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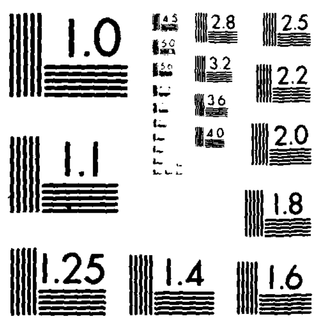

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TEST AND EVALUATION OF REDUCED RATE MULTIPLEXERS

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This report contains the results of a test and evaluation utilizing commerically available Reduced Rate Multiplexers performed by RADC's Digital Communication Experimental Facility (DICEF) in support of DCA/DCEC. Unlike previous work in this area, the subject program considered the effect of an analog telecommunications channel prior to digitization by a Continuously Variable Slope Delta Modulation (CVSD) encoder. The major conclusion drawn from this evaluation is the fact

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) that a system incorporating a 32 KB/S CVSD in tandem with a conventional analog telephone channel of relatively poor quality can support 2400 B/S modem transmission.

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Introduction

Through 1980, a test and evaluation of commercially available Reduced Rate Multiplexers was performed at RADC's Digital Communications Experimental Facility to determine their suitability for use in DCS long haul circuits. This program was sponsored by the Defense Communications Agency and focused on two systems incorporating Continuously Variable Slope Delta Modulation. This report presents the results of this evaluation.

Background

The Defense Communications Systems, as currently being configured, will make use of the North American standard 64 KB/S pulse code modulation, mu-law companded, voice frequency digitizers. This selection was based primarily upon the consideration that 64 KB/S PCM would guarantee channel quality sufficient to allow a significant number of tandem analog-to-digital conversions, and would support the transmission of quasi-analog signals from high speed data modems.

However, recognizing the potential economics that could result from operating at data rates lower than 64 KB/S, this T&E program is structured to provide the information necessary for the possible system engineering of reduced rate multiplexers (RRM) into the DCS. Although RRM's have inherent performance limitations as compared to 64 KB/S PCM, the potential bandwidth economics that these techniques offer compel their consideration for some portion of the DCS. For example, the NATO SATCOM II Satellite Ground Terminal has been designed to incorporate 32 KB/S CVSD channels as well as 64 KB/S PCM channels. It has been proposed that such CVSD channels be employed as segments in the switched analog long haul DCS circuits. In an application of this nature the signal presented to the CVSD encoder would be corrupted by various noise and phase fluctuations arising in the tandem analog transmission segments.

Although considerable testing has been performed on various RRM's, particularly CVSD, it has been primarily concerned with voice performance. Some testing has been directed towards performance of non-voice quasi-analog signals, but was inconclusive because of the limited selection of digitizers and the fact that the test configuration was not representative of real world circuit conditions. The major test defect to date has been applying the modem signal directly to the digitizer. In an actual application seldom does the signal source reside at the digitizer location. Most frequently the signal must first pass through an analog channel for considerable distance and is thereby distorted before it encounters the digitizer.

The subject program simulated the effects of the analog channel prior to digitization by the use of a simulated channel as part of the test configuration. In this way the modem signals will pass through the simulated channel, suffer the degradations inflicted by analog transmission, and then be digitized in the RRM. The resulting signal, after being restored to analog form at the far end of the digital link, can then be analyzed to determine suitability of the overall link in meeting DCS requirements for transmission. Additionally, the subject program expands the field of digitizers analyzed and recorded. It includes the CVSD system contemplated for use in the aforementioned NATO SATCOM II system.

General

The report will be organized as follows. There will be some general discussions applicable to the overall program. A separate section will be devoted to each of the two systems evaluated and the report will conclude with a summary of the more important results and recommendations.

The report will build on previous work in the area. In particular, the summary presented by O'Neal[1] will serve as an excellent foundation and the subject effort will build constructively on the modem performance tests reported by May et al[2]. As such, this report will assume the reader has a basic knowledge of PCM and CVSD encoders and the associated multiplex systems. If information is required, the reader is referred to Jayant's work[3].

In order to maintain impartiality and eliminate any misunderstandings regarding endorsements, the two systems evaluated will be referred to by the acronyms CVSD #1 and CVSD #2.

The basic test configuration used for this evaluation is shown in Figure 1. Attention is first drawn to the source and sink for the digital data used for each experiment. The pseudo-random data source and associated bit error rate tester was an International Communications Corporation Transmission Test Set. The set was modified in the DICEF for expanded error, total block, and bad block counting but otherwise is the standard 2047 bit maximal length sequence generator and comparator with an EIA RS-232 interface commonly used for bit error rate testing.

Several modems were interchanged throughout the test to perform the modulation and demodulation function shown in the test configuration. In many instances, the modems were operated at two or three different data rates. Table 1 gives a short description of each of the modems used throughout this evaluation.

The next point on the block diagram is the switch option for the type of analog channel to be placed in tandem with the RRM. During the evaluation both the DICEF telephone channel simulator and real AUTOVON circuits were used before and after the RRM. The telephone channel simulator reproduces the impairments found in a real 4 KHz channel but in a completely controlled and repeatable manner. This system proved to be invaluable for the subject experiments. A complete description of the simulator can be found in an RADC technical report[4] and an operations manual available in the DICEF facility. Real AUTOVON circuits were also used in tandem with the RRM. The DICEF has 4 wire access lines to two local switching centers and dial-through units placed at switching centers throughout the continental US.

The representation of the RRM is used to depict the manner of loop-back for tandem codec (coder-decoder) operation. It is noted that the channel decoder converts the signal back to its analog form prior to connection to another channel coder or digitizer.

The high speed aggregate data channel from the multiplexer was then applied to DICEF's Data Link Simulator. This unit simulates the effect of a real digital communications channel by introducing complex pseudo-random errors into a data link. The wide range of error conditions including burst modes of operation permit the simulation of virtually any data link. The heart of the simulator consists of feedback shift registers

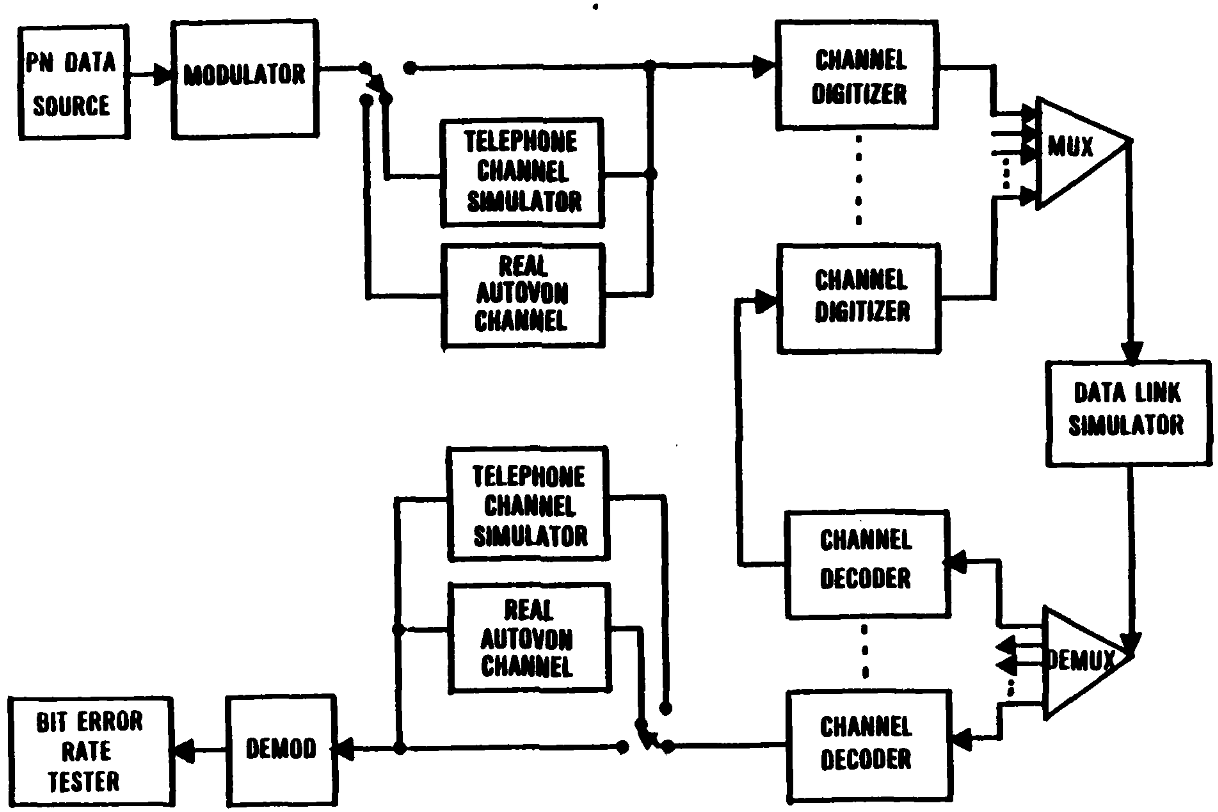

FIGURE 1. TEST CONFIGURATION

Hughes HC-276(MD-823)

Differential Phase Shift Keying, 4 phase keying of 1800 Hz carrier, 1200 and 2400 B/S data rates.

Paradyne LSI-96

Full Response, Pulse amplitude modulation transmitted as a vestigial sideband line signal, -16 dB carrier 2853 Hz added in quadrature, 4 level 4800 baud 9600 B/S, 4800/7200/9600 B/S data rates.

Codex LSI-4800

Double sideband suppressed carrier quadrature amplitude modulation, 2400 and 4800 B/S data rates 1600 baud 3-bit samples 4800 B/S, 1706 Hz carrier.

Lenkurt 26C

Synchronous frequency shift keying, data transitions occur at carrier zero-crossings, 2 carrier frequencies—1200 and 2400 Hz, 1200 B/S data rate.

Table 1. Modem Descriptions.

which generate maximum-length, pseudo-random binary sequences. The register outputs are combined to generate statistically random error signals. These error signals are then modulo-2 added to the data. The two primary variables for this test program are the average burst rate and the average errors per burst. Their relationship to the average bit error rate is shown below:

$$BER \leq \underbrace{(m \times 10^{-n})}_{\substack{\text{Burst Rate} \\ \text{(bursts/bit)}}} \times \underbrace{opq}_{\text{Errors per Burst}} \text{ (errors/bit)}$$

Where m and n are switch selectable from 0 to 9 and opq switch selectable from 0 to 999.

For clarity, units which can be broadly classified as signal conditioners have been omitted from the block diagram. Reference to specific analog signal levels in the test descriptions imply the use of the proper attenuators and amplifiers within this general test configuration. Since CVSD #2 was not a complete system but only the channel cards, the evaluation involved some non-standard interfaces with associated logic conversions. Finally, timing signals are implied for each of the digital paths shown in Figure 1.

<u>CVSD #1 Test Results</u> - <u>General</u>

The first system evaluated, uses continuously variable slope delta modulation (CVSD) and digital multiplexing to convert up to 40 analog channels and signaling information into a single high speed data stream of 1.544 MB/S (T-1) for transmission on cable pairs. The sampling rate for the channel coder is 35.9 KHz. The dynamic range of the system allows it to operate unrepeatered on 26 gauge exchange cable up to 5000 feet. Operation over longer distances is accomplished by using standard T-1 repeaters.

The system provides most of the administrative or signalling functions expected of a telephone carrier system. It is capable of bridged ringing, loop control and no restrictions apply for manual or automatic tone dialers. The system is compatible with step, crossbar, and electronic switch equipment. Assigned channels are dedicated lines. No concentration is employed, therefore no traffic related impairments or service denials are applicable.

The CVSD #1 system evaluated in the DICEF consisted of two complete central logic mainframes or multiplexers and a total of 24 channel units. Both 4-wire and 2-wire channel units were tested. The 2-wire units required some additional hardware. A "central office simulator" was constructed to provide the loop holding current for these channels. A telephone company type "A" relay was used to provide "battery" power to the channel cards. The effect on AC testing was minimal. As will be seen, the 2-wire card had slightly more low frequency attenuation due to this external circuitry but the modem performance was the same for both cards.

Another discrepancy arose beyond the generalized test configuration described earlier. The Data Link Simulator shown in Figure 1 is a synchronous device requiring clocked data at EIA RS-232, MIL STD 188, or TTL levels. The CVSD #1 multiplexer employs the bipolar, alternate mark inversion (BAMI) standard with telephone T-carrier. In addition to the desirable power spectral density of this waveform, it consolidates the normally separate data and timing waveforms into a single signal. However, this property necessitates a sophisticated line receiver incorporating a phase-locked loop to maintain timing between "mark" pulses. Although BAMI to TTL data and clock converters are very common components in telephone systems, a stand-along unit was not available off-the-shelf. A converter was designed and built under this project.

Prior to the subject evaluation, the New York Telephone Company conducted a field trial of a prototype of CVSD #1. Their results will be referred to within this section. The reference can be obtained through this author.

CVSD #1 Test Results - Analog

The first series of tests performed on the CVSD #1 system were a standard set of analog parameter measurements to obtain some figure of merit for the channels. The primary test instrument used here was the Halcyon 520B Universal Test System, augmented with some of the specialized tests described below. The test results for the 4-wire cards were similar to the 2-wire. The only noticeable discrepancy was the aforementioned amplitude versus frequency characteristics. Therefore, with the exception of this parameter, results will be given only for the 4-wire channels.

The channels were configured per the operating manual for a -16 dBm analog input to the coder yielding a +7 dBm analog output at the decoder. The idle channel noise measured for a terminated input was 22 dBrn. The C-notched noise was as follows:

Holding Tone (dBm):	+7	0	-10	-20	-30	-40
C-notched Noice (dBm):	-23	-31	-41	-48	-57	-64
S/N (dB):	30	31	31	28	27	24

The peak-to-peak phase jitter was measured at 2.5 degrees. The non-linear distortion measurements using the standard two tone pair system were:

4 Tone Composite Input Level (dBm):	-16	-23	-33
Second Order Products (dB):	-34	-36	-39
Third Order Products (dB):	-30	-32	-36

The amplitude and relative delay versus frequency measurements are plotted in Figure 2. The effect of the "central office simulator" on the low frequency response of the 2-wire channel can be seen.

The analog data belies the actual performance of the channel for data transmission. A close examiniation of all of the above data indicates a very good channel using classical telecommunication standards. The CVSD channel has idiosyncrasies which are not apparent using standard test methods. The most obvious characteristics affecting modem performance is the "trackability" of a CVSD coder. That is the ability of the staircase approximation generated by the encoder to follow the signal input without slope overload. A satisfactory method of measuring this anomaly (without digital "run" detectors connected to the internal comparators) has not been found, however, some standard measurements acknowledge its presence. For example, an HP 331A distortion analyzer was used

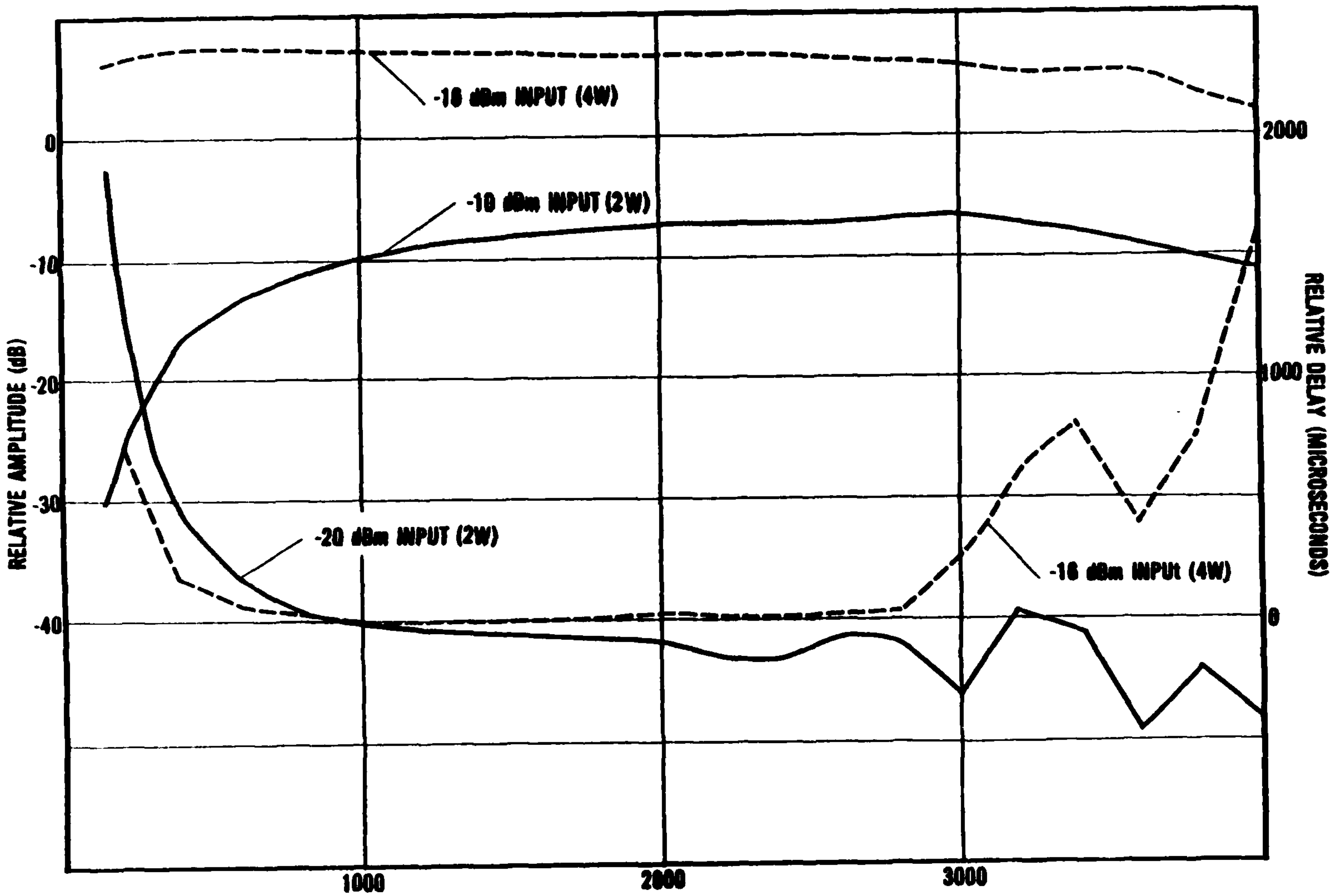

FIGURE 2. AMPLITUDE AND DELAY DISTORTION FOR CVSD # 1

to measure the distortion products present on the CVSD channel as a function of frequency. A representative sample is given below.

Frequency (Hz)	50	100	200	400	700	1000	1500	2000	2500	3000	3500	4000
Distortion Products (dB)	-15	-33	-40	-35	-34	-30	-25	-23	-17	-14	-11	-3

As expected, excellent low frequency performance was obtained. However the rapid deterioration above about 1.5 KHz shown here was not readily perceived from the traditional measurements—in particular, the amplitude response shown in Figure 2. Although a strong fundamental component is transferred at the higher frequencies, it is a highly distorted signal. Examination of the CVSD signal with an oscilloscope provides some insight into the problem. At high frequencies of the analog input signal the encoder oscillates between over- and under-estimating the correct slope. This slope overload results in an amplitude modulated respresentation of the original sine wave. This unwanted modulation's depth and frequency is not only dependent on codec parameters (e.g., integration time constants, sampling rate, step size) but on the harmonic relationship between the input analog signal and the codec's sampling rate.

The major conclusion drawn from these analog measurements is the fact that traditional methods are inadequate for CVSD channels. It is recommended that a sound and reasonable test procedure be developed to quantify the quality of these channels. That is not to say no work in this area is being done. Measurements of the percentage of slope overload as a function of frequency, maximum and minimum voltages of syllabic filters, and a variety of applicable ratios of same, are becoming quite common. However, a technique should be developed for performing a "black box" type of measurement not requiring direct access to the CVSD device which may be at the far end of an integrated communications link. This test procedure should also be amenable to field service personnel and equipment.

CVSD #1 Test Results - HC-276 Modem

The first series of modem tests involved operation of the CVSD channels without additional distortion or high speed bit errors imparted. The modem was operated at both 2400 and 1200 B/S and the results are consistent with those reported by May et al[2]. That is, with a single CVSD #1 channel or two channels in tandem, the HC-276 modem operated error free at 2400 B/S. With more tandem connections the following results were obtained:

Data Rate	# Tandem Links	Bit Error Rate
2400 B/S	3	2.7×10^{-7}
2400 B/S	4	7.9×10^{-6}
2400 B/S	5	3.4×10^{-5}
2400 B/S	6	1.2×10^{-4}
2400 B/S	7	2.7×10^{-4}
2400 B/S	8	6.2×10^{-4}
1200 B/S	6	1.5×10^{-5}
1200 B/S	7	7.5×10^{-5}
1200 B/S	8	2.3×10^{-4}

The next series of tests were performed with the telephone channel simulator placed in tandem with the CVSD channel. The relative amplitude and delay versus frequency characteristic used for these tests is shown in Figure 3. It is a channel used often in the DICEF to simulate a typical AUTOVON channel and has been designated the "4A" line. Two parameters varied during this portion of the evaluation were additive Gaussian noise and phase jitter. The modulation waveform for the phase jitter was a 60 Hertz sine wave. As a reference, the modem performance at 2400 B/S through the telephone channel simulator without the CVSD channels was as follows:

Parameter	Bit Error Rate
16 dB S/N, 4A line	7.6×10^{-7}
14 dB S/N, 4A line	3.9×10^{-5}
12 dB S/N, 4A line	5.2×10^{-4}
10 dB S/N, 4A line	4.2×10^{-3}
16 dB S/N, 40° P-PØJ, 4A line	2.0×10^{-6}

The parameters are listed in terms of signal to noise ratio (S/N) and degrees peak-to-peak of phase jitter (°P-PØJ). Also note that the modem is quite robust, performing well in the presence of high noise levels.

When the CVSD channel was added, the first observation made was the fact that modem performance was the same whether the telephone channel simulator was placed before or after the CVSD encoder. Although it may be reasonable to assume that different mechanisms should be involved for each of these cases, time did not permit technical analysis.

Although it is not necessary to reproduce all the data here, several key data points will serve to illustrate some trends. The following performance was obtained at 2400 B/S with a single CVSD #1 channel in tandem with the 4A telephone channel and parameters shown:

Parameter	Bit Error Rate
16 dB S/N, 40° P-PØJ	1.8×10^{-5}
16 dB S/N, 20° P-PØJ	9.5×10^{-6}
18 dB S/N, 40° P-PØJ	7.3×10^{-7}
18 dB S/N, 20° P-PØJ	1.5×10^{-7}

The first data point above can be compared with the previous table without the CVSD #1 channel. There is about an order of magnitude increase in the bit error rate when the CVSD channel is added. However, note the high degree of channel degradation at which this occurs. Progressing to the last entry above, it can be seen

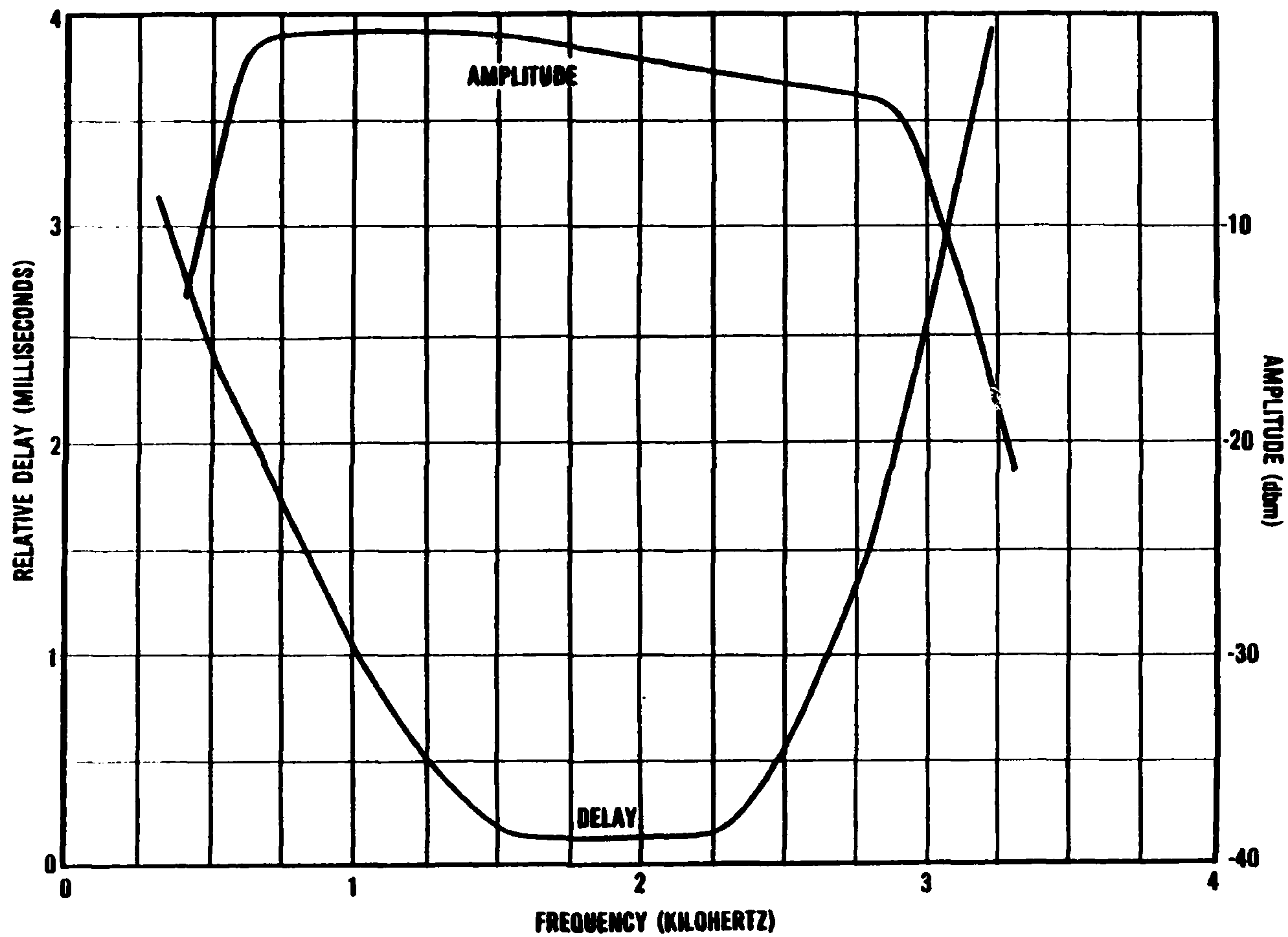

FIGURE 3. TELEPHONE CHANNEL SIMULATOR "4A" RELATIVE AMPLITUDE AND DELAY VERSUS FREQUENCY

that excellent performance can be obtained with a signal-to-noise ratio of 18 dB and 20 degrees peak-to-peak of phase jitter. This is still a poor grade tandem channel and it can be concluded that this configuration provides acceptable performance.

Tests were next performed with 2 tandem CVSD #1 channels—one before the 4A telephone channel simulator and a second after the simulator. The results are shown below with the corresponding points from the last table.

BIT ERROR RATE

Parameter	1 Tandem CVSD #1 Channel	2 Tandem CVSD #1 Channels
16 dB S/N, 20^{o} P-PØJ	$9.5x10^{-6}$	$1.6x10^{-5}$
17 dB S/N, 20^{o} P-PØJ		$5.5x10^{-6}$
18 dB S/N, 20^{o} P-PØJ	$1.5x10^{-7}$	$1.1x10^{-6}$

A degradation in performance did result but operation was still acceptable at the benchmark 18 dB S/N, 20^{o} P-PØJ channel. Note that the percentage contribution due to the second channel becomes less as the telephone channel noise increases.

The next variable added to the test configuration was the number of bit errors injected by the data link simulator shown in Figure 1. For these tests a CVSD #1 channel was connected before and after the telephone channel simulator. The bit errors are being imparted on both CVSD encoders. The effect of these injected errors did not become measurable until an error rate of about $1x10^{-5}$ was imparted. Some data is listed below for the 4A channel.

Parameter	Injected Bit Error Rate	Measured Modem Bit Error Rate
18 dB S/N, 20° P-PØJ	0	1.1×10^{-6}
18 dB S/N, 20° P-PØJ	1×10^{-5}	1.9×10^{-6}
18 dB S/N, 20° P-PØJ	1×10^{-4}	8.8×10^{-6}
20 dB S/N, 20° P-PØJ	1×10^{-5}	3.0×10^{-7}

Again we see acceptable performance for our benchmark channel. More data will be given and observations made on the subject of errors on the encoded channel further on in this report.

The telephone channel parameters discussed so far are historically considered the most important and informative for characterizing modem performance. However, for this evaluation it was deemed necessary to test operation with a transient type of parameter that may produce overload problems for the encoder. The parameter chosen was impulse noise. For this test series a CVSD #1 channel was placed before and after telephone channel simulator, the 4A line was used, impulses occurred at an average rate of 45 per minute and had a forcing function with a 200 microsecond time width (the observed impulse response had the time dispersion associated with the bandwidth characteristics of the 4A line). The test variable was the peak level in decibels above the modem RMS signal level. The data is reproduced below.

	BIT ERROR RATE	
Impulse/Signal Level	Without CVSD #1	With CVSD #1
0 dB	No Errors	No Errors
5 dB	2.6×10^{-6}	7.3×10^{-6}
10 dB	1.5×10^{-4}	1.5×10^{-4}
15 dB	5.3×10^{-4}	5.1×10^{-4}
20 dB	4.8×10^{-3}	1.1×10^{-3}

As a point of reference, with the modem operating at 2400 B/S, the aforementioned impulse bit rate corresponds to 3.1×10^{-4} impulses/bit. Upon examination of the above data, it was concluded that the impulses had no more deleterious an effect on channels with CVSD #1 encoders than those without.

In summary, the HC-276 modem provides acceptable operation at 2400 B/S through a tandem connection of two CVSD #1 channels and a marginal analog channel.

CVSD #1 Test Results - Paradyne LSI-96 Modem

As shown in Table 1, the Paradyne LSI-96 modem is designed for high speed operation up to 9600 B/S. As expected these data rates were too taxing for the encoder in the CVSD #1 system. Representative performance data is shown below for tandem combinations of CVSD #1 channels with no additional analog distortion or high speed bit errors injected:

Data Rate	# Tandem Links	Bit Error Rate
4800 B/S	1	1.9×10^{-5}
4800 B/S	2	7.0×10^{-4}
4800 B/S	3	would not sync
7200 B/S	1	1.7×10^{-3}
9600 B/S	1	4.8×10^{-3}

Based on this data, no more tests were performed and it was concluded that the CVSD #1 system cannot support data transmission using the Paradyne LSI-96 modem.

CVSD #1 Test Results - Codex LSI-4800 Modem

Testing of the Codex LSI-4800 through the CVSD #1 system was very extensive. This modulation technique at 4800 B/S appears to be at the transition between acceptable and unacceptable operation through CVSD #1. As a result, a very large data base was required in order to analyze trends. Operation in this transition region also provided insight into mechanisms not obvious when operating over "too" good or "too" bad a channel.

The first anamoly was observed while investigating the effect of analog input signal level on modem performance. It was determined that the optimum signal level was a complicated function of the bit error rate injected on the high speed encoded data stream. As a foundation for subsequent discussion, reference is made to

May et al[2]. The report stated that "for DM and PCM channels, having errors inserted on transmission lines, the BER performance of a modem is superior for DM channels than for PCM channels, when both are operating at an effective bit rate of 64 KB/S. Results indicate that the modem BER exponentially tends toward zero as the DM line BER decreases, whereas it linearly tends toward zero as the PCM line BER decreases." This statement referred to a 4800 B/S modem operating through a 64 KB/S encoder. In the subject case, there is a 4800 B/S modem operating through a 35.9 KB/S encoder—a much higher information rate to sampling rate ratio. In this case, the modem bit error rate tends toward a non-zero value producing a performance curve with a slope opposite to that shown in May et at[2].

This performance characteristic is further confounded by the aforementioned signal level into the encoder. Reference is now made to Figure 4 which illustrates the relationship found. The graph contains two families of curves—one family for the modem operating through a single CVSD #1 channel and another for the modem operating through a tandem connection of two CVSD #1 channels (each channel having errors injected per the abscissa). The graph confirms the preference for low signal levels for CVSD encoders reported by May et al[2] when the high speed line error rate is small. However, it is now reported that this preference swings to higher signal levels as line bit error rate increases.

These observations may only be of academic value. It can be seen in Figure 4 that operation of the Codex LSI-4800 at 4800 B/S through two tandem CVSD #1 channels is unacceptable and operation through a single channel is marginal after careful adjustment of signal levels and with no additional perturbations.

The telephone channel simulator was placed in tandem with a CVSD #1 channel. The first observation made was the difference between operation with CVSD #1 before the simulator and operation with it after. As contrasted with the previously discussed 2400 B/S case, there was a significant difference. On the average, operation with the CVSD #1 channel after the telephone channel simulator produced about five times the number of bit errors as operation with CVSD #1 before the simulator using the Codex LSI-4800 B/S. Some typical data is presented below for the 4A line and a -16 dBm input level into the CVSD #1:

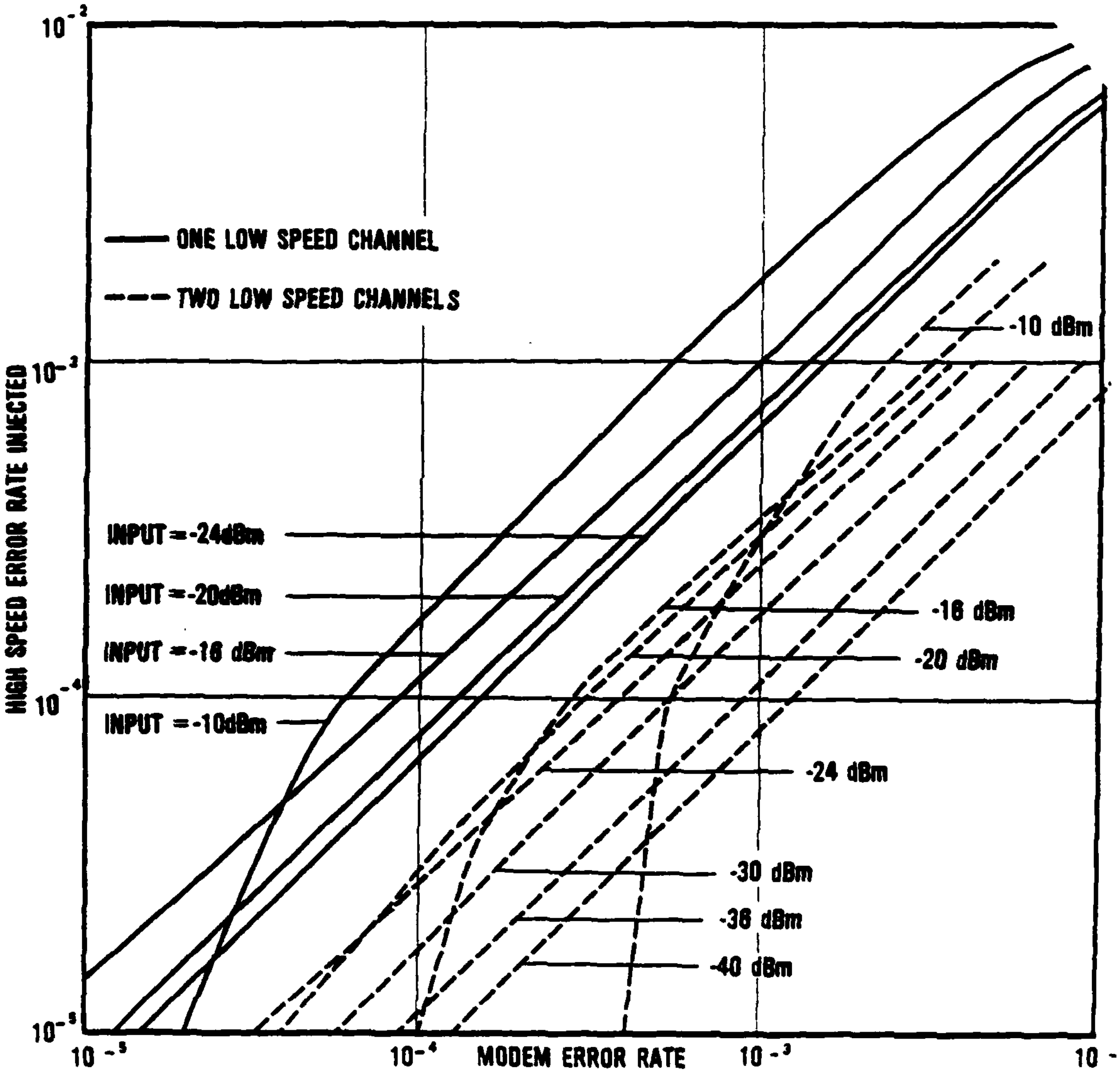

FIGURE 4. CODEX LSI-4800 PERFORMANCE THROUGH ONE AND TWO CVSD #1 CHANNELS

Parameter	CVSD Channel Relative to Simulator	Modem Bit Error Rate
30 dB S/N, 10^{o} P-PØJ	after	$8.3x10^{-6}$
26 dB S/N, 15^{o} P-PØJ	after	$1.4x10^{-5}$
23 dB S/N, 20^{o} P-PØJ	after	$2.3x10^{-5}$
26 dB S/N, 15^{o} P-PØJ	before	$2.4x10^{-6}$
20 dB S/N, 25^{o} P-PØJ	before	$1.4x10^{-5}$

Notwithstanding the better performance of the "before" case, it is concluded from these tests that the CVSD #1 channel in tandem with the telephone channel simulator does not provide acceptable 4800 B/S data transmission using the Codex LSI-4800.

Tests were performed with the CVSD #1 system in tandem with real CONUS AUTOVON circuits. The DICEF facility has data grade access to two switching centers and a dial-through capability at four more CONUS switching centers. Due to the nonstationary random process involved, it was not possible to draw any self-sufficient, statistically valid conclusions from these tests within the time constraints of this program. However, it is very interesting and assuring that the results obtained confirmed the previous observations using the simulated telephone channel.

Over seventy tests were performed incorporating a variety of data rates and CVSD #1 configurations. A test series normally proceeded as follows. A random circuit through the AUTOVON was dialed. A series of analog measurements were performed and logged to characterize the channel and highlight any anamolies. A bit error rate test was performed at 4800 B/S without CVSD #1 connected. A 4800 B/S test was performed with a CVSD #1 channel before and after the telephone channel. Based on results, a 4800 B/S test may have been performed with a single CVSD #1 channel before the telephone channel. Next, a separate test was performed with the CVSD #1 channel after the telephone channel. Finally, a series of 2400 B/S tests were performed. At 2400 B/S, the initial test utilized a CVSD #1 channel before and a second after the AUTOVON channel. If acceptable performance was obtained, the series was terminated; if the error rate was significant a test at 2400 B/S without CVSD #1 was performed. A total of 15 test series were performed through a complete work week. The exposure to busy hour traffic was probably representative. However, the circuit length was biased toward the "long" side with subsequent exposure to channel noise and distortions. For example, six of the 15 test series were routed through a California switch.

The effect on 4800 B/S modem performance of the CVSD #1 channel was significant. At 4800 B/S, 14 of the 15 AUTOVON channels tested had bit error rates less than the $1x10^{-5}$ without CVSD #1 channels connected in tandem. When a CVSD #1 channel was connected before the real AUTOVON and a second CVSD #1 channel placed after the telephone channel, the Codex LSI-4800 operating at 4800 B/S always produced a bit error rate greater than $1x10^{-5}$. It is difficult and perhaps dangerously misleading to relate more specific observations on this small a data base. A factor contributing to the difficulty of presentation is the fact that 7 of the 15 channels tested provided error free 4800 B/S operation without the CVSD #1 channels connected, thus making quantitative comparisons such as differences and ratios, with and without CVSD, meaningless. (Note that these seven channels were included in the observation at the outset of this paragraph, i.e., seven channels went from error free transmission to an unacceptable bit error rate when the CVSD #1 channels were added.)

Tests were also performed with the Codex LSI-4800 operating at 2400 B/S through CVSD #1 in tandem with both the simulated and real telephone channel. The results were excellent. Since the results of one 2400 B/S modem have been reported in detail earlier, the results for the Codex LSI-4800 tests will simply be compared. Performance relative to the HC-276 modem can be expressed along several dependent points of view. Tests showed that all other parameters being equal, the Codex LSI-4800 at 2400 B/S always had at least an order of magnitude better bit error rate performance than the HC-276, . From another point of view all other parameters held constant, the Codex LSI-4800 was able to withstand 3 dB more noise for a given bit error rate than the HC-276. As previously mentioned, the Codex LSI-4800 was also tested at 2400 B/S over the real AUTOVON circuits. Twelve channels were tested at 2400 B/S with a CVSD #1 before the AUTOVON channel and a second CVSD #1 connected after. The error distributions were as follows:

no errors	7 channels
better than 10^{-5} BER	3 channels
1.1×10^{-5} bit error rate	1 channel
3.9×10^{-5} bit error rate	1 channel

It should be pointed out that the two channels above producing a bit error rate greater than 1×10^{-5} were both the aforementioned New York to California and return loops. Despite these atypical cases, the trend toward a very robust channel is clearly illustrated.

In conclusion, the Codex LSI-4800 provides excellent operation through a tandem connection of two CVSD #1 channels and a marginal quality analog channel at 2400 B/S. However, operation of the modem at 4800 B/S through this configuration has been judged unacceptable.

CVSD #1 Test Results - Lenkurt 26C Modem

A limited amount of testing was performed using the Lenkurt 26C modem through the CVSD #1 system. Extensive testing was not deemed necessary since a large enough data base was developing to support a positive recommendation for 2400 B/S transmission through a CVSD system of this type. Secondly, there was concern about the objectivity of this particular test. The modem available for testing was equipped with a manually adjustable delay equalizer. Although the GTE Engineering Practice Standard for this modem was carefully adhered to, it was found that widely divergent performance was attained after each alignment attempt. This dilemma frustrated attempts to characterize performance as a function of the parameters of interest. However, testing did substantiate the fact that the Lenkurt 26C, like the other 2400 B/S modems, will support data transmission through a tandem connection of two CVSD #1 channels and a marginal quality analog channel. For example, a modem bit error rate of 8.6×10^{-6} was obtained under the following test configuration: the modem operated through a tandem connection of a CVSD #1 channel before and another CVSD #1 channel after the telephone channel simulator. Each of the CVSD #1 channels had a 1×10^{-6} bit error rate injected into the high speed aggregate digital port of the multiplexer.

The telephone channel simulator was operating with the 4A line and a 19 dB signal to noise ratio.

CVSD #1 Test Results - Voice Operation

As stated earlier, the subject effort dealt primarily with modem testing, however, the sponsoring organization thought that an informal voice check out might prove informative. Due to the extensive amount of literature on voice testing through CVSD devices already available, a formal test such as the Diagnostic Rhyme Test was not considered. It was decided that even a cursory voice check of this system as a function of bit errors injected on the high speed aggregate port would be useful. As described earlier the bit error injector has the capability of producing random error bursts and this mode was exercised for this test. The analog source for this experiment was a Diagnostic Rhyme Test type containing disjoint words. The results are shown below in the necessarily subjective terms of the author. There was no intention for these terms to coincide with any standard terminology in the field.

Burst Rate	Errors per Burst	Bit Error Rate	
$2x10^{-3}$	1	$2x10^{-3}$	negligible effect
$4x10^{-3}$	1	$4x10^{-3}$	just noticeable degradation
$7x10^{-3}$	1	$7x10^{-3}$	annoying
$2x10^{-2}$	1	$2x10^{-2}$	some words unintelligible
$4x10^{-2}$	1	$4x10^{-2}$	many words unintelligible
$5x10^{-2}$	1	$5x10^{-2}$	unintelligible
$2x10^{-3}$	10	$2x10^{-2}$	just noticeable degradation
$3x10^{-3}$	10	$3x10^{-2}$	annoying
$4x10^{-3}$	10	$4x10^{-2}$	some words unintelligible
$5x10^{-3}$	10	$5x10^{-2}$	many words unintelligible
$9x10^{-3}$	10	$9x10^{-2}$	unintelligible
$2x10^{-4}$	100	$2x10^{-2}$	just noticeable degradation
$3x10^{-4}$	100	$3x10^{-2}$	annoying
$5x10^{-4}$	100	$5x10^{-2}$	some words unintelligible
$1x10^{-3}$	100	$1x10^{-1}$	many words unintelligible
$2x10^{-3}$	100	$2x10^{-1}$	unintelligible
$2x10^{-6}$	999	$2x10^{-3}$	annoying popping

As can be seen, the CVSD #1 system is quite robust for voice communications. The channel quality was excellent. When a CVSD #1 channel was connected before and after the telephone channel simulator the CVSD #1 system had no discernible effect.

CVSD #2 Test Results - General

The second unit evaluated which will be referred to as CVSD #2 also employs a continuously variable slope delta modulation technique. However, the sampling rate is 32 KHz which is slightly lower than that of CVSD #1. A complete channel bank and multiplexer was not available for this evaluation. Only two codec channel cards could be released from production commitments. Although this greatly limited testing possibilities, the close correlation with CVSD #1 results permits a comfortable extrapolation.

Operation of the codec in a stand-alone environment presented some implementation difficulties. A physical test jig was constructed, three power supplies adapted, system clock provided, and three data interfaces implemented. It was then determined that one of the two codec cards was defective, so tests proceeded with a single channel operational.

CVSD #2 Test Results - Analog

The analog signal level straps on the CVSD #2 card were set up for a -14 dBm signal input level and a +3 dBm output level. The idle channel noise measured with a terminated input was 7 dBrn using a 3 KHz flat weighted filter on the Halcyon measuring instrument. Noise measurements using the C-notched method were as follows:

Holding Tone (dBm)	+12	+3	-6	-16
C-notched noise (dBm)	-15	-24	-35	-44
S/N (dB)	27	27	29	28

The peak-to-peak phase jitter was 3.0 degrees. The non-linear distortion measurements using the standard two tone pair system were:

4 Tone Composite Input Level (dBm):	-8	-14	-20	-26
Second Order Products (dB):	-29	-37	-39	-41
Third Order Products (dB):	-30	-34	-36	-37

Finally, the amplitude and relative delay versus frequency measurements taken are plotted in Figure 5.

The apprehension concerning these traditional analog measurements expressed earlier in this report notwithstanding, there were no significant differences noted between CVSD #1 and CVSD #2.

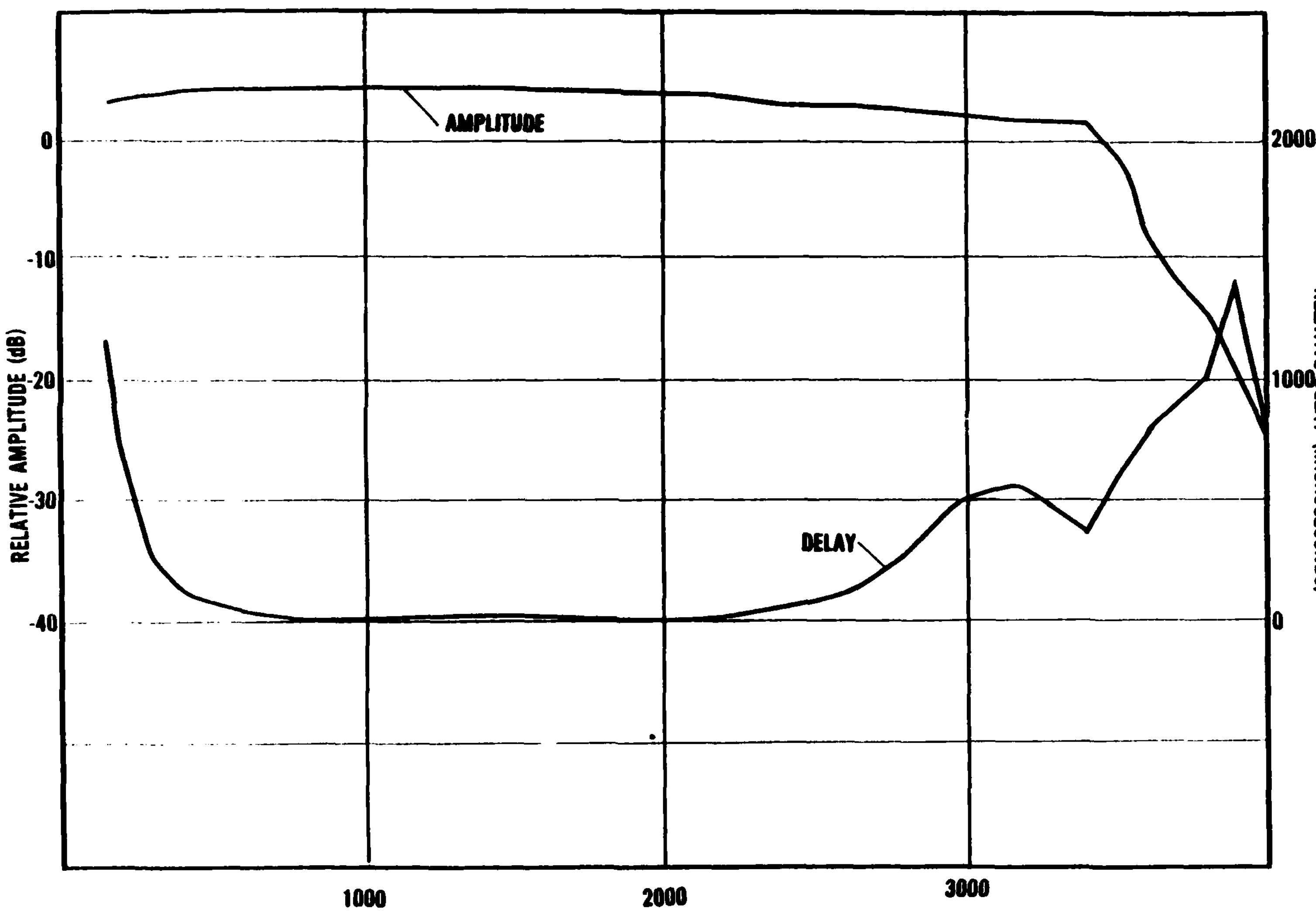

FIGURE 5. AMPLITUDE AND DELAY DISTRIBUTION FOR CVSD #2

CVSD #2 Test Results - Digital

Modem performance tests comprised operation through CVSD #2 using the Codex LSI-4800 at both 4800 and 2400 B/S and the Hughes HC-276 at 2400 B/S. The results were so similar to those using CVSD #1 that performance will be described relative to these prior discussions. At the outset, an analysis and data will be presented to support the extrapolation of CVSD #1 results to CVSD #2. Specific extensions based on the CVSD #2 tests will then be presented.

A comparison of the CVSD #1 and CVSD #2 data set yields a match of eleven tests in which CVSD #1 and CVSD #2 were excercised under the same conditions. The number of matches was relatively small because the vast majority of CVSD #1 tests were performed using more than one tandem codec channel. As previously stated only one CVSD #2 channel was available for this evaluation. The conditions under which these tests were performed are contained in Table 2a. Table 2b contains the bit error rates obtained using each CVSD technique. The ratio of performance with CVSD #2 to the performance using CVSD #1 is also shown. The most commonly used method for performing statistical analyses on ratios is to next take the logarithm of these values. This transformation is the most effective manner of fairly distributing ratios about the unit value. The logarithm to the base ten is also shown in Table 2b. The sample mean and unbiased sample variance of these logarithms were then computed and antilogarithms determined. The mean ratio for these eleven samples was 1.76 with a standard deviation of 2.83. Several inferences can be made from this analysis. The performance differences are not statistically significant since the null hypothesis cannot be discredited and the unit ratio is included in any of the standard confidence intervals.

As expected because of the higher sampling rate, slightly better performance was obtained using CVSD #1. However, the point of the analysis in the last paragraph was to show that this difference was not significant. It is hoped that this quantitative analysis passes the scrutiny of the statistician. There are some qualitative arguments that cannot pass a rigorous test but nevertheless deserve mention. There were many tests performed using CVSD #2 that compared very favorably with those using CVSD #1 that could not be included in the above comparison because there was not a perfect

Test	Modem	Data Rate	Wireline Simulator Parameters	CVSD Channel Relative to Simulator	Injected Error Burst Rate	Injected Errors Per Burst
A	LSI-4800	4800	4A, 16 dB S/N	before	—	—
B	LSI-4800	4800	4A, 16 dB S/N	after	—	—
C	LSI-4800	4800	4A	before	$1x10^{-4}$	1
D	LSI-4800	4800	4A	before	$1x10^{-5}$	10
E	LSI-4800	2400	4A, 15 dB S/N, 25^{o} PJ	after	—	—
F	LSI-4800	2400	4A, 14 dB S/N, 30^{o} PJ	after	—	—
G	LSI-4800	2400	4A, 14 dB S/N, 30^{o} PJ	before	—	—
H	LSI-4800	2400	4A, 14 dB S/N, 30^{o} PJ	before	$1x10^{-3}$	1
J	HC-276	2400	4A, 16 dB S/N, 40^{o} PJ	after	—	—
K	HC-276	2400	4A, 18 dB S/N, 20^{o} PJ	after	—	—
L	HC-276	2400	4A, 16 dB S/N, 40^{o} PJ	before	—	—

Table 2a. Comparison of Some CVSD #1 and CVSD #2 Test Results

Test	BER Using CVSD #1	BER Using CVSD #2	CVSD #2 / CVSD #1	$\log_{10} \frac{\#2}{\#1}$
A	1.20×10^{-4}	2.03×10^{-4}	1.69	0.23
B	1.93×10^{-4}	1.16×10^{-4}	0.60	-0.22
C	1.44×10^{-4}	1.58×10^{-4}	1.10	0.04
D	1.62×10^{-4}	2.33×10^{-4}	1.44	0.16
E	5.43×10^{-7}	2.93×10^{-6}	5.40	0.73
F	1.66×10^{-5}	1.43×10^{-5}	0.86	-0.07
G	1.69×10^{-5}	8.79×10^{-6}	0.52	-0.28
H	6.40×10^{-5}	1.03×10^{-4}	1.61	0.21
J	1.28×10^{-5}	3.62×10^{-5}	2.83	0.45
K	1.53×10^{-7}	3.03×10^{-6}	19.8	1.30
L	2.25×10^{-5}	3.24×10^{-5}	1.44	0.16

Table 2b. Comparison of some CVSD #1 and CVSD #2 Test Results

match of test parameters. These included tests in which an insignificant amount of bit errors were injected on the encoded data and those in which there was a slight variation in wireline simulator parameters. The results of CVSD #2 tests were well within a reasonable experimental error variation of CVSD #1 results due to level variations, noise measurement accuracy, and normal random process variance (i.e., bit error injector, Gaussian noise source, and modem scrambler statistics). Ironically, the worst two deviations between CVSD #2 and CVSD#1 results were included in Table 2 since there was a match of test parameters.

The particular test parameter emphasized during the CVSD #2 tests was the high speed injected error distribution. This parameter could not be satisfactorily exercised in the CVSD #1 tests since the encoded CVSD data from each channel is interleaved with that of other channels in the high speed data port of the multiplexer. An error burst injected into the high speed aggregate data is therefore dispersed among a number of low speed channels. The result as seen through the channel decoder is a randomization of the errors. This situation contrasts with that for CVSD #2. As a consequence of the stand-alone operation of the codec, a direct mapping of injected error bursts into the encoded data stream was possible.

The effect of injected error distributions was quite different on a modem operating at 4800 B/S as contrasted to operation at 2400 B/S. Two test series will be presented which are representative of all results during this portion of the evaluation. Test commonalities will be discussed first. The two subject test series utilized the Codex LS1-4800. The configuration shown in figure 1 was used with the CVSD #2 channel connected before the wireline simulator and the data link simulator used to inject error bursts as previously described in this report. The 4A amplitude and delay characteristic was used in the wireline simulator. Based on the analysis of all the CVSD #2 test data (Codex LS1-4800 @ 4800 and 2400 B/S; Hughes HC-276 @ 2400 B/S), it was determined that no difference in performance was obtained when the codec was placed before or after the wireline simulator. It was also determined that an injected bit error rate of less than $1x10^5$ regardless of error distribution had a negligible effect on modem performance. This last statement has profound significance relative to the discussions to follow. That is, in an operational environment, the error rate on the aggregate high speed channel should never exceed $1x10^5$ and no effect on the analog is expected. Thus, the analysis to follow which necessarily includes higher bit error rates is of only academic value in order to gain some insight into the performance of the codec.

The first test series were performed with the Codex modem operating at 4800 B/S and the wireline simulator set up with an 18 dB signal-to-noise ratio and 10 degrees peak-to-peak of 60 hertz phase jitter. The average bit error rate injected by the data link simulator was $1x10^{-4}$ but the error distribution was varied using the errors/burst control as explained earlier in this report. The results were as follows:

Injected Error Burst Rate	Injected Errors/Burst	Measured Modem Bit Error Rate
0	0	$4.2x10^{-5}$
$1x10^{-4}$	1	$3.2x10^{-4}$
$1x10^{-5}$	10	$3.4x10^{-4}$
$1x10^{-6}$	100	$1.9x10^{-4}$
$1x10^{-7}$	999	$3.3x10^{-4}$

The data indicates that there is essentially no effect on 4800 B/S modem performance due to the distribution of errors. Modem performance could be predicted by simply knowing the average bit error rate on the encoded data.

Operation at 2400 B/S did show an effect due to error distribution. In order to see any trends at all the telephone channel distortion had to be increased significantly. For the 2400 B/S test series a 14 dB signal-to-noise ratio and 30 degrees peak-to-peak of 60 hertz phase jitter were used. The results follow:

Injected Error Burst Rate	Injected Errors/Burst	Measured Modem Bit Error Rate
0	0	8.8×10^{-6}
1×10^{-3}	1	1.0×10^{-4}
1×10^{-4}	10	1.7×10^{-3}
1×10^{-5}	100	1.1×10^{-3}

In the 2400 B/S case, there is an order of magnitude increase in the modem bit error rate as the average errors per burst is increased from one to ten while keeping the average bit error rate on the encoded channel constant. This apparent discrepancy between 4800 and 2400 B/S operation could not be explained. It is a function of codec parameters, information bits per band of modem, and the modem baud rate. It is of course important to realize that in an operational multiplexed system the error dispersive effects mentioned earlier will take precedence.

CVSD Tests - Conclusions

The major conclusion drawn from this evaluation is that a system incorporating a CVSD #1 or CVSD #2 can support 2400 B/S modem data transmission under a wide variety of conditions. The system included a tandem connection with a conventional analog telephone channel of relatively poor quality. Although the wide variety of modems tested differed significantly in performance, they all provided acceptable operation with up to two tandem CVSD's included in the system.

Modem data transmission at 4800 B/S and above was unacceptable through a system including CVSD #1 or CVSD #2. Although marginal performance could be obtained at 4800 B/S through a stand-above CVSD after careful level adjustments, the inclusion of a conventional analog telephone channel of relatively high quality rendered the system unsuitable for data transmission.

As expected, these 36 and 32 KB/S CVSD's provided excellent voice operation. It was also pointed out that the traditional analog measurements used to assess a telephone channel's quality were inadequate for a system incorporating a CVSD and that other methods should be investigated.

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