COMPARISON OF PCM CODES FOR DIRECT RECORDING[1]

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Summary. The bit packing performance of randomized-non-return-to-zero (randomized-NRZ,) odd parity-NRZ, delay modulation, and bi-phase (Bi-0) in direct recording was experimentally compared at a bit error probability (BEP) of 10^{-6}. The effect of bit patterns, record and reproduce levels, bias level, tape speed, tape recorder bandwidth, bit synchronizers, and crossplay between tape recorders on bit packing density was investigated. At high bit packing densities, significant variations in data quality were found for changes in these parameters. This imposes limitations on practical bit packing densities. Some bit synchronizers were found to seriously reduce bit packing densities. Results show randomized-NR.Z to be superior to the other codes in bit packing density.

Introduction. High pulse code modulation (PCM) bit rates cannot be pre-detection (pre-D) recorded because their spectral occupancy exceeds tape recorder bandwidth. The direct record process, while also limited by tape recorder bandwidth, permits recording of higher PCM bit rates than obtainable by pre-D methods. A simple quantitative evaluation of direct, PCM baseband recording is bit packing density in bits per lineal inch. However, bit packing density in direct recording depends signficantly on the PCM code used. In attempts to maximize bit packing density subject to a given error tolerance, various codes have been developed whose characteristics match tape recorder channel characteristics. References 1, 2, and 3 discuss desirable code characteristics. They are, briefly, efficient use of tape recorder bandwidth, low d.c. content, good synchronization and bit detection characteristics, and low susceptability to noise, intersymbol interference, pulse crowding and flutter. Unfortunately, no one code possesses all of these characteristics and thus code selection for direct recording may depend upon constraints of the particular application. In this experiment, the performance of four more commonly used codes in direct recording, delay modulation (DM), Bi-0, randomized-NRZ, and odd parity-NRZ, was compared (advantages and disadvantages of these codes are mentioned in references 1 and 2). Performance of the codes was judged on bit packing density in kilo-bits per inch (KBI) at a bit error probability (BEP) of 10^{-6}. Sensitivity of each code’s bit packing density to bit patterns, record and reproduce levels, tape recorder bias level, tape speed, tape recorder bandwidth, bit synchronizers, and crossplay between tape recorders was investigated.

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[1] This work was sponsored by the Naval Air Systems Command under a task assignment in support of the Telemetry Group of the Range Commanders Council.

Test Configuration and Procedures. The test configuration is diagrammed in figure 1. Pseudo-random (PN) and fixed DM, Bi-Ø, and NRZ codes were generated in the Electro-Mechanical Research (EMR) 721 bit error rate detector. The pseudo-random PCM data was a 2047 bit sequence and was used in all tests except those for bit patterns. The configuration in figure 1a was used for performance checking of DM, Bi-Ø, and NRZ codes. The EMR randomizer/ derandomizer necessitated a change in test configuration. Randomized-NRZ was evaluated using the configuration in figure 1b. The randomizer mixed the data with an internally generated pseudo-random pattern which insured data transitions and a balance of “1’s” and “0’s.” The derandomizer recovered the data by mixing with an identical pseudo-random pattern. Bit pattern testing required a special bit error rate detector because the EMR 721 could not handle PCM sending-receiving delays of more than 8 bits.

Two wideband II tape recorders, denoted A and B, were aligned, according to procedures in IRIG Document #118-73 for a flat frequency response in the signal passband and 1% third harmonic distortion. Typical frequency response curves for the tape recorders are shown in figure 2. The signal-to-noise ratio (SNR) of tape recorder A was 34 decibels (db) and the SNR of tape recorder B was 28 dB. Frequency response and alignment was checked before and after every test. It was noted that the frequency response of the tape recorders would change slightly from beginning to end of tape. But, in all cases, the response remained within the IRIG specification of ±3 dB of 1 root-mean-square volt (Vrms). The tape recorder bandwidth changed by as much as 10% from beginning to end of tape, but in most cases changed less than 5%.

Tape recorder tests for affect of record and reproduce levels, bias level, tape recorder bandwidth, bit patterns, and bit synchronizers on bit packing density were conducted at 30 and 120 inches per second (IPS). As one parameter was varied, all others were either held constant or were as noted in Table 1. Table 1 gives conditions for all tests. Upper bandedge (UBE) tape recorder frequency (3 dB bandwidth) was defined as 500 kilohertz (kHz) at 30 IPS and 2.0 megahertz (MHz) at 120 IPS. The PCM bit rate into the tape recorder was always adjusted to maintain an approximate BEP of 10^{-6}. Bit patterns, for each code, were investigated with respect to d.c. and high-frequency energy effect on bit packing density.

Effect of crossplay between tape recorders was investigated by recording a crossection of bit rates for each code on each tape recorder. Playback of tapes on opposite recorders required azimuth and equalization adjustments to maximize signal level. BEP was noted at each of the recorded bit rates to indicate crossplay effect.

A bit synchronizer test was performed with 400 Hz to 500 kHz (tape recorder passband at 30 IPS) Bessel and Butterworth bandpass filters as shown in figure 1a. The test determined bit synchronizer peculiarities to filtered data and signal level. Since the filter lacked typical tape recorder noise, flutter, tape dropouts, and pulse crowding characteristics, this test also gave results placing an upper bound on bit packing density. Four bit synchronizers were used in this test and the bit packing density test. Bit synchronizers 1 and 4 were capable of detecting DM, Bi-0, and NRZ codes. Bit synchronizer 2 was only capable of detecting DM and NRZ and bit synchronizer 3 could detect only Bi-0 and NRZ. A fifth bit synchronizer was contained in the EMR randomizer/ derandomizer but was involved only in bit packing density tests.

Bit Synchronizer Results. Bit synchronizer test results are listed in Table 2. Results show fairly equivalent performance of all bit synchronizers, except 4, for filtered NRZ but significant differences for DM and Bi-0. No attempt will be made to explain differences, results are presented to show that differences in bit synchronizer performance do exist. Note that the nonlinear phase response of the Butterworth filter significantly reduced bit rates for a BEP of 10^{-6}. This suggests that reproduce amplifier equalization adjustments in crossplay between tape recorders can reduce bit packing if phase distortion is introduced. Reproduce amplifiers should have phase as well as amplitude equalization for direct recording of PCM. Each bit synchronizer exhibited one or two optimum input levels for each PCM code. Other input levels resulted in several orders of magnitude change in BEP, however, only slight reductions in bit rate were required to bring the BEP to 10^{-6}.

Tape recorder noise, flutter, and other anomalies, for the most part, made bit synchronizers' input signal level characteristics unobservable. Bit packing results for the four bit synchronizers are shown in Table 3, which summarizes results for most of the experiment. These results show significant differences in bit synchronizer performance in terms of bit packing of the PCM codes.

Bit synchronizer 4 showed drastic reductions in bit packing relative to bit synchronizer 1 for NRZ and DM at 30 and 120 IPS. Bit synchronizer 2 showed a significant DM bit packing loss relative to bit synchronizer 1 at 30 and 120 IPS and also showed a significant DM bit packing packing loss between tape speeds. Bi-0 results were relatively consistent between tape speeds and bit synchronizers, NRZ showed consistency between tape speeds but variation between bit synchronizers, and DM showed variation between speeds and bit synchronizers.

Bi-0 Results. The bit packing density of Bi-0 in Table 3 at 30 IPS with tape recorder A and bit synchronizer 1 was 23.3 KBI (700 kilobits per second, (kb/s)). At 120 IPS the bit packing density was 20.6 KBI (2.48 megabits per second, (Mb/s)), a 12% reduction from 23.3 KBI. Since tape recorder noise power in the bit synchronizer passband is greater at 120 IPS than 30 IPS a reduction in bit packing should be expected. Variations in bit synchronizers resulted in bit packing densities from 21 to 23 KBI at 30 IPS on tape recorder A and from 19 to 21 KBI at 120 IPS (see Table 3).

Bi-Ø bit packing density was found to be fairly insensitive to tape recorder bandwidth changes. A 20% decrease in UBE at 30 IPS resulted in slightly less than a 5% loss in bit packing. A 20% increase in UBE produced no change in bit packing. At 120 IPS, a 25% decrease in UBE had no effect on bit packing whereas a 25% increase caused an 11% decrease in bit packing.

Reference to the power spectral density of a normalized 700 kb/s Bi-Ø signal in figure 3 for 30 IFS shows considerable signal energy beyond the UBE tape recorder bandwidth. Note the energy lost and gained for the ±20% bandwidth changes at 30 IPS. It might therefore be expected that an increase in tape recorder bandwidth would improve Bi-Ø bit packing and that a decrease in bandwidth would degrade the bit packing. Since bandwidth was observed to cause little change, other factors are affecting Bi-Ø bit packing density. The most significant factor is probably noise. The noise power to the bit synchronizer changes with tape recorder bandwidth. Figure 4 illustrates the noise characteristics of tape recorder A for the three bandwidths tested at 30 IPS. A decrease in bandwidth from UBE causes a reduction in signal phase and amplitude margins (references 1 and 2) such that bit detection is more sensitive to noise. The noise power, however, is also reduced and as a result does not begin to significantly affect bit packing until tape recorder bandwidth is reduced by approximately 20% of UBE. An increase in bandwidth will improve signal phase and amplitude margins but also increases the noise power. Consequently, bit packing does not increase or decrease significantly for less than a 20% increase in bandwidth.

Changing the bias level to 0 dB seemed to have no effect on bit packing at 120 IPS but at 30 IPS a 3% increase from 23.3 KBI occurred. Furthermore, the bit packing at 30 IPS with 0 dB bias increased to 25.9 KBI at a 600 kHz bandwidth before it began to roll off with further increases in bandwidth. It was found that the tape recorder could not be aligned to within IRIG specifications for -1 dB bias and that 5 dB bias, while difficult to align, caused significant reduction in bit packing. The effect of too little bias was signal loss and distortion of the lower signal frequencies. Too much bias reduced high-frequency signal energy and increased high-frequency phase distortion.

The tape recorder reproduce level did not affect bit packing for levels below 2.0 Vrms so long as the bit synchronizer remained in synchronization. Above 2.0 Vrms the reproduce amplifier went into saturation and the bit packing dropped by as much as 10% for some levels. This result was observed at both 30 and 120 IPS. The record level did not significantly change the bit packing for levels below 1.25 Vrms. As a general rule, above 1.25 Vrms the bit packing dropped as the record level increased. Signal distortion gradually increased for levels above 1.0 Vrms from either record amplifier or magnetic saturation. Sine wave third harmonic distortion was measured to be 2.5% at a record level of 1.25 Vrms and 9% at 2.0 Vrms. Similar results for record and reproduce level tests were observed from DM and NRZ. An 8% reduction from 23.3 KBI occurred in Bi-∅ bit packing for a 2.0 Vrms record level.

It should be noted that, as test parameters such as bandwidth and reproduce and record levels were varied, small changes in bit packing density were equivalent to several orders of magnitude change in BEP. For example, in the Bi-∅ record level test at a record level of 1 Vrms, the BEP was 10^{-6} and bit packing density was 23.3 KBI; at a record level of 1.5 Vrms, the BEP increased to 10^{-3} and the bit packing density decreased less than 2%. The BEP of Bi-∅ was much more sensitive to these parameters than either DM or NRZ.

Crossplay between tape recorders A and B produced some interesting results. A 700 kb/s Bi-∅ signal recorded and reproduced at 30 IPS on tape recorder A produced a BEP of 10^{-6}. The same signal reproduced on tape recorder B produced a BEP of 10^{-2}. It was not until a 610 kb/s (20.3 KBI) Bi-∅ signal was recorded on A that B reproduced a signal with a BEP of 10^{-6}. This amounts to a 13% reduction in bit packing for equivalent data quality. At 120 IPS, a 2.5 Mb/s Bi-∅ signal recorded and reproduced on tape recorder A resulted in a BEP of 10^{-6} whereas reproduction on B produced a BEP greater than 10^{-2}. Reducing the recorded bit rate on A to 2.2 Mb/s (18.3 KBI) gave a reproduced BEP of 10^{-6} on B. This amounts to a 12% reduction in bit packing for equivalent data quality.

For tapes reproduced on tape recorder B, only the azimuth was adjusted for maximizing the signals high frequency levels. However, even with azimuth adjusted for maximum signal level, it was observed that crossplay resulted in high-frequency signals being attenuated. Equalizer adjustments could have been made to boost the signal’s high-frequency components, but this amplification, as seen later, served only to increase BEP by increasing noise and possibly introducing phase distortion. The reduction in performance of tape recorder B was mainly attributed to its lower SNR.

When a Bi-∅ signal was recorded on tape recorder B and played back on A, reproduce amplifier equalization was attepmted to boost attenuated high frequency signals even after azimuth was adjusted. For the azimuth adjustment only, a 610 kb/s Bi-∅ signal at 30 IPS producing a BEP of less than 10^{-6} on tape recorder B produced no errors on A. A 700 kb/s signal producing a BEP of 10^{-2} on tape recorder B produced a BEP of 10^{-4}, on A. At 120 IPS, a 2.2. Mb/s signal produced a BEP of 10^{-6} on B and no errors on A. A 2.5 Mb/s signal produced greater than 10^{-2} BEP on B and a 10^{-6} BEP on A. The 6 dB difference in SNR of the tape recorders seems to be the main factor. Equalization of tape recorder A was attempted to increase signal bandwidth lost in crossplay by boosting the signal’s high frequency levels. The equalizer adjustment increased the BEP to 10^{-1} at 2.5 Mb/s, and a 20% reduction in bit rate was required to reduce the BEP to 10^{-4}. The increase in noise power to the bit synchronizer and possible phase distortion introduced by increasing the equalizer gain was thought to be the cause of degradation.

Because of the lack of a d.c. component in Bi-0, the code avoids low frequency response problems of tape recorders. Bi-0 is limited by its high frequency response, therefore all “1’s” and all “0’s” bit patterns producing square waves with frequency equal to the bit rate were tested. A bit rate of 760 kb/s at 30 IPS and 2.8 Mb/s at 120 IPS was found for both patterns at a BEP of 10^{-6}. This improvement in bit rate over PN Bi-0 was due to changes in spectral energy distribution. Arbitrary one-zero patterns gave results close to those obtained with the PN sequence.

Delay Modulation Results. The bit packing density of DM at 30 IPS with tape recorder/reproducer A and bit synchronizer 1 was found to be 38.3 KBI (1.15 Mb/s) and at 120 IPS was found to be 36.7 KBI (4.4 Mb/s), a 4% reduction. Variations in bit packing density with bit synchronizers ranged from 17 to 38 KBI on tape recorder A at 30 IPS and from 17 to 37 KBI at 120 IPS.

DM bit packing was found to be much more sensitive to tape recorder bandwidth changes than either Bi-0 or NRZ. A 20% decrease in UBE at 30 IPS resulted in a 13% reduction from 38.3 KBI in bit packing whereas a 20% increase in UBE caused a 26% reduction in bit packing. At 120 IPS, a 25% decrease in UBE resulted in an 11% decrease from 36.7 KBI and a 25% increase in UBE caused a 30% decrease. For a ±10% change in tape recorder bandwidth at 30 IPS, a 1.5% decrease in bit packing occurred for the decreased bandwidth and a 9% decrease in bit packing occurred for the increased bandwidth. Figure 5 indicates, for a normalized 1.15 Mb/s DM bit rate and 500 kHz BW at 30 IPS, that most of the DM signal energy lies below the UBE tape recorder bandwidth. The 20% bandwidth reduction at 30 IPS cuts off significant signal energy, much more than experienced by Bi-0. However, the reduction in tape recorder noise is essentially the same as the Bi-0 case, thus the bit packing density of DM might readily be expected to have a larger percentage change than that of Bi-0. Increasing the tape recorder bandwidth by 20% serves only to increase the noise for a small increase in total signal power. It is the compacting of DM spectral energy that makes its bit packing density more sensitive to bandwidth changes.

DM was also more sensitive to bias level than either Bi-0 or NRZ. A 17% reduction in bit packing occurred when the bias was changed from 2 dB to 0 dB at 30 IPS. A 9% reduction occurred at 120 IPS.

DM crossplay tests at 30 IPS for a 1.15 Mb/s bit rate recorded on tape recorder A produced a BEP of 10^{-6} on A and a BEP of approximately 10^{-3} on tape recorder B. Reducing the recorded bit rate to 0.81 Mb/s gave zero BEP on A and a 10^{-6} BEP for tape recorder B reproduction. This is approximately a 30% decrease in bit packing from 38.3 KBI for maintenance of data quality. A 33% reduction in bit packing density from 36.7 KBI was observed at 120 IPS for data recorded on A and reproduced on B.

A 0.8 Mb/s DM signal recorded on B at 30 IPS produced a BEP of 10^{-6} on B and zero BEP on A. The recorded bit rate on B was increased to 1.1 Mb/s where a BEP of 10^{-5} was obtained on A. At 120 IPS , a 3.0 Mb/s bit rate recorded on tape recorder B produced a BEP of 3 x 10^{-6} on B and zero BEP on A. The recorded bit rate on B was increased to 3.8 Mb/s where A produced a BEP of 5 x 10^{-6}. An equalizer adjustment was again made to boost the high frequency level of the signal which was attenuated by crossplay. This adjustment in reproduce amplifier gain increased the noise power to the bit synchronizer and possibly introduced high frequency phase distortion. The BEP at 3.8 Mb/s increased to 10^{-2} and for a BEP of 10^{-6} the bit rate was reduced to 2.7 Mb/s.

While the DM energy spectrum of figure 5 shows low d.c. content for a PN sequence, DM is capable of large d.c. components. The "101101101.." code maximizes DM d.c. content. For this pattern 1/3 of the signal energy is at d.c. Equipment limitations did not permit testing of this code, however, a repetitive 16 bit code with 1/4 of the signal energy at d.c. was tested. The 16 bit code was "1101101101101010." At 30 IPS using this pattern the bit rate was reduced by 33% from that rate obtained using a PN sequence; at 120 IPS, the bit rate was reduced by 30% from the PN rate. Bit synchronization was unstable for all one and all zero bit patterns because they lacked the 101 synchronization pattern required for DM. A fifteen bit "1" and one bit "0" pattern was tested instead (1111111111111110); this code provided stable synchroniation but reduced the bit rate to 4.1 Mb/s, a 7% reduction from the PN bit rate.

NRZ Test Results. Since odd parity-NRZ is the addition of a parity bit after every seven data bits, the odd parity-NRZ bit rate is 8/7 that of the NRZ bit rate. This amounts to a 14% increase in bit rate for the same data transfer. Bit packing density and bit rate results of odd parity-NRZ will be the same as for NRZ except that the data rate is cut by 14%. Thus when speaking of odd parity-NRZ bit packing density or bit rate, the true data rate will be used instead. Odd parity-NRZ results are derived from the PN NRZ results.

PN NRZ gave better bit packing than either Bi-0 or DM. The bit packing density of PN NRZ at 30 IPS was 41.0 KBI (1.23 Mb/s) and at 120 IPS was 38.3 to 40.8 KBI (4.6 to 4.9 Mb/s). For odd parity-NRZ this amounts to an information rate of 1.06 Mb/s (36.3 KBI) at 30 IPS and 3.96 to 4.2 Mb/s (33 to 35 KBI) at 120 IPS. Once again different bit synchronizers caused large changes in bit packing. A range from 33 to 41 KBI was observed with bit synchronizers on tape recorder A at 30 IPS and from 31 to 41 KBI at 120 IPS (see Table 3).

NRZ bit packing was more sensitive to tape recorder bandwidth changes than Bi-0 but less sensitive than DM. A 20% decrease in UBE at 30 IPS, reduced the bit packing 11% from 41 KBI, whereas increasing the UBE 20% raised the bit packing 1.6%. Increasing the UBE 10%,produced a PN NRZ bit packing density of 43.0 KBI at 30 IPS. At 120 IPS, a

25% decrease in UBE reduced the bit packing by 14% from 40.8 KBI and a 25% increase in UBE reduced the bit packing 16%.

The PN NRZ spectrum for a normalized 1.23 Mb/s signal at 30 IPS is shown in figure 6. Despite the fact that noise power was reduced for a tape recorder bandwidth 20% less than UBE, the signal phase and amplitude margins were also reduced such that noise still caused a significant reduction in bit packing. For bandwidths larger than 120% of UBE, the increased noise power was enough to reduce bit packing even though phase and amplitude margins were improved.

NRZ was also more sensitive to bias changes than Bi-0 but less sensitive than DM. NRZ showed only a 3% loss in bit packing at 0 dB bias for 30 IPS and a 10% loss at 120 IPS. Sensitivity to record and reproduce levels was the same as for Bi-0 and DM. Record levels below 1.25 Vrms did not significantly change NRZ bit packing (i.e. the bit packing remained very nearly at 41.0 KBI for 10^{-6} BEP). Higher record levels drastically reduced bit packing. A 1.5 Vrms record level at 120 IPS reduced the NRZ bit rate to 3.8 Mb/s for 10^{-6} BEP, a 22% loss in bit packing density due to signal distortion.

NRZ crossplay tests showed more reduction in data quality for data recorded on tape recorder A and reproduced on B than did Bi-0 and DM. A 1.23 Mb/s NRZ bit rate of 30 IPS had a BEP of 10^{-6} when reproduced on tape recorder A and a BEP on 10^{-3} when reproduced on B. Reduction of the bit rate to 0.95 Mb/s gave a BEP of 10^{-6} on tape recorder B. At 120 IPS the bit rate was reduced to 4.1 Mb/s from 4.6 Mb/s on A to obtain equivalent data quality on B. These results are mainly attributed to the SNR difference between tape recorders.

A 1.1 Mb/s NRZ bit rate recorded on tape recorder B gave a BEP of 10^{-6} when reproduced on B and a BEP of 10^{-5} when reproduced on A. This departure from an increase in data quality when reproduced on tape recorder A, as exhibited by Bi-0 and DM, indicates some unknown factors are reducing the NRZ data quality which did not affect Bi-0 And DM. These factors became quite significant at 120 IPS where a recorded bit rate of 4.2 Mb/s on tape recorder B resulted in a BEP of 10^{-6} when reproduced on tape recorder B and a BEP of 10^{-2} when reproduced on tape recorder A. Reducing the bit rate to 3.8 Mb/s and adjusting the reproduce equalizer gain of tape recorder A gave a BEP of 10^{-6}. NRZ seems to be more susceptible to crossplay effects than either DM or .

Odd parity-NRZ can result in a maximum string of 14 ones (0111111111111110). The d.c, content of this pattern is 3/4 of the signal energy. This sequence resulted in a bit rate of only 0.35 Mb/s (11.7 KBI) at 30 IPS and 0.9 Mb/s (7.5 KBI) at 120 IPS. These are very significant reductions from rates obtained using PN NRZ. A 1111111011111110 pattern, 3/4 d.c. content, gave identical results. An NRZ pattern with 1/4 of the signal energy at d.c. (1101101101101100) gave a bit rate of 1.7 Mb/s (56.7 KBI) at 30 IPS and 4.8 Mb/s (40 KBI) at 120 IPS. A pattern with the same d.c. content, 1111111111000000, gave a 5.1 Mb/s rate (42.5 KBI) at 120 IPS.

Randomized-NRZ bit packing was identical to PN NRZ results. The BEP of derandomized NRZ was three times worse than the BEP of the randomized-NRZ when reproduced from the tape recorder due to error multiplication of the derandomizer. This increase in BEP resulted in no detectable change in bit packing density. Thus performance of randomized-NRZ was very nearly equivalent to that of PN NRZ. Randomized-NRZ was almost completely insensitive to d.c. content of the nonrandomized data and no change in bit packing density was observed for any bit patterns. The exception was an all “1’s” or all “0’s” pattern for which synchronization problems occurred.

Conclusions. The results show that, under nearly identical conditions, randomized-NRZ offers the best performance in terms of bit packing density. PN NRZ bit packing (equivalent to randomized-MG) ranged from 31 to 41 KBI (Table 3), odd parity-NRZ ranged from 26 to 35 KBI, DM ranged from 17 to 38 KBI, and Bi-0 ranged from 18 to 23 KBI. However, d.c. content of DM and odd parity-NRZ can drastically reduce the bit backing density. Data in Table 3 under bit synchronizer 1, tape recorders A and B, indicate that odd parity-NRZ performs better than DM under the lower SNR conditions of tape recorder B (due to amplitude and phase margin characteristics) and performs worse than DM for tape recorder A. The codes under test showed different degrees of bit packing sensitivity to tape recorder bandwidth, tape speed, bias level, record and reproduce levels, bit patterns, bit synchronizers, and crossplay between tape recorders. Bi-0 bit packing showed the least variance to these parameters (except in tape speed) followed by NRZ and DM in that order. Two of the more significant parameters, with regard to DM and NRZ were bit synchronizers and tape recorder SNR. Bit synchronizer performance can be a major limiting factor in bit packing for direct recording of PCM and, between the two tape recorders, a significant bit packing difference was found due to SNR.

It should be emphasized that the experimental results are for comparative purposes only and in no way suggests that the bit packing densities obtained should be used in practice. Crossplay between tape recorders and changes in tape recorder bandwidth, tape speed and bias level, can result in several orders of magnitude change in BEP for the high bit packing densities observed. Consequently, reproduction of high bit rates on another tape recorder or even on the same tape recorder can yield data with large error rates. Crossplay results show that bit packing densities must be reduced substantially in order to maintain good data quality in reproduction on different machines. Future testing will be done to determine practical bit packing densities as determined by BEP sensitivity to crossplay, tape recorder bandwidth, bias level, bit patterns, and record and reproduce levels and a report will be published at that time.

References.

1) W. N. Waggener, “PCM Code Selection for Bandlimited Transmission and Tape Recording,” EMR Technical Memorandum.

2) Bell and Howell Company, “Practical Considerations for Selection of High Density Magnetic Recording Codes,” Proposal to IRIG Committee Conference, Albuquerque, New Mexico, 24 July 1975.

3) J. A. McDowell, et. al., “Channel Coding for Digital Recording,” IEEE Trans. Magn., Vol, MAG-10, pp. 515-518, Sept 1974.

Note: Later bit pattern tests for effect of maximum d.c. offset on odd-parity NRZ using bit synchronizers 2 and 4 and recorder A showed only a 10% to 20% degradation in bit packing density versus bit packing density for pseudorandom odd-parity NRZ. This is a much smaller degradation than with bit synchronizer 1 which gave a 70% reduction. Bit pattern tests with DM on bit synchronizers 2 and 4 gave nearly identical results to the previous data of bit synchronizer 1.

PARAMETER UNDER TEST

		BANDWIDTH	BIAS	REPRODUCE LEVEL	RECORD LEVEL	BIT PACKING DENSITY	BIT PATTERNS	CROSSPLAY	BIT SYNCHRONIZER TEST
Status of Other Parameters*	Bandwidth	Varied ±20% of UBE	UBE	UBE	UBE	UBE	UBE	UBE	400 Hz to 500 kHz
	Bias (dB)	0 and 2	0,2	2	2	2	2	2	
	Record Level (Vrms)	1.0	1.0	1.0	Varied from .5 to 4.0	1.0	1.0	1.0	Input to filter was varied .5 to 4.0.
	Reproduce Level (Vrms)	1.0	1.0	Varied from .5 to 2.5	1.0	1.0	1.0	1.0	
	Tape Speed (IPS)	30;120	30;120	30;120	30;120	30;120	30;120	30;120	
	Bit Synchronizer	1	1	1,2,3	1,2,3	1,2,3,4 and Randomizer/ Derandomizer	1 and Randomizer/ Derandomizer	1	1,2,3,4
	Tape Recorder	A	A	A	A	A,B	A	A,B	400 Hz to 500 kHz Bessel or Butterworth Bandpass Filter

* When a paramter other than the one under test has multiple values, this indicates a repetition of the test for all values of that other parameter.

Table 1 Test Conditions

		Bessel Filter								Butterworth Filter					
	Bit Synchronizer	1		2		3		4		1		2		3	
		BR* Mb/s	BPD** KBI	BR Mb/s	BPD KBI	BR Mb/s	BPD KBI	BR Mb/s	BPD KBI	BR Mb/s	BPD KBI	BR Mb/s	BPD KBI	BR Mb/s	BPD KBI
PCM CODE	NRZ	2.3	77	2.2	73	2.3	77	1.5	50	1.5	50	1.5	50	1.6	53
	DM	2.2	73	1.6	53			0.72	24	1.5	50	0.9	30		
	Bi-Ø	2.1	70			2.1	70	1.4	47	0.8	27			0.8	27

* Bit rate

** Equivalent bit packing density for 30 IPS tape recorder bandwidth.

Table 2 Bit Synchronizer Test Results

	Tape Speed (IPS)	30								120							
	Bit Synchronizer	1				2	3	4	Derandomizer	1				2	3	4	Derandomizer
	Tape Recorder	A	B	Recorded A Playback B	Recorded B Playback A	A	A	A	A	A	B	Recorded A Playback B	Recorded B Playback A	A	A	A	A
PCM CODES*	NRZ	41.0	36.7	31.7	33.3	38.7	41.0	33.3		38.3 to 40.8	35.0	34.2	31.6	37.5	38.3	30.8	
	Odd-Parity NRZ	35.3	31.6	27.3	28.6	33.3	35.3	28.6		35.0	30.1	29.4	27.2	32.3	32.9	26.5	
	Randomized-NRZ								41.0								40.8
	DM	38.3	26.7	27.0	36.7	25.0		16.6		36.7	25.0	23.3	31.7	16.6		17.2	
	Bi-Ø	23.3	20.3	20.3	23.3		22.7	21.6		20.6	18.3	18.3	20.8		19.2	20.2	

* Results are with pseudo-random bit sequences.

Table 3 Summary of Bit Packing Density Results in KBI

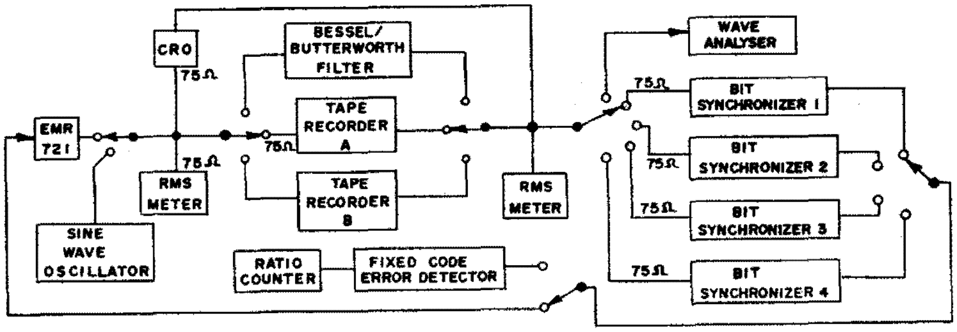

Figure 1A Test Configuration

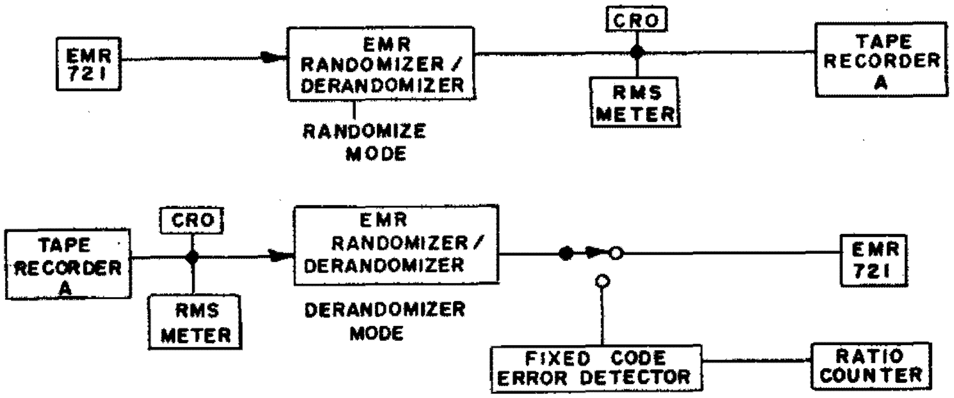

Figure 1B Randomized-NRZ Test Configuration

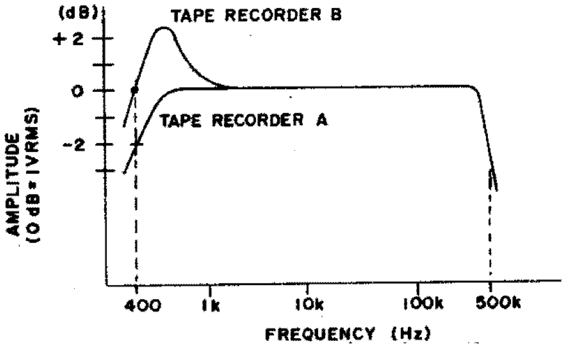

Figure 2A Tape Recorder Frequency Response at 30 IPS

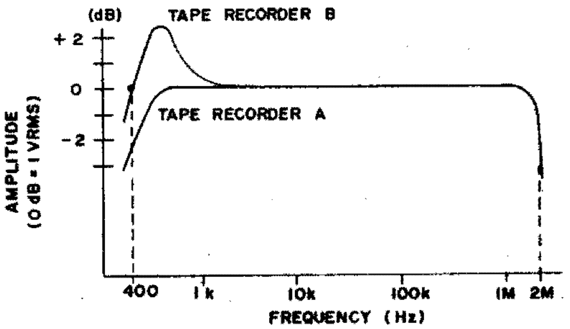

Figure 2B Tape Recorder Frequency Response at 120 IPS

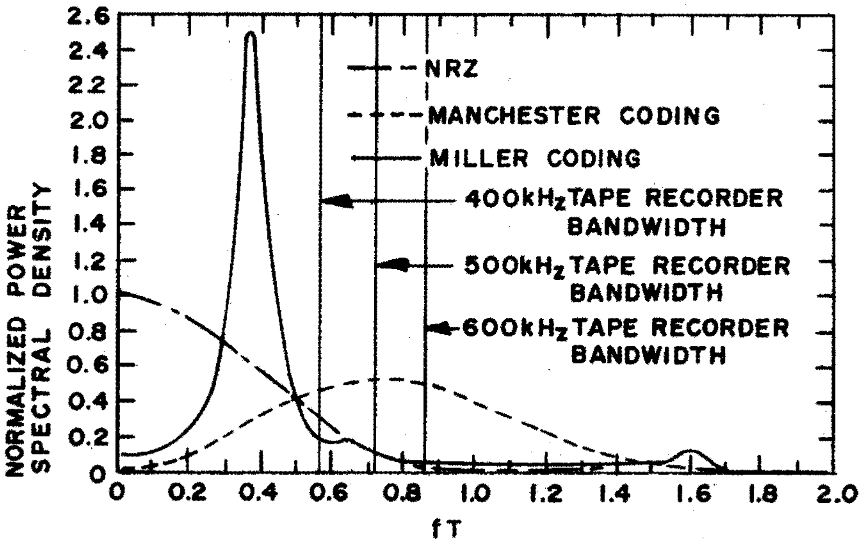

Figure 3 Spectral Density of Random NRZ, Bi-Ø and DM Codes with Respect to Tape Recorder Bandwidth at 30 IPS. (Normalized for 0.7 Mb/s)

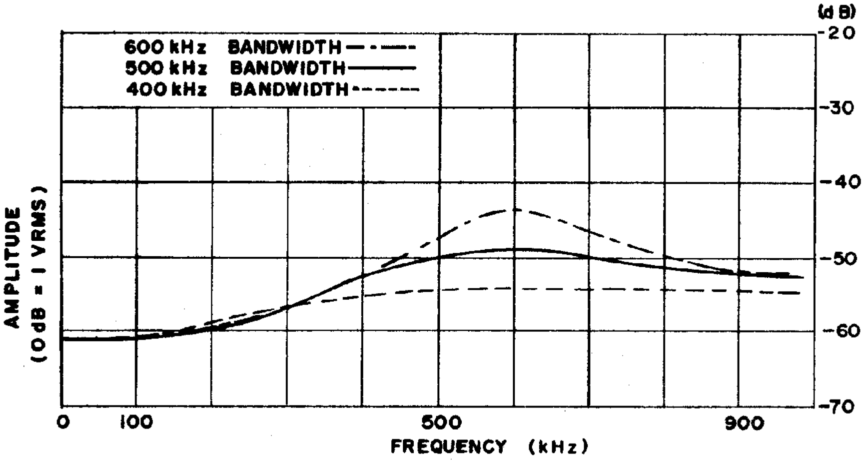

Figure 4 Noise Characteristics of Tape Recorder "A" at 30 IPS

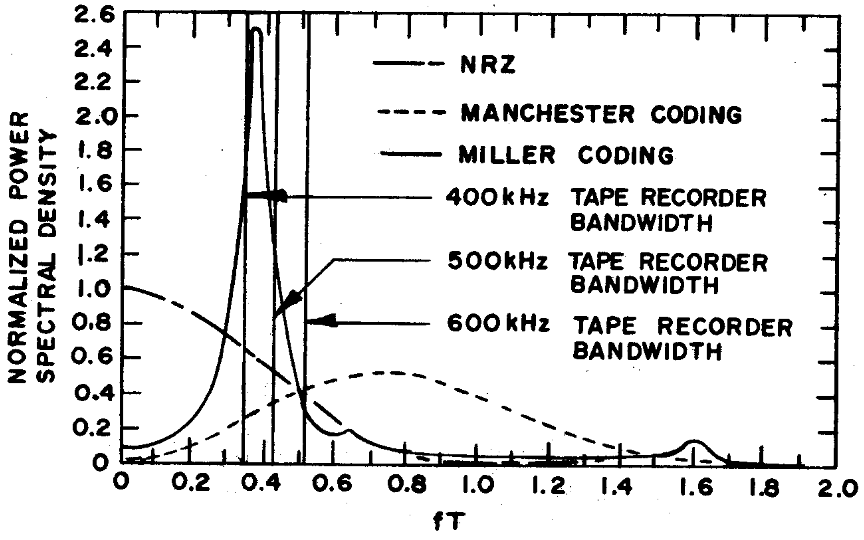

Figure 5 Spectral Density of Random NRZ, Bi-0 and DM Codes with Respect to Tape Recorder Bandwidth at 30 IPS. (Normalized for 1.15 Mb/s)

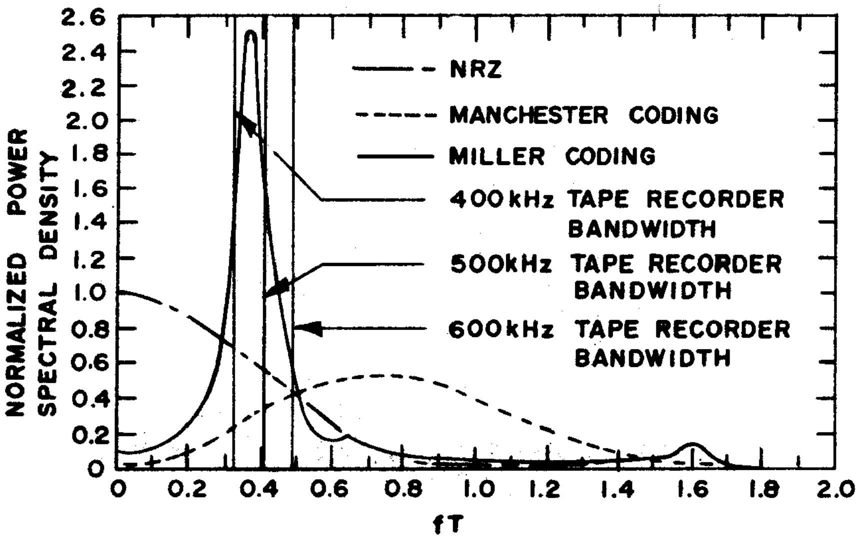

Figure 6 Spectral Density of Random NRZ, Bi-O and DM Codes with Respect to Tape Recorder Bandwidth at 30 IPS. (Normalized for 1.23 Mb/s)