SERIAL HIGH DENSITY DIGITAL RECORDING USING AN ANALOG MAGNETIC TAPE RECORDER/REPRODUCER

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ABSTRACT

A great deal of interest is being generated in the area of high density digital recording (HDDR) because of the need to record high rate digital signals. This paper presents the results of a study where digital data was recorded on ordinary analog magnetic tape recorder/reproducers using several of the currently popular codes. It is shown that bit packing densities of 25 kilobits per inch (or higher) are achievable with analog wideband 2.0 MHz recorder/reproducers.

INTRODUCTION

Time division multiplex telemetry data has usually been recorded by pre-detection techniques. However, the maximum pulse code modulation (PCM) bit rate that can be recovered from a 900 KHz pre-detection carrier (highest standard frequency at 120 inches per second (in/sec)) is only slightly over 1.0 megabit per second (Mb/sec) for non-return-to-zero level (NRZ-L) data. Therefore, in order to record higher data rates the user has to either use a higher tape speed than 120 in/sec or use HDDR. The maximum tape speed currently available is about 240 in/sec which limits the NRZ-L data rate to about 2.0 Mb/sec and also uses 20 feet of tape per second. Dedicated HDDR systems can record 4 Mb/sec at 120 in/sec which yields four times as many data bits per lineal inch of tape as pre-detection recording. The Pacific Missile Test Center (PACMISTESTCEN) has previously reported on the maximum bit packing densities achievable with various codes[1] and the signal-to-noise ratio (SNR) required to get a 10^{-6} bit error probability (BEP) for various data rates and various codes[2]. This paper reports on the bit error probabilities of PCM data recorded on six tracks of one machine and reproduced on either the same machine or a different machine. The tape machines and bit synchronizer are typical of hardware in existence at the various National Ranges and elsewhere. The codes included

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in this paper are randomized NRZ-L (RNRZ-L), NRZ-L, delay modulation (DM), and bi-phase-level (Biϕ-L). These codes were selected because the last three are available as outputs of most commercial bit synchroizers and previous studies[1,2] have shown good performance with RNRZ-L. The Miller Squared and odd-parity NRZ-L codes also perform well but were not included because the Miller Squared code is not available on commercial bit synchronizers and the odd-parity NRZ-L code is somewhat more difficult to implement and its performance is greatly influenced by the DC restorer used. The data patterns were a 2047-bit pseudo random (PR) sequence and a 6-bit ramp with each value repeated 256 times[3]. All the data was taken using an Electro Mechanical Research (EMR) Model 720 PCM bit synchronizer.

TEST DESCRIPTION

A block diagram of the test set-up for recording the data is shown in Figure 1A. The NRZ-L data source generated either a 2047-bit PR sequence or a 6-bit ramp with each 6-bit word repeated 256 times. The NRZ-L data was then either sent over a simulated radio frequency (RF) link or when that was not feasible the data was sent directly to the encoding hardware. The NRZ-L data was then either converted to DM or Biϕ-L, randomized, or not modified. Next, the data was buffered and the same data was recorded on 6 tracks of a 7-track 1/2 inch analog recorder using standard analog recording techniques (2 dB overbias for wide-band 2.0 MHz and 1 volt rms record level). The output of the recorder/reproducer was monitored on an oscilloscope. Data were recorded on both wideband 1.5 MHz and wideband 2.0 MHz recorder/reproducers. Descriptions of the three recorder/reproducers used in this study are:

Recorder/reproducer A - Wideband 2.0 MHz machine usually used in experimental studies in a laboratory environment. This machine is the same as machine A in reference (1).

Recorder/Reproducer B - Typical wideband 1.5 MHz machine used for recording telemetry data during range operations at the PACMISTESTCEN. This machine was not “tweaked up” to record the HDDR data but was used “as is.” It is usually used to record predetection telemetry data.

Recorder/Reproducer C - Wideband 2.0 MHz machine usually used for data playback. This machine was also used “as is” and is also usually used with analog data.

A swept frequency signal was recorded on the leader of each tape to aid in azimuth alignment.

The tapes used in this study (Ampex 786 and Ampex 795) had a basic error probability of between better than 10^{-7} and better than 10^{-9} depending on the particular tape and track. The errors caused by severe dropouts were not included in the test results because they are mostly a random tape phenomena and not a code phenomena. However, very few severe dropouts were encountered in this study. The edge tracks had about one severe dropout per 3000 feet of tape and the center tracks had very few severe dropouts. The basic data quality was at least an order of magnitude better on the center tracks than on the edge tracks for a packing density of 25 kilobits per inch (Kb/in) and PR NRZ-L data.

The randomizer[2] used in this study was a 17-stage device. The output has a nearly random distribution of "ones" and "zeros" for most inputs. The randomizer can output a long string of "ones" (or "zeros") if the register is loaded with all "ones" (or "zeros") when a long sequence of "ones" (or "zeros") starts. The output will have 17 more consecutive "ones" (or "zeros") than the input. The output will return to normal when the input does. The probability of this happening for a normal data stream is 2^{-17} times the probability of a long run of "ones" plus the probability of a long run of "zeros". A test was performed to see how often this happened for a 6-bit ramp with each 6-bit word repeated four times. It was discovered that the resulting data had three mutually exclusive modes of operation:

1. There was about a 0.5 probability that no long runs (longer than 23) of "ones'. or "zeros" would appear.

2. There was about a 0.25 probability that a run of 41 "ones" would occur every 6×10^7 bits.

3. There was about a 0.25 probability that a run of 46 "zeros" would occur every 6×10^7 bits.

The different lengths of runs for "ones" and "zeros" are caused by the fact that the input has one run of 24 "ones" and one run of 29 "zeros" every 1536 bits., The expected result was a run of 41 "ones" and a run of 46 "zeros" every 2×10^8 bits. However, the ramp data is very non-random and the run of "zeros" immediately follows the run of "ones" so it is not surprising that the result is not the result that was predicted from the assumption of random data. It is believed that the possible runs of "ones" and "zeros" will not cause any problems with actual telemetry data at tape speeds of 7.5 in/sec and above. The runs can be detected and stopped by inverting one bit in the register and the recorded data stream. This does introduce one bit error but is a standard feature of the latest Sangamo randomized HDDR systems.

TEST RESULTS

A representative sample of test results is presented in Tables I, II, III, and IV. The data playback test set-up is shown in Figure 1B. The data are grouped by bit error probability for a given set of test conditions. The bit error probability groupings are:

10^{-7} means	BEP $\leq 10^{-7}$
10^{-6} means	10^{-7} < BEP $\leq 10^{-6}$
10^{-5} means	10^{-6} < BEP $\leq 10^{-5}$
10^{-4} means	10^{-5} < BEP $\leq 10^{-4}$
10^{-3} means	10^{-4} < BEP $\leq 10^{-3}$
Bad Track means	BEP $\leq 10^{-3}$

The code, packing density, bit pattern, record machine, and playback machine are given for each group of data. The playback tape speeds are listed with the record tape speed designated by the asterisk.

The data in Tables I, II, and III show that a bit error probability of 10^{-6} or better can be achieved with RNRZ-L or PR NRZ-L at a packing density of 25 Kb/in. for tape speeds of 7.5 in/sec to 120 in/sec with a wideband 2.0 MHz recorder and reproducer . This result was achievable in all cases where the tape recorder/reproducer electronics were working properly. The two exceptions in Table I were due to severe reproduce electronics problems. This data also shows that more than one-half of the tracks gave BEPs of less than 10^{-6} with PR NRZ-L at 33.3 Kb/in. The performance of PR NRZ-L and RNRZ-L at 3.75 in/sec was poor at any packing density (BEP of 10^{-6} could not be achieved on any track of any recorder/ reproducer tested). The data in Table IV show that a BEP of better than 10^{-6} at a packing ,density of 20 Kb/in with PR NRZ-L is achievable on most tracks if data is recorded on a wideband 1.5 MHz machine and played back on a wideband 2.0 MHz machine. One track of recorder B was found to be badly overbiased. This plus the previously mentioned problems with the reproduce electronics of machine A account for the bad tracks. A BEP of better than 10^{-6} was achievable at 25 Kb/in with PR NRZ-L and RNRZ-L on about one-half of the tracks.

The data in Tables I, II, and III show that DM gives a bit error probability of 10^{-6} or better on most tracks at a packing density of 20 Kb/in. The exceptions were tracks which had either a low SNR or poor phase characteristics. Since DM has mid-bit transitions it is more sensitive to phase distortion and low SNR than NRZ[4]. DM also performed well at a packing density of 25 Kb/in on more than one-half of the tracks. The data in Table IV show that DM gives a BEP of better than 10^{-6} on most tracks at 16.7 Kb/in when the PCM data is recorded on a wideband 1.5 MHz machine and played back on a wideband 2.0 MHz machine.

The data in Tables II, III, and IV show that Biφ-L works well at a packing density of 16.7 Kb/in for both wideband 1.5 MHz and wideband 2.0 MHz machines. Biφ-L was also the only code which gave good results (BEP $\leq 10^{-6}$) at a speed of 1.875 in/sec. However, DM performed slightly better (higher packing density for 10^{-6} BEP) than Biφ-L at 3.75 in/sec. Randomized NRZ-L might work at the lower tape speeds if the DC restorer was optimized for this condition.

Overall, DM appears to perform as well as NRZ if the DM packing density is about 80% of the NRZ packing density. The relative performance is a function of the "goodness" of the phase equalization, the SNR and the amplitude equalization. If the amplitude equalization is adjusted so that the amplitude is about 5- to 6-dB down at the upper bandedge, DM performs almost as well as NRZ (more than 90% as high packing density for 10^{-6} BEP). This agrees with the data in Table 3 of reference (1) with tape recorder A. References (1) and (2) show that DM gives a packing density of 50% to 110% of NRZ depending on the test conditions. The 80% nominal value of this report falls in the middle of the above extremes. The recommended packing densities of 25 Kb/in for NRZ, 20 Kb/in for DM, and 16.7 Kb/in for Biφ-L are approximately 80% of the lowest "best track" values of reference (1). These values are also between 60% and 70% of the values at a 22 dB SNR in Figure 4 of reference (2). Since reference (1) dealt with the best track performance and reference (2) replaced the tape recorder by a linear phase bandpass filter, the results of this paper correlate reasonably well with the previous results. A technical report which will include the results of all of these studies plus additional crossplay data will be published by the PACMISTESTCEN in 1979.

SUMMARY

It has been shown that good HDDR performance (bit error probability of less than 10^{-6}) can be achieved with existing range equipment for packing densities of 25 Kb/in for RNRZ-L, 20 Kb/in for DM, and 16.7 Kb/in for Biφ-L. These results can be achieved with the following set of constraints:

1. Use of a wideband (2.0 MHz) recorder/reproducer system set-up to Inter-Range Instrumentation Group (IRIG) standards for analog recording.

2. Tape speeds of 7.5 to 120 inches per second.

3. Conditioning of the reproduced bit stream from the recorder/reproducer with a good, commercially available bit synchronizer such as an Electromechanical Research (EMR) model 720 or its equivalent.

4. Crossplay between recorder/reproducer systems as with analog signal crossplay.

5. Good quality commercially available wideband magnetic tape.

6. Phase equalizers in the reproduce electronics of the recorder/reproducer systems.

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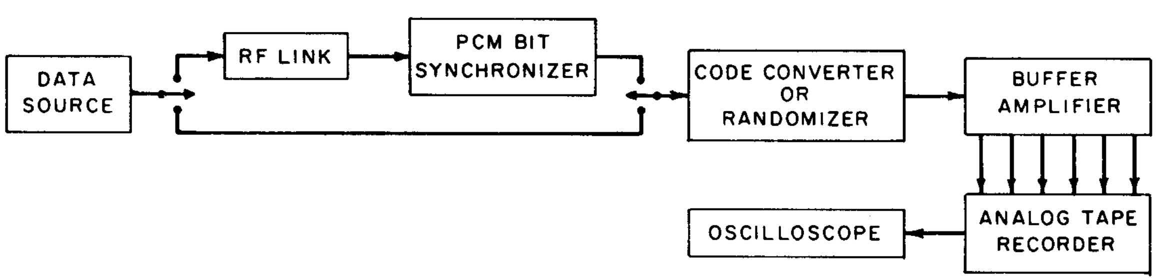

FIGURE 1A. TEST SET-UP FOR DATA RECORDING

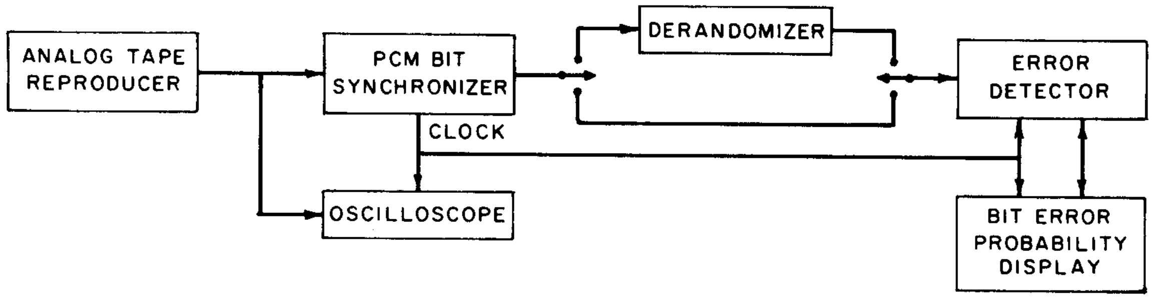

FIGURE 1B. TEST SET-UP FOR DATA PLAYBACK

TABLE 1. FREQUENCY BREAKDOWN OF BIT ERROR PROBABILITIES FOR DATA RECORDED AND REPRODUCED ON MACHINE A (6 TRACKS)

Parameters	Speed (in/sec)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	Bad Track
33.3 Kb/in NRZ-L 2047-bit PR	120	3	1		1	1	
	60	6					
	* 30	6					
	15	4	1				1
	7.5	2	1	1		1	1
	3.75					3	3
25 Kb/in RNRZ-L 6-bit ramp	120	6					
	60	6					
	* 30	6					
	15	5					1
	7.5	5					1
	3.75				4	2	
20 Kb/in DM 6-bit ramp	120	4	2				
	60	3	2		1		
	* 30	4	1	1			
	15	4				1	1
	7.5	2		2	1		1
	3.75			2		3	1

TABLE II. FREQUENCY BREAKDOWN OF BIT ERROR PROBABILITIES FOR DATA RECORDED ON MACHINE C AND REPRODUCED ON MACHINE A (5 TRACKS)

Parameters	Speed (in/sec)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	Bad Track
33.3 Kb/in NRZ-L	* 120	1	2	1		1	
2047-bit PR	7.5	2	1		1		1
25 Kb/in NRZ-L	* 120	5					
2047-bit PR	7.5	5					
25 Kb/in DM	* 120	2	2			1	
2047-bit PR	7.5	3		2			
20 Kb/in DM	* 120	4				1	
2047-bit PR	7.5	5					
16.7 Kb/in Biϕ-L	* 120	5					
2047-bit PR	7.5	5					

TABLE III. FREQUENCY BREAKDOWN OF BIT ERROR PRO ABILITIES FOR DATA RECORDED AND REPRODUCED ON MACHINE C (4 TRACKS)

Parameters	Speed (in/sec)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	Bad Track
33.3 Kb/in NRZ-L	* 120	4					
2047-bit PR	15					1	3
25 Kb/in NRZ-L	* 120	4					
2047-bit PR	15	4					
25 Kb/in DM	* 120	2			2		
2047-bit PR	15	4					
20 Kb/in DM	* 120	4					
2047-bit PR	15	4					
16.7 Kb/in Biϕ-L	* 120	4					
2047-bit PR	15	2			1	1	

TABLE IV. FREQUENCY BREAKDOWN OF BIT ERROR PROBABILITIES FOR DATA RECORDED ONMACHINE B AND REPRODUCED ON MACHINE A (6 TRACKS

Parameters	Speed (in/sec)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	Bad Track
25 Kb/in NRZ-L	* 120		2	1	1		2
2047-bit PR	30	3			1	1	1
	7.5	3	1				2
25 Kb/in RNRZ-L	* 120		3		1		2
6-bit ramp	30	2	1	1		1	1
	7.5	2	2				2
20 Kb/in NRZ-L	* 120	4		1			1
2047-bit PR	30	5			1		
	7.5	4					2
20 Kb/in RNRZ-L	* 120	2	2		1		1
6-bit ramp	30	4		1		1	
	7.5	3	1				2
20 Kb/in DM	* 120	1	2	1	1		1
2047-bit PR	30	2	3			1	
	7.5	3		1	1		1
16.7 Kb/in DM	* 120	3	1	1		1	
2047-bit PR	30	4	2				
	7.5	3	2	1			
16.7 Kb/in Biϕ-L	* 120		5				1
2047-bit PR	30	5				1	
	7.5	4	1				1