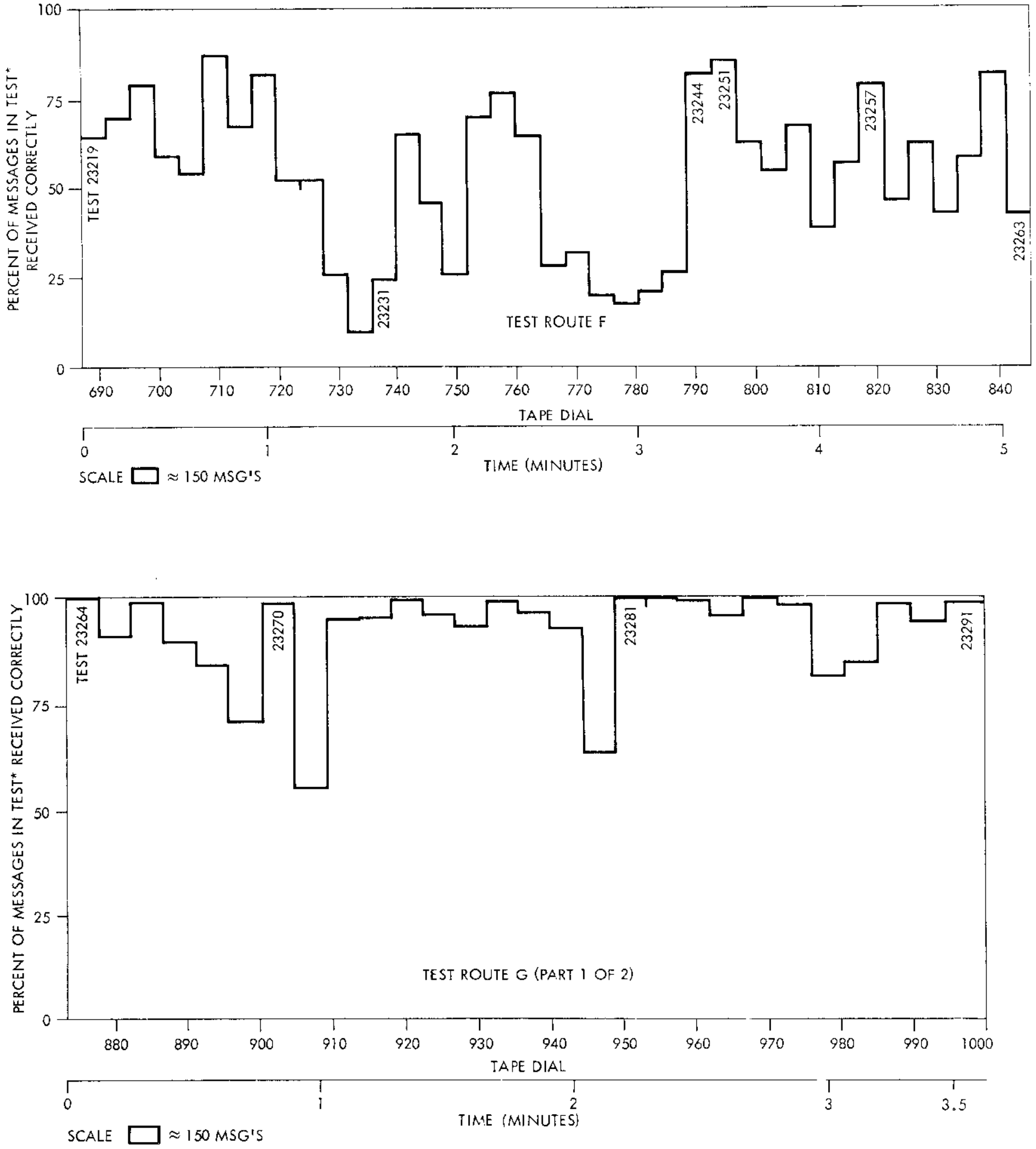

Fig. 19. Reliability as a Function of Distance Traveled on Test Route (continued)

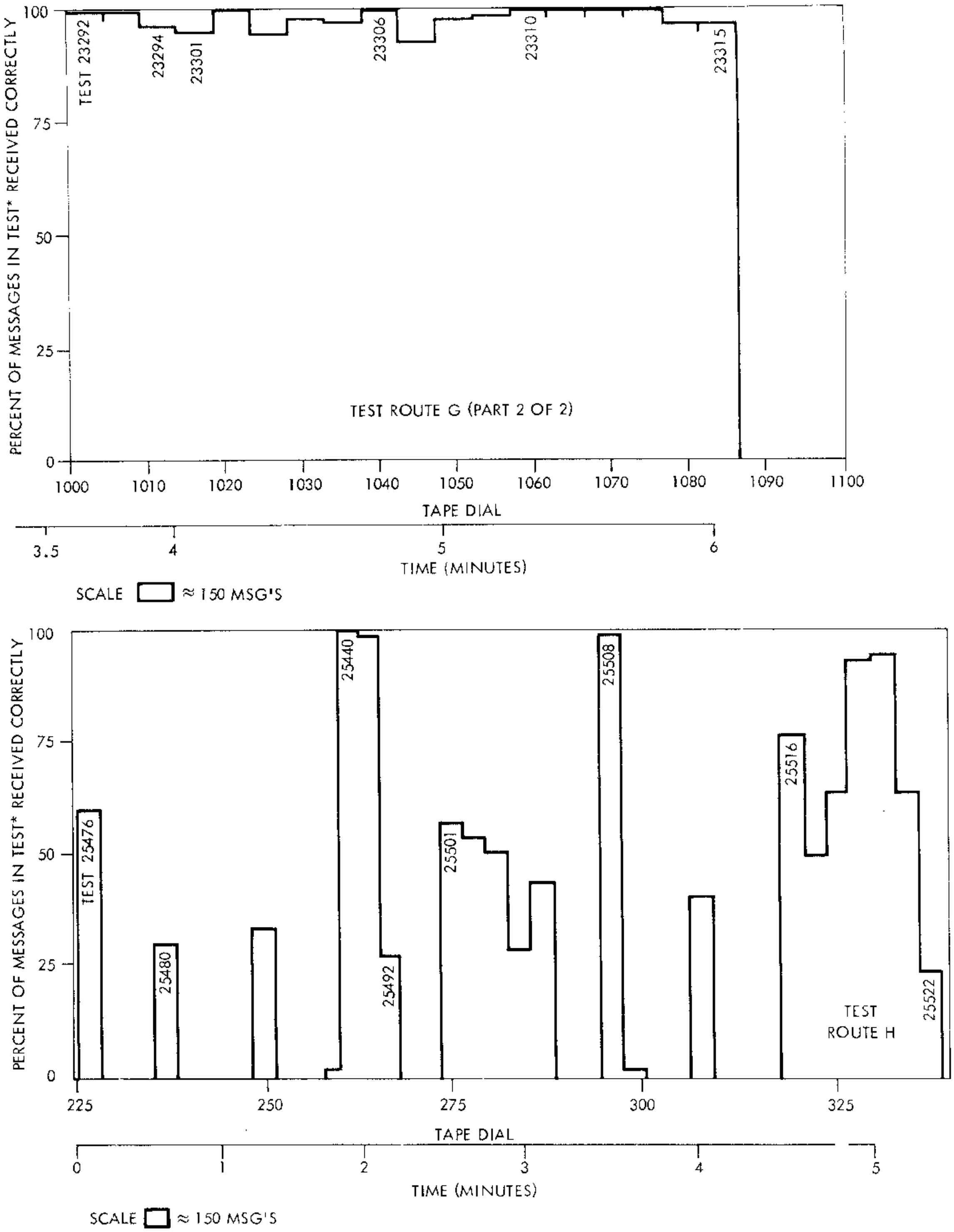

Fig. 19. Reliability as a Function of Distance Traveled on Test Route (continued)

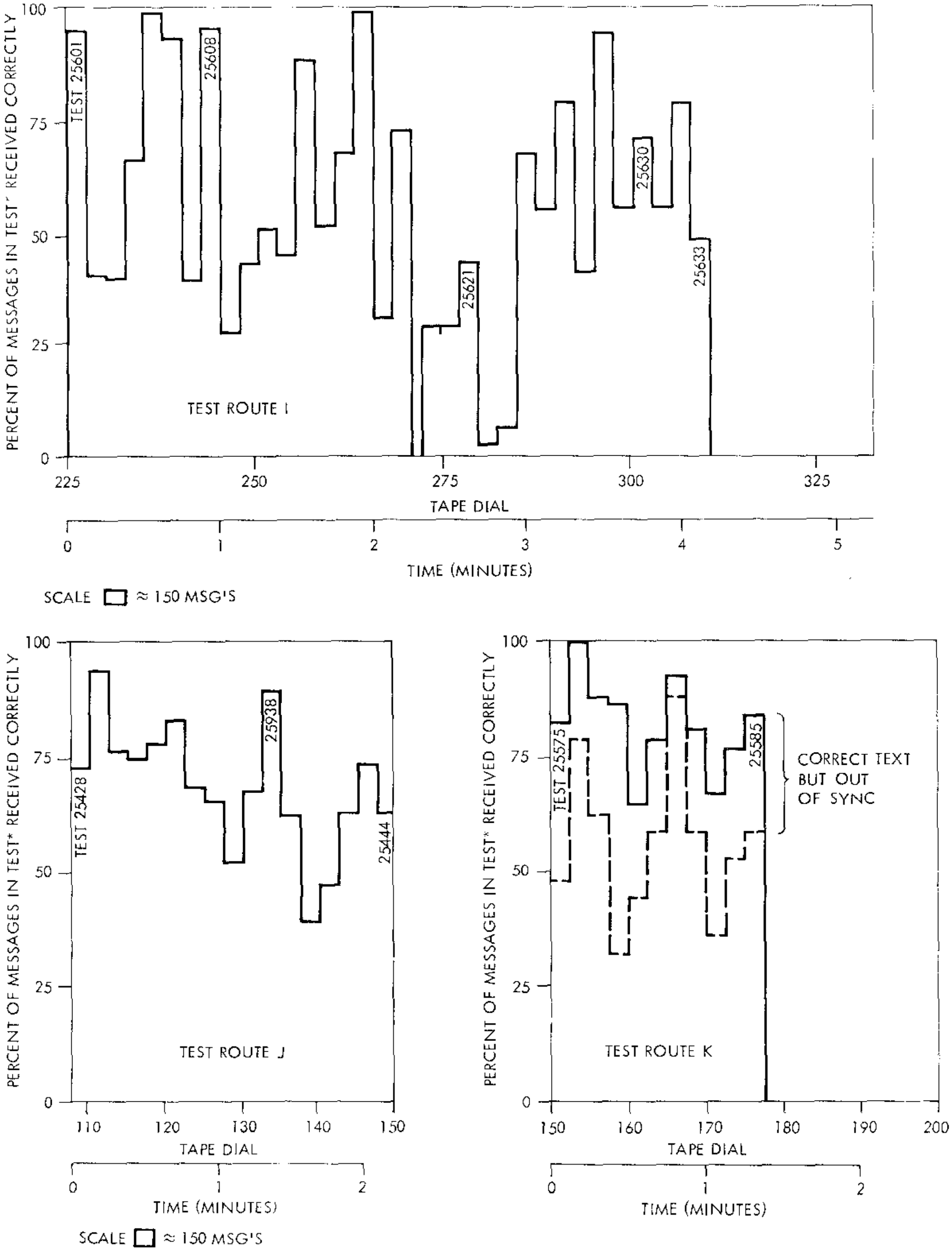

Fig. 19. Reliability as a Function of Distance Traveled on Test Route (continued)

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K23108P    1R    0M253 0 S14   0000000000000000000000000000000000000000008
K23108P   40R    0M 29 M S14   0000[illegible]88888888888888888888888888888888888888
K23108P   41R    0M229 M S14   0000[illegible]7655283[illegible]62055[illegible]88888
K23108P  104R    1M253 0 S14   0000000[illegible]0000000000000000000000000000000000008
K23108P  136R    1M253 M S14   00000000000000000000000000000000000000000[illegible]8
K23108P  137R    6M253 1 S14   0000000000000000000000000000000000000000008
K23108P  140R    0M253 0 S14   0000000000000000000000000000000000000000008
K23108P  150R    0M253 0 S14   0000000000000000000000000000000000000000008
M23108P  150W    0/ 145A    2B    0C    0D    1E    0F    0G    0H    0 X    1Y    0Z   110
N23108P1500W     0/1423A   20B   15C    9D    9E    0F    0G    3H    0 X   12Y    7Z   220
O23108P4485W     1/4175A   92B   62C   34D   22E    2F    2G   13H    0 X   49Y   24Z   10 3
U23108P4485W     1/4175A   92B   62C   34D   22E    2F    2G   13H    0 X   49Y   24Z  1020

12 CARDS
```

▨ = LOSS OF MESSAGE DUE TO FALSE END-OF-MESSAGE

■ = RANDOM ERRORS (A FEW ARE SYNC ERRORS)

Fig. 20. Error Patterns and Statistics (Test 23108, Set D), Approaching an Interchange

Under the intermodulation conditions, the reliability dropped to 9%. Route E, from Sunnyvale on Persian Road to Alviso on Highway 237 and on to Milpitas and south on Main Street in Milpitas. The percentage of error-free messages on this run was 83%. The one severe dip (dial reading 550-585, Fig. 19E) appears to be the Fairoaks overpass over Persian Road and Highway 237.

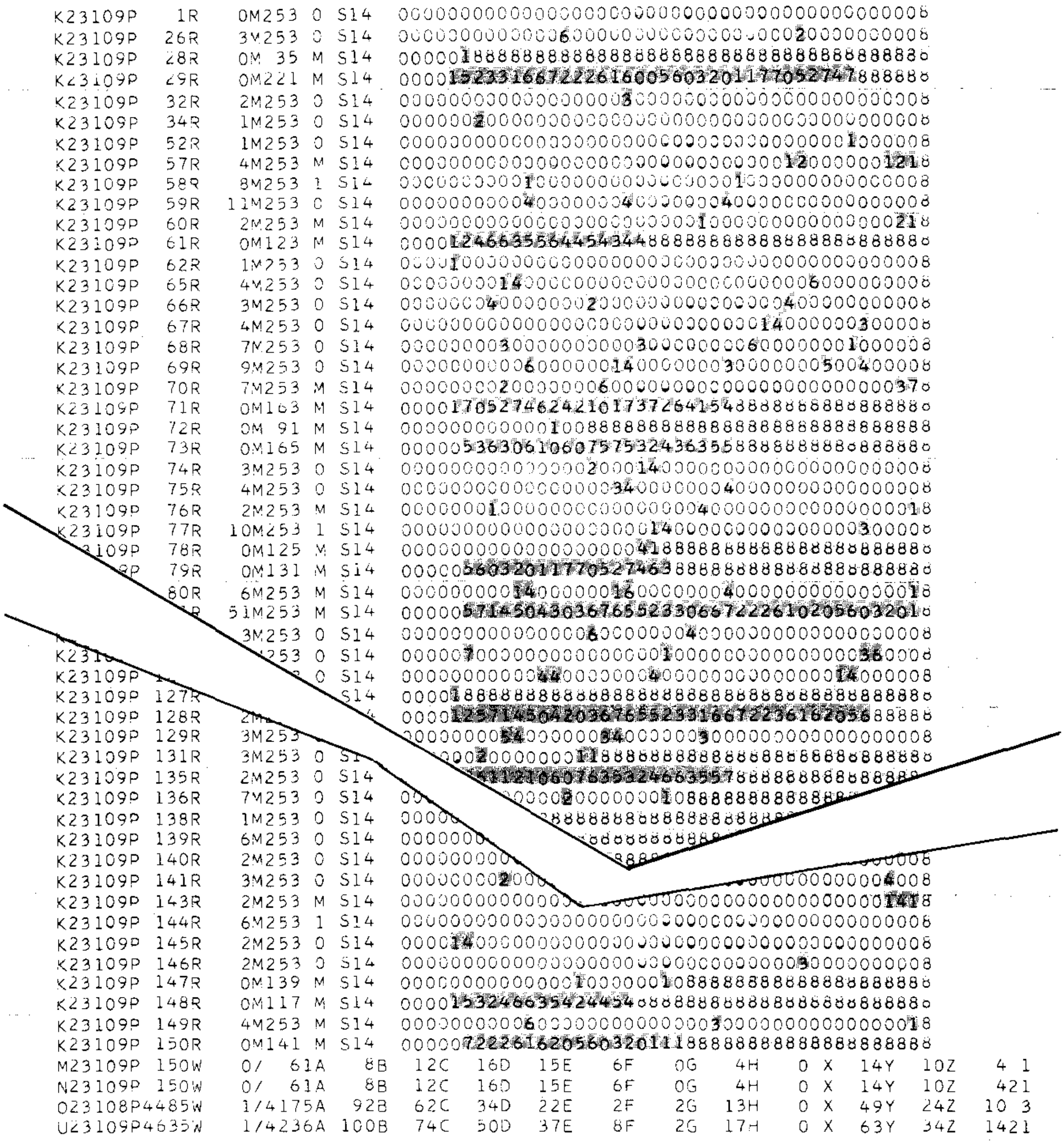
Route F (Fig. 19F) for downtown San Jose shows severe drops in the percentage of error-free messages, on sections of the route where the tall buildings cause a multipath problem. Here the average percentage of error-free messages is 54%. Comparison with voice operation driving down the same route indicated, as expected, that the voice reception was bad at the same points where the high error-rates on digital transmission occurred.

Route G (Fig. 19G), testing base-to-mobile transmission from the IBM Plant in San Jose along Downer Avenue (renamed Blossom Hill Road) toward Almaden Road, shows 95% error-free messages. The path from transmitter to station wagon was between 2 1/2 and 5 miles on this set of tests. This set of tests, comprising 6,000 messages, is continued in Fig. 19G (Part 2).

We found it more complicated to test mobile-to-base transmission. To do this, we fed digital messages into the modulator section of the modem, and recorded the phase-modulated output on tape. In the tests, the prerecorded tape was played back on the tape recorder in the moving station wagon, and the recorder output was coupled into the audio input of the VHF-FM Radio. The tape recorder in the station wagon had to be shielded so that the VHF radiated waves could not disturb the speed control circuit on the tape recorder.

We found that our experimental system required more careful adjustment in these tests, perhaps partly because a second step of audio recording was required. Also, we found that in a significant number of the mobile-to-base messages, the bit sequence had shifted plus or minus one bit time. To by-pass this synchronization problem at this stage, we recorded complete sets of messages for mobile-to-base operation from downtown San Jose and from a country road for comparison. Then we simulated on the 1620 computer the effect of adding an extra bit to make the sync-idle sequence 15 bits instead of 14 bits. This simulated allowance of a larger sync-idle time recovered more text-correct messages, particularly from the vicinity of tall buildings and when passing hills that caused multipath problems.

We investigated the effect of trying better control characters such as are specified on the IBM Binary Synchronous Communication (BSC) specifications. We noticed that there were a number of messages with



```
K23109P    1R   0M253 0 S14   0000000000000000000000000000000000000000008
K23109P   26R   3M253 0 S14   0000000000000600000000000000000020000000008
K23109P   28R   0M 35 M S14   0000018888888888888888888888888888888888888
K23109P   29R   0M221 M S14   0000152331667222616005603201177052747888888
K23109P   32R   2M253 0 S14   0000000000000000003000000000000000000000008
K23109P   34R   1M253 0 S14   0000002000000000000000000000000000000000008
K23109P   52R   1M253 0 S14   0000000000000000000000000000000000001000008
K23109P   57R   4M253 M S14   0000000000000000000000000000000120000001218
K23109P   58R   8M253 1 S14   0000000000100000000000000001000000000000008
K23109P   59R  11M253 0 S14   0000000000400000004000000040000000000000008
K23109P   60R   2M253 M S14   0000000000000000000000001000000000000000218
K23109P   61R   0M123 M S14   0000124663556445434488888888888888888888888
K23109P   62R   1M253 0 S14   0000100000000000000000000000000000000000008
K23109P   65R   4M253 0 S14   0000000014000000000000000000000006000000008
K23109P   66R   3M253 0 S14   0000000400000002000000000000000400000000008
K23109P   67R   4M253 0 S14   0000000000000000000000000000014000000300008
K23109P   68R   7M253 0 S14   0000000030000000000300000000600000001000008
K23109P   69R   9M253 0 S14   0000000000600000014000000030000000500400008
K23109P   70R   7M253 M S14   0000000020000000600000000000000000000000378
K23109P   71R   0M163 M S14   0000170527462421017372641548888888888888888
K23109P   72R   0M 91 M S14   0000000000001008888888888888888888888888888
K23109P   73R   0M165 M S14   0000053630610607575324363558888888888888888
K23109P   74R   3M253 0 S14   0000000000000002000140000000000000000000008
K23109P   75R   4M253 0 S14   0000000000000000034000000040000000000000008
K23109P   76R   2M253 M S14   0000000100000000000000004000000000000000018
K23109P   77R  10M253 1 S14   0000000000000000000140000000000000000300008
  3109P   78R   0M125 M S14   0000000000000000000418888888888888888888888
     9P   79R   0M131 M S14   0000056032011770527463888888888888888888888
          80R   6M253 M S14   0000000001400000016000000040000000000000018
            R  51M253 M S14   0000057145043036765523306672226102056032018
                3M253 0 S14   0000000000000006000000040000000000000000008
K231              253 0 S14   0000070000000000000001000000000000000360008
K23109P                 0 S14   0000000000044000000040000000000000014000008
K23109P  127R             S14   0000188888888888888888888888888888888888888
K23109P  128R   2M            0000125714564203676552331667223616205688888
K23109P  129R   3M253           0000000054000000340000003000000000000000008
K23109P  131R   3M253 0 S1       0002000000011888888888888888888888888888
K23109P  135R   2M253 0 S14         41121060763532466355788888888888888
K23109P  136R   7M253 0 S14   00      000002000000010888888888888
K23109P  138R   1M253 0 S14   00000       888888888888888888
K23109P  139R   6M253 0 S14   0000000        88888888888
K23109P  140R   2M253 0 S14   000000000         888                000008
K23109P  141R   3M253 0 S14   000000002000              00000000000004008
K23109P  143R   2M253 M S14   00000000000000 0000000000000000000000001418
K23109P  144R   6M253 1 S14   0000000000000000000000000000000000000000008
K23109P  145R   2M253 0 S14   0000140000000000000000000000000000000000008
K23109P  146R   2M253 0 S14   0000000000000000000000000000000030000000008
K23109P  147R   0M139 M S14   0000000000000010000001088888888888888888888
K23109P  148R   0M117 M S14   0000153246635424454888888888888888888888888
K23109P  149R   4M253 M S14   0000000000600000000000000300000000000000018
K23109P  150R   0M141 M S14   0000072226162056032011188888888888888888888
M23109P  150W   0/  61A   8B  12C  16D  15E   6F   0G   4H   0 X  14Y  10Z   4 1
N23109P  150W   0/  61A   8B  12C  16D  15E   6F   0G   4H   0 X  14Y  10Z   421
O23108P4485W   1/4175A  92B  62C  34D  22E   2F   2G  13H   0 X  49Y  24Z  10 3
U23109P4635W   1/4236A 100B  74C  50D  37E   8F   2G  17H   0 X  63Y  34Z  1421
```

= LOSS OF MESSAGE DUE TO FALSE END-OF-MESSAGE

▨ = RANDOM ERRORS (A FEW ARE SYNC ERRORS)

Fig. 21. Error Patterns and Statistics (Test 23109, Set D), Inside Interchange

approximately half the bits in error. Processing these with a correlation routine on the 1800 computer showed that many of these were textually correct, but were out of synchronization by plus or minus one bit. Therefore, in the following plots for mobile-to-base tests, we have two sets of data: the original 14-bit sync-idle data and the 15-bit sync-idle data, where it permitted better reception of correct digital messages.

The downtown mobile-to-base data is plotted in Figs. 19H and 19I. Route H (601-633) is for the 14-bit sync-idle time, and Route I (475..... 522) is for the 15-bit sync-idle. In the center of downtown, the 15-bit sync-idle generally permitted a higher percentage of error-free messages to get through. As we left downtown, we found that the original 14-bit sync-idle time gave reasonable results. In the downtown sections where we used the 15-bit sync-idle time, we obtained 60% error-free messages.

The Downer Avenue (renamed Blossom Hill Road) mobile-to-base tests showed an additional feature: these are plotted as Route J and Route K in Figs. 19J and 19K. For Route K, where some hills cause multipath problems superimposed on the tape recording inaccuracies and possible tape speed regulation problems, we used the long sync-idle time and the correlation function in the error analysis program.

On Route J, where there was a greater clear path to the laboratory, we obtained 69% error-free messages. As the station wagon transmitted from below the low hills, the reliability dropped drastically to around 25%.

For the section near Snell Road toward Cottle Road where the hill shown in Fig. 8 interferes, we re-ran the test as Route K with a 15-bit sync-idle, which gave 58% error-free messages. When we re-analyzed the data on the 1800 computer with a correlation function, we found many correct messages that had been out of synchronization by plus or minus one bit. Counting these as usable messages raised the percentage of error-free messages to 80%. This would be valid only if the improved sync-idle and EDT characters are used.

Next we examine the detailed distribution of error messages within one highway interchange. Consider Tests 23108, 23109, and 23110 in Route B, Highway 17-Highway 280 in Fig. 19B.

Test 23108 is for the approach to an interchange. Here, 145 out of 150 messages are error-free. Test 23108 appears to include the passage directly under the overcrossing, and Test 23110 covers the section leaving the overcrossing on the side away from the transmitter.

The sample error patterns printed out by the 1800 computer under program MT203-Vers J7 are shown in Figs. 20-22. The header on each line is defined as follows: K23108 means test number 23108, P00104

```
K23110P    1R    0M187 M S14   0000003000000000000000000000014888888888888
K23110P    2R    0M 69 M S14   0000065164788888888888888888888888888888888
K23110P    3R    4M253 M S14   000000000001[illegible]000000400000000000000400000018
K23110P    4R   56M253 M S14   0000[illegible]72651[illegible]5018
K23110P    8R    1M253   S14   0000000000000000000000000000000020000000008
K23110P    9R    3M253   S14   000000[illegible]000000[illegible]00000000000000000000000000008
K23110P   11R    1M253   S14   00000[illegible]0000000000000000000000000000000000008
K23110P   12R    3M253   S14   00000000000000000000000001000000[illegible]000000008
K23110P   32R    2M253 M S14   0000000000000000000000000000000000000000618
K23110P   33R    8M253   S14   0000000000[illegible]00000000000000000000000000000008
K23110P   34R    2M253   S14   0000000000000000000000000000000000000030008
K23110P   36R    1M253   S14   0000000000000000040000000000000000000000008
K23110P   39R    2M253   S14   0000000000000000200000000000001000000000008
K23110P   40R    3M253   S14   0000000000000000000000030000010000000000008
K23110P   41R    5M253   S14   0000000000000002040000100010000000200000008
K23110P   42R    0M 95 M S14   0000000000000011888888888888888888888888888
K23110P   43R    0M161 M S14   0000136252106675753246635578888888888888888
K23110P   47R    1M253   S14   0000000000000000000000000000000000000004008
K23110P   49R    1M253   S14   0000000000000000000000000000000000001000008
K23110P   50R    1M253   S14   0000000000000000000000001000000000000000008
K23110P   72R    2M253   S14   0000000000000000000000000400000000004000008
K23110P   76R    1M253   S14   0000000000000000000000000001000000000000008
K23110P   77R   12M253   S14   0000000800000010004400140010005000000030008
K23110P   78R    0M 39 M S14   0000038888888888888888888888888888888888888
K23110P   79R    0M163 M S14   0000178528482911417372651648888888888888888
K23110P  102R    1M253   S14   0000000000000000000000000000000000000002008
K23110P  105R    7M253   S14   0000000060000000640000004000001000000000008
K23110P  116R    0M139 M S14   0000000000000000000000088888888888888888888
K23110P  117R    0M117 M S14   0000153248635564454888888888888888888888888
K23110P  128R    1M253   S14   0000000000000000040000000000000000000000008
K23110P  132R    2M253   S14   0000000000000000003000000000000000000000008
K23110P  133R    3M253   S14   0000000400000000000000000000060000000000008
K23110P  134R    1M253   S14   0000000000000000200000000000000000000000008
K23110P  140R    0M253   S14   0000000000000000000000000000000000000000008
K23110P  142R    2M253   S14   0000000000000000000000000000000000014000008
K23110P  144R    0M253 M S14   0000000000000000000000000000000000000000018
K23110P  145R    6M253   S14   0000000000000000000000000000000000000000008
K23110P  146R    3M253   S14   0000000000000000004300000000000000000000008
K23110P  148R    1M253   S14   0000000000000000000000000000000000004000008
K23110P  150R    0M253   S14   0000000000000000000000000000000000000000008
M23110P  150W   0/ 113A   11B    6C    6D    4E    1F    0G    1H    0 X    4Y    3Z    1 2
N23110P  300W   0/ 174A   19B   18C   22D   19E    7F    0G    5H    0 X   18Y   13Z    522
O23108P4485W    1/4175A   92B   62C   34D   22E    2F    2G   13H    0 X   49Y   24Z   10 3
U23110P4785W    1/4349A  111B   80C   56D   41E    9F    2G   18H    0 X   67Y   37Z   1522
```

= LOSS OF MESSAGE DUE TO
FALSE END-OF-MESSAGE

▨ = RANDOM ERRORS (A FEW
ARE SYNC ERRORS)

Fig. 22. Error Patterns and Statistics (Test 23110, Set D), Leaving Interchange

means message number 104 in the test; R0001 means one error found in the message: M253 means 253 half cycles after the first were checked (corresponds to 127 bits examined). The zero indicates the record mark is where it should be, at the end of the message.

An M here indicates record mark missing or substitute record mark inserted. Messages that were cut short as indicated when the number that follows M is less than 253, are not checked for number of errors, so R is left equal to zero.

Certain apparent inconsistencies in Fig. 20 can be checked by examination of Fig. 23. For example, message P-137 in Fig. 20 has R = 6 for six errors, but the error pattern shows all zeros. Checking the same message in Fig. 23, we find that the six errors are not in the message text, but in the header and sync-idle section of the record. Examination of the preceding message, i.e., message P-36, in Fig. 23 shows that NRM indicates the message control program could not find a record mark at the end of No. P-136 and inserted the marker "13130" at the end to prevent any further overflow problems, but some information had already overflowed into the header and sync-idle section of the core memory reserved for the next message.

To simplify the visualization of the error distribution within each of the sample tests, the parts of the error pattern containing errors have been shaded and the tail ends of messages lost due to false EOM characters have been blanked out.

The significance of Figs. 20-22 is graphically shown in Fig. 24, where the path for 100 feet before an overcrossing to a point 100 feet after the overcrossing is plotted to where the error messages occurred. Parallel abscissa are shown for time (seconds) and the number of messages (13 characters or 127 bits). Also, the number of eight-bit characters of continuous transmissions are shown. The average percentage of error-free messages in groups of 50 messages are also plotted in Fig. 24.

A sample set of punched cards for the error analysis is shown in Fig. 25. Each group of four cards or 320 numeric digits represents a message. The alphabetic characters in these records are equivalent to the numerics 1-9 with flags.

When the received signal is demodulated and temporarily stored in core under program MTS 164, a Header (Column 21-59 in card A or a) is added. The meaning of these numbers is defined in Table 4. Then the header and message are stored in three disk records (300 numerics). This stores card A (Column 21-80) plus cards B, C, and D under Program 105. Space is left for the 20-numeric label of card A (Column 1-20). (See Table 4 for the definitions of the label parameters.)

```
                 LABEL                           HEADER                     → MESSAGE →
                                                                          (INCLUDES SYNC IDLE)
                                                 COLUMN
        1       10        20        30        40        50        60        70        80
CARDS A P000001Q000000R00000J023108K000001L07Q297002530987300000000 00000000000000000000
      B 00000000717170707170717070707170707071717070707071717171707171717171707170717170
      C 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      D 70717070707071707171717070707070717170717070707070717070717171717171717170 0Z0000
      a P000040Q000001R00000J023108K000040L07Q297000290000000NRM000 00000000000000000000
      b 000000000Z0000000000000000000000000000000000000000000000000000000000000000000000
      c 00000000000000000000000000000000000000000000000000000000000000000000000000000000
      d 00000000000000000000000000000000000000000000000000000000000000000000000000000000
      A P000041Q000002R00000J023108K000041L07Q297002290000000NRM000 00000000000000000000
      B 00000000707171707070707171717170717171717170717071717071707170707171707171707071
      C 71717071717071717170717070717070717071717070707171717070717070707071707171717070
      D 70707071717071707070707070717070717171717171717100Z000000000000000000000000000000
      a P000104Q000003R00001J023108K000104L07Q297002530000000000000 00000000000000000000
      b 00000000717170707170717170707170707071717070707071717171707171717171707170717170
      c 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      d 70717070707071707171717070707070717170717070707070707170707171717171717170 0Z0000
      A P000136Q000004R00001J023108K000136L07Q297002530000000NRM000 00000000000000000000
      B 00000000717170707170717070707170707071717070707071717171707171717171707170717170
      C 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      D 7071707070707170717171707070707071717071707070707070717070717171717170131 30Z0000
      a P000137Q000005R00006J023108K000137L07Q297072530070717071707 70717070707171707070
      b 70717171717170707170717070707170707071717070707071717171707171717171707170717170
      c 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      d 70717070707071707171717070707070717170717070707070707170707171717171717170 0Z0000
      A P000140Q000005R00000J023108K000140L07Q297002530000000000000 00000000000000000000
      B 00000000717170707170717070707071707071717070707071717171707171717171707170717170
      C 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      D 70717070707071707171717070707070717170717070707070707170707171717171717170 0Z0000
      a P000150Q000005R00000J023108K000150L07Q297002530000000000000 00000000000000000000
      b 00000000717170707170717070707170707071717070707071717171707171717171707170717170
      c 71707170707171707171707071717170717170717171707170707170707170717170707071717170
      d 70717070707071707171717070707070717170717070707070707170707171717171717170 0Z0000
```

UNDERLINE INDICATES SYNC IDLE

0Z = RECORD MARK

Fig. 23. Sample of Detailed Listing of Messages in Error (Test 23108)

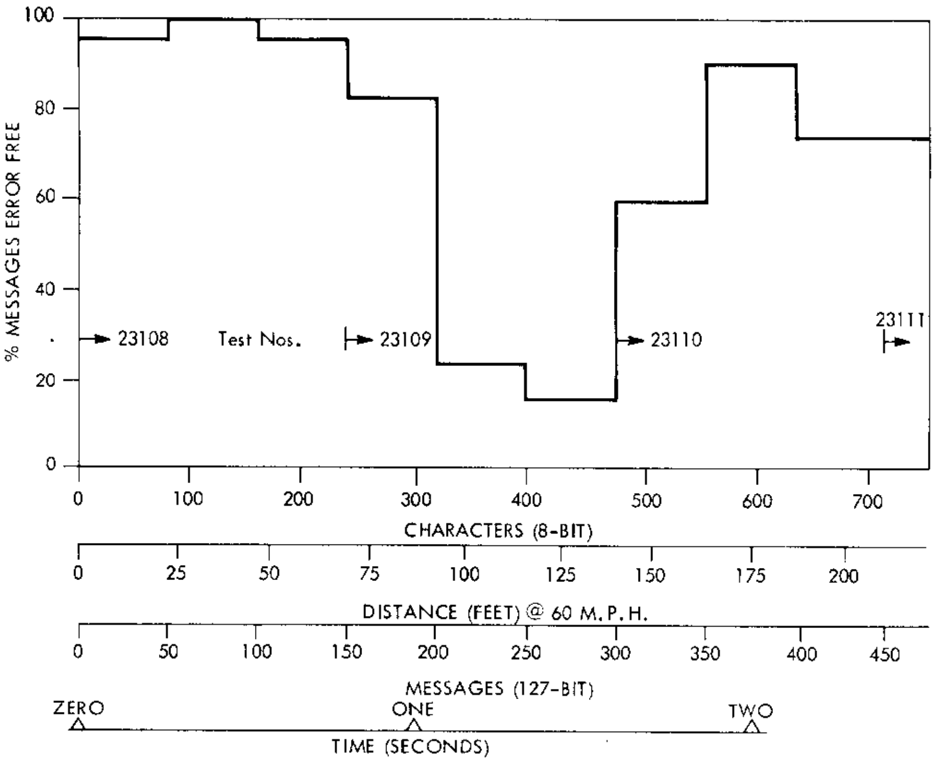
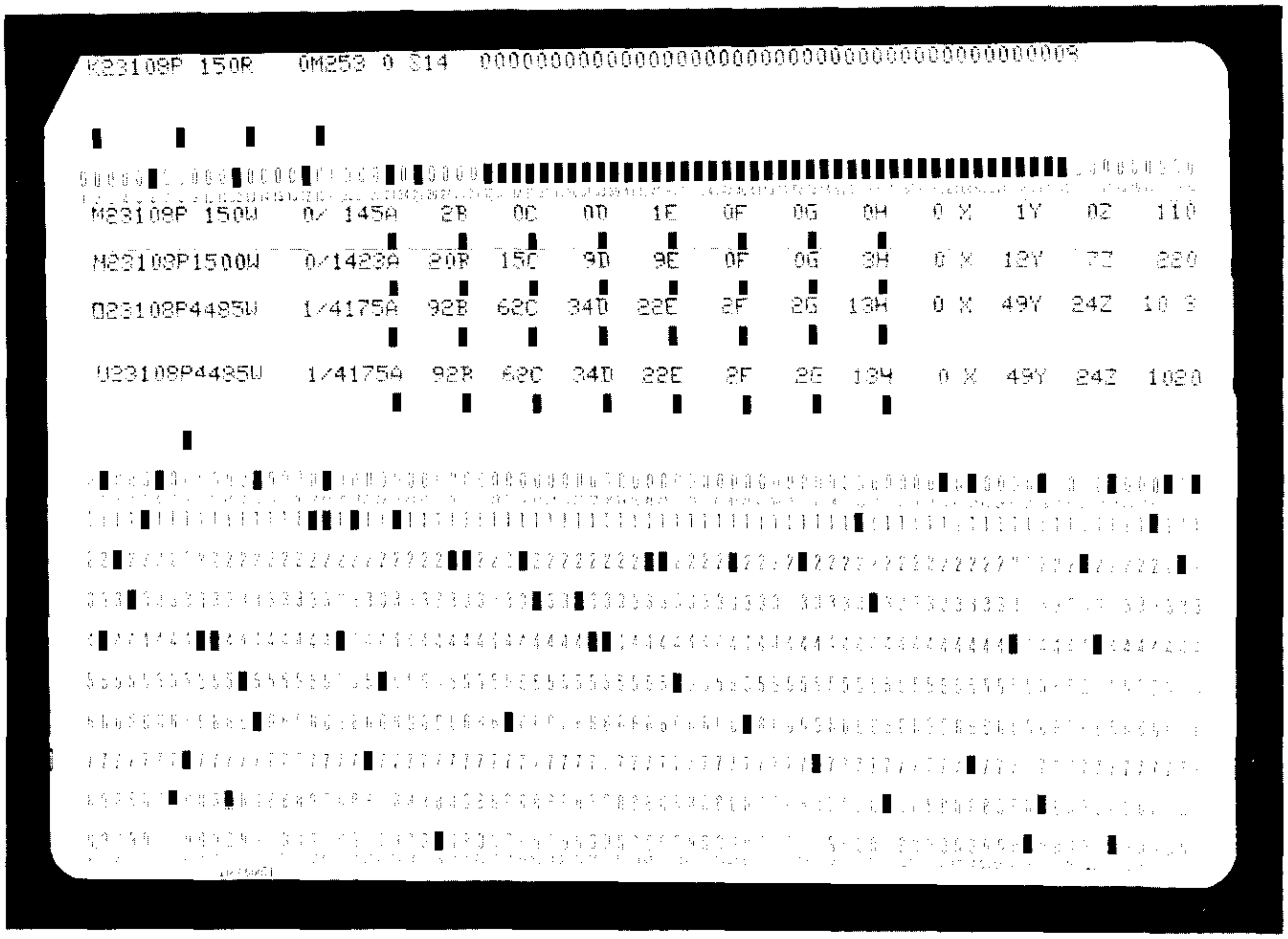


Fig. 24. Summary of Error Patterns Entering, Inside, and Leaving Interchange (Freeway Overcrossing)



```
K23108P 150R   0M253 0 S14  0000000000000000000000000000000000000000008
M23108P 150W   0/ 145A   2B   0C   0D   1E   0F   0G   0H   0 X   1Y   0Z   110
M23108P1500W   0/1423A  20B  15C   9D   9E   0F   0G   3H   0 X  12Y   7Z   220
023108P4485W   1/4175A  92B  62C  34D  22E   2F   2G  13H   0 X  49Y  24Z  10 3
U23108P4485W   1/4175A  92B  62C  34D  22E   2F   2G  13H   0 X  49Y  24Z  1020
```

Fig. 25. Punched Card Format for Error Statistics Analysis

Table 4. Key to Error Distribution Data

Card Col. Numbers	Function	Notes
2	Type of Batch	K = Error pattern of one message M = Summary of error distribution for one test of 1 to 150 messages. N = Cumulative summary for current batch of one to ten tests. O = Summary for last integral number of ten tests. U = Cumulative summary for a set of tests for a specified street or part of town.
3-7	Test Number	First two digits indicates ten-day period of year 1967 during which field tests were made. I.E. 23 indicates period starting with 230-th day of the year. Last three digits are serial identification numbers assigned under 1620 message control program where messages were stored on disk pack. The third digit is the batch number. The fourth and fifth digits are derived from the disk file address. XX= (Disk Address (450) + (1 or 51)
9-12(P=)	No. of Messages	KCARD P=number of this message MCARD+ P=number of messages analyzed in this group.
14-17 (R=)	No. of Errors	KCARD R=number bits in error in this message. R=O, if message was incomplete.
14-17 (W=)	No. of Messages	MCARD+ W=number of textually correct messages counted in error because of sync problem
19-21 (M)	Length of Msg.	KCARD M=number of half-cycles of messages received after first half cycle. (Normally, M=253 for 127 bits recd)
19-22 (I)	No. of Error-free	MCARD+ I=number of error-free messages in the batch of messages.
22(0)	Alert	KCARD M indicates record mark at end of message was missing. Other symbols indicate overflow from previous message.
25-27	Sync-Idle	KCARD S14 or S15 indicate 14-bit or 15-bit sync idle period used in message control program on 1620
30-71	Error-Pattern	KCARD The error pattern is in octal notation (0-7). An 8 means end of message. A string of 8s means the message was cut off by false EOM code. An 18 at end indicates the message control program inserted SS or 1313 to cover a missing EOM.
		MCARD, NCARD, OCARD, & UCARD Number of messaaes with number of bit errors:
24-27	A	$M = 1$
29-32	B	$M = 2$
34-37	C	$M = 3, 4$
39-42	D	$5 \leq M \leq 8$
44-47	E	$8 \leq M \leq 16$
49-52	F	$16 \leq M < 32$
54-57	G	$32 \leq M < 64$
59-62	H	$64 \leq M < 128$
		MCARD, NCARD, OCARD & UCARD Number of Short Message with length:
65-68	X	$64 \leq \text{LENGTH} < 128$
70-73	Y	$32 \leq \text{LENGTH} < 64$
75-78	Z	$1 \leq \text{LENGTH} < 32$
79-80	Serial No.	MCARD Serial No. 1-10 of tests being added into NCARD
79-80	Count	NCARD Count of 1-60 of number of tests included so far in serial.
79-80	Serial No.	OCARD Serial No. 1-6 of batches of ten tests
79-80	Count	UCARD Count of 1-60 of number of tests included in totals.

The record format was kept in 1620 alphanumeric form to permit substitution of sample alphabetic messages in place of the pseudorandom binary sequences if desired during the next phase of this project.

The results of the detailed analysis of error distributions by number of errors per message, as tabulated under Program MT 203 on the 1800 computer, are given in Table 5. The results are also plotted in Figs. 26A - 26G (for base-to-mobile tests) and in Figs. 26H - 26J (for mobile-to-base tests).

Table 5. Error Distributions for Different Transmission Paths

	BASE TO MOBILE							MOBILE TO BASE			
	TEST A Country Road, 1 to 3 mi.	TEST B Intercity Freeway 4 to 10 mi.	TEST C City St. & Depressed Highway, 10 to 13 mi.	TEST D Industrl. Freeway 14 mi. (Intermodulation Noise)	TEST E Country Highway 13 mi.	TEST F Downtwn Street 6 to 7 mi.	TEST G Suburb. Thru-Street 2 to 5 mi.	TEST H Downtwn Street 6 to 7 mi. (14-Bit Sync Idle)	TEST I Downtwn Street 6 to 7 mi. (15-Bit Sync Idle)	TEST J Suburb. Thru-Street 2 to 5 mi. (14-Bit Sync Idle)	TEST K Suburb. Thru-Street 2 to 5 mi. (15-Bit Sync Idle)
Messages Sent	4682	6877	4150	1331	4499	5829	6000	3246	4932	2547	1647
Short Messages (%)											
126 bits	6.14	1.60	9.00	18.30	2.16	6.90	0.70	14.90	10.60	2.12	3.8
63 bits	5.34	1.05	8.83	23.05	1.86	6.60	0.55	14.64	10.88	1.18	3.3
31 bits	3.23	0.44	7.15	21.00	0	1.80	0.06	3.99	1.60	0.08	0.4
Error-Free Messages (%)	68.40	88.60	37.90	9.45	83.00	54.00	94.80	53.90	60.20	69 ~~69.00~~	57.5
Sync Bad, But Text OK	0.15	0.01	0.41	0.02	0.07	0.01	0.07	0.18	1.50	0	22.9
	68.55	58.61	38.31	9.47	83.07	54.01	94.87	54.08	61.70	69.06	80.4
ERROR DISTRIBUTIONS %											
No. of Errors											
1	4.75	2.53	10.11	3.46	5.15	10.02	2.29	2.14	5.25	19.70	6.3
Cumulative %	73.31	91.14	48.42	12.93	88.22	64.03	97.16	56.22	66.95	88.70	86.7
2	3.78	1.98	10.64	3.38	3.70	7.60	0.74	1.34	1.75	5.81	1.3
Cumulative %	77.09	93.12	59.06	16.31	91.92	71.63	97.90	57.56	68.70	94.57	88.0
3-4	2.46	1.56	6.68	3.90	1.68	5.20	0.35	1.04	1.20	1.38	1.3
Cumulative %	79.55	94.68	65.74	20.21	93.60	76.65	98.25	58.60	69.90	95.89	89.3
5-8	2.29	1.43	4.26	5.78	1.12	4.70	0.38	1.77	0.95	0.16	0.9
9-10	1.11	0.34	1.62	2.55	0.40	1.30	0.09	0.64	0.41	0.04	0.1
17-32	0.42	0.04	0.85	1.50	0.04	0.10	0	0.09	0.08	0.39	0.1
33-64	2.14	0.38	2.92	7.59	0.61	1.50	0.55	5.38	6.10 + 1.50^{s}	0.31	6.5 + 22.9^{s}
65-127	0.04	0	0.01	0.01	0	0	0	0.03	0	0	0

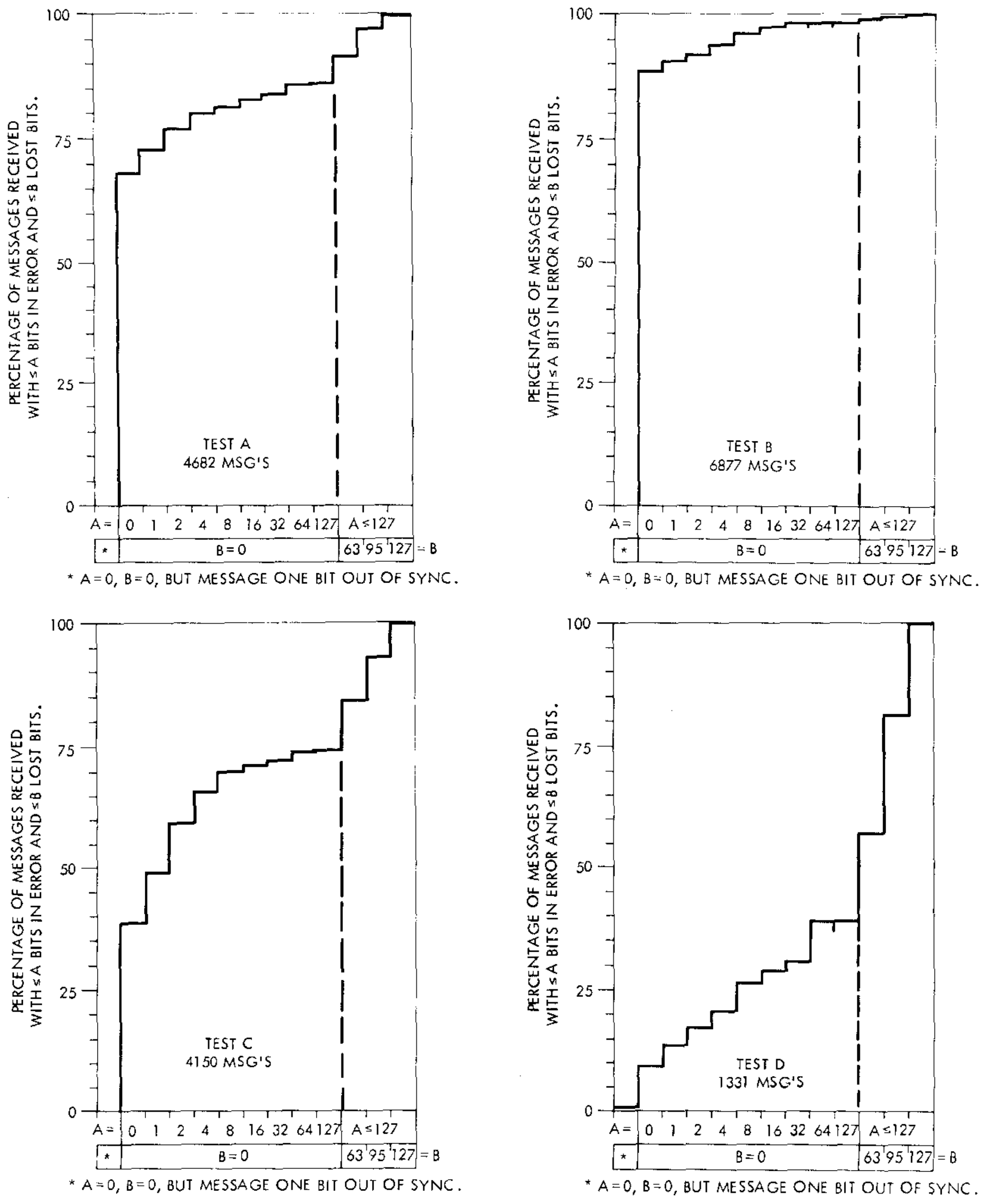


Fig. 26. Error Distributions for Different Transmission Paths

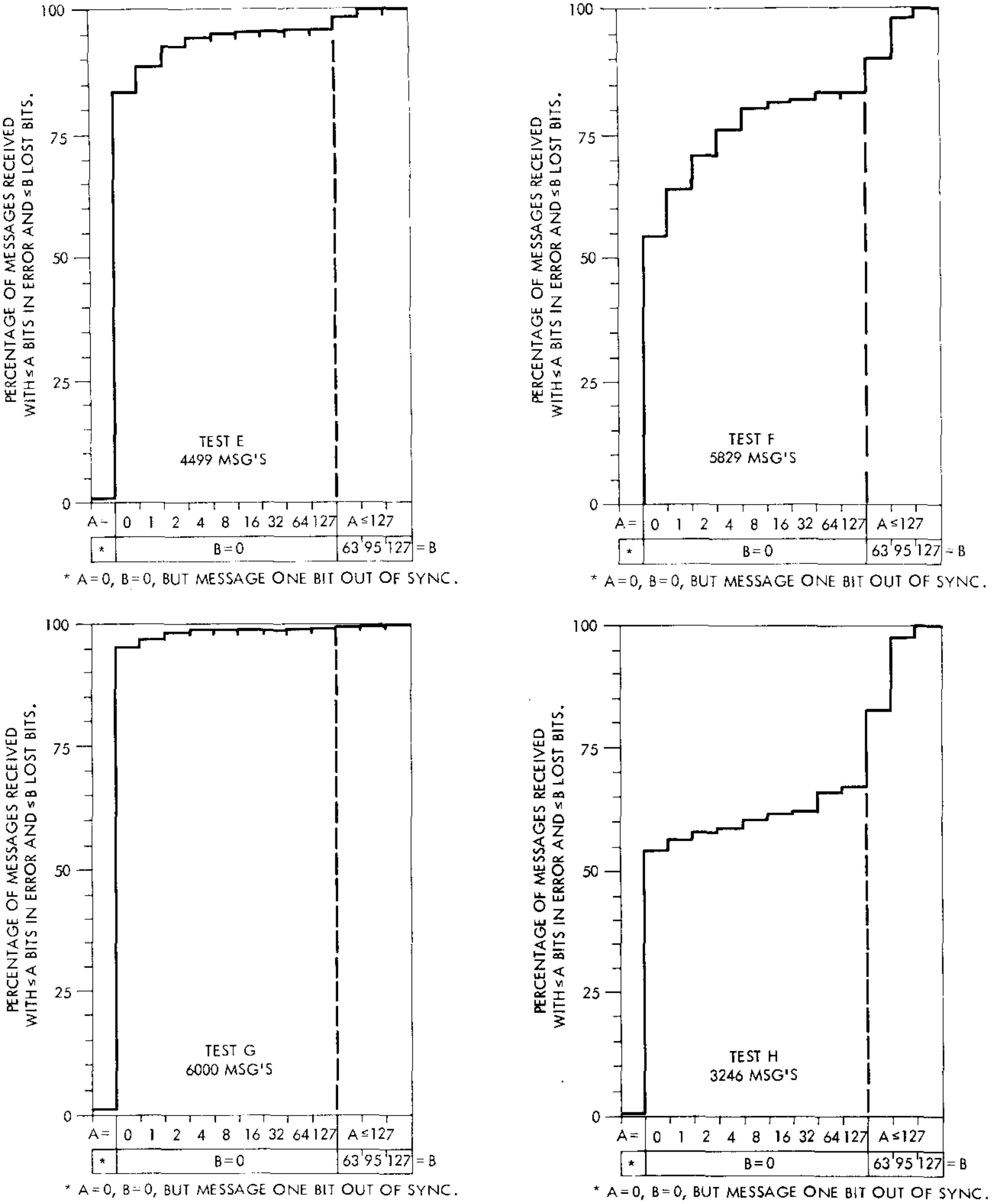


Fig. 26. Error Distributions for Different Transmission Paths (continued)

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