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NAVAL UNDERWATER SYSTEMS CENTER

NEW LONDON LABORATORY

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TECHNICAL MEMORANDUM

THE APPLICATION OF HIGH DENSITY DIGITAL RECORDING TECHNIQUES TO DATA STORAGE REQUIREMENTS

REFERENCE ONLY

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High Density Digital Recording (HDDR), a technical evolution of magnetic tape recording, has the capability of handling data in excess of 100 megabits/second, on a fixed head, multiple track system. This technical memorandum explains the fundamentals of HDDR including clock requirements, error control, and the encoding process. This is intended to be used by personnel at NUSC to assist in determining the best format for their digital data using a given HDDR system or as a guide to the HDDR system to be used when given a data format.

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ADMINISTRATIVE DETAILS

The research for this memorandum was conducted under NUSC Project No. A12218 "Wide Aperture Array", A21071 "Data Record and Playback System for AN/SQS-53C TECHEVAL", and A47022 "SUBACS HDDR".

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INTRODUCTION

This memorandum introduces general principles and applications information about High Density Digital Recording. Program managers, chief engineers, and instrumentating technicians will find it a useful tool in planning for recording of digital data in an R&D effort. The reader should have at least a general background in the use of magnetic tape recorders, since all HDDR systems involve a magnetic recording device as well as a processing device.

There are several technical books on magnetic tape recording basics, such as: Modern Instrumentation Tape Recording by EMI Technology, Magnetic Tape Recording Technical Fundamentals by Datatape Division of Kodak, and The Complete Handbook of Magnetic Tape Recording by Finn Jorgenson, Tab Books.

FUNCTIONAL DESCRIPTION OF A TYPICAL HDDR SYSTEM

The typical HDDR system is represented in Figure 1. Most manufacturers of HDDR equipment generate systems which, in principle, perform the following functions.

FORMATTING

The user data rate and clock frequency determines the combination of tape speed and number of recording channels required. A standard Wideband Direct instrumentation recorder is capable of handling 4 Megabits per channel at 120 inches per second tape speed. The user data may be formatted to utilize more channels for several reasons:

1. The user data rate may exceed 4 Megabits. By formatting to 2 channels, the data rate per channel is one-half the original, or 2 Megabits per channel. A 28 track system could handle 112 Megabits per second (and more in some cases). The user data must be reduced somewhat due to systems overhead, which will be explained later.

2. The user may desire a slower tape speed. The running time of a 9200 foot reel of tape at 120 Inches Per Second (IPS) is 15 minutes. The high cost of magnetic tape and the frequency of attention required to change reels are good reasons for keeping tape speed as low as possible. By formatting to two channels, the tape speed may be reduced to 60 IPS with 30 minutes of running time, or four channels at 30 IPS with one hour of running time, and so on.

3. The user may require the lowest rate of errors possible. Practically, the recording of digital data on magnetic tape will always result in some errors during playback. Since

more errors are predicted at the upper bandedge frequency of the system, formatting of the data to two or more channels lowers the packing density (bits per inch) and yields less errors at a given tape speed.

ENCODING

Although the digital data may be recorded on a direct channel without modifying it, the reproduced data will contain excessive errors, due to the inherent problems of wideband magnetic tape recording. One of these problems involves the clocking of the digital data. Although the data is meaningless without a clock, the clock itself is not recorded on the tape for several reasons. One reason is the clock frequency. In digital recording the system is looking for flux changes, or transitions on the tape from one polarity to another. Up to 33,000 transitions per linear inch can be distinquished by the wideband reproduce head. It takes two transitions or zero crossings to represent the clock, one negative to positive, one positive to negative. So only one-half of the 33,000 transitions can be used for the clock, while each of them could represent one or more data bits, depending upon the rules of the particular encoding method. If the clock had to be recorded on tape, the maximum data rate would only be one-half the amount possible without recording it. If we lowered the data rate in order to record the clock on a separate track, the timing errors between tape tracks is serious enough to render this approach unusable except at perhaps very low data rates.

Therefore, any clock used to time the data being reproduced off tape must be regenerated in the reproduce circuits. This is accomplished by reconstructing the clock in a phase-locked loop called a bit synchronizer. The loop is tuned to the clock frequency and synchronized by the data bits.

A second concern is the low frequency rolloff of a wideband direct recording channel. The nature of magnetic tape recording prohibits the recovery of DC and long wavelength signals. The wideband channel rolls off at about 400 Hertz. If, for example, a 12 bit sample of all zeroes is followed by a sample of all ones (000000000000111111111111) the wavelength is 24 times that of the clock. This could conceivably fall below the 400 Hertz rolloff of the system and the data would be lost for two reasons: (1) the bit synchronizer might lose lock, and (2) the data itself may fall into the noise and be undetectable.

A third concern is the Bit Error Rate (BER), the rate of errors in the reproduced data per number of data bits. The recording channel is subject to system noise which may obliterate the data as recorded or as reproduced resulting in a one time or permanent loss. Non-uniform dispersion of the magnetic coating on the tape may cause dropouts or losses of data over one or more tracks. The physical length of the imperfection causing the dropout is constant, causing more and more bits to be lost as the packing density increases. While certified tape (tape which has been specially tested and guaranteed, to minimize dropouts) is a preventive measure, some errors will still occur due to other factors such as electromagnetic interference.

It is desirable to have some indication of the number or frequency of errors in order to determine a degree of confidence in the quality of the reproduced data. The indicator may be a flashing light or a digital readout in total errors or errors per 10^x bits. It is usually the output of some type of parity or check word circuitry located on the reproduce side of the system. Before recording, the data is grouped or blocked, each group being assigned a parity bit or a cyclic redundancy check word. The parity bit or check word is appended to the group. During the reproduce function the parity or check word is examined to see if it still agrees with its data group. An incorrect result triggers the error indicator.

A fourth concern, related to the reason for recovering the clock from the data itself and not a second track, is encountered in word parallel recording of the digital data. Should the data format result in the necessity to use two or more channels for recording, the problem of interchannel time displacement error must again be dealt with, and a different solution applied than for the clock. It is impossible to preserve the proper alignment of the data bits in the column across the heads. The solution is generally in the form of a holding buffer to store a frame of data until the frames of the other channels are all aligned. The frames are then released as an output to the user. The frames are designated by a marker of some nature written into the data stream. The marker may be a separate series of bits distinct from the data. Or, it may be a modified cyclic redundancy check word. In either case it is often referred to as a "deskewing word" (since "skew" is another name for the problem encountered).

With these concerns in mind the encoding process is established. The user data is modified to ensure limits to the run length (the maximum number of ones or zeroes which can occur before a transition occurs). This aids in overcoming the low frequency rolloff problem and helps keep the bit synchronizer locked in phase with the data. Parity or cyclic redundancy check words are appended to the data at intervals designed according to the application of the principles of information theory. The data is framed by the insertion of a deskewing word to aid in the realignment of the data during reproduction. Because of the additional control bits the frame of data recorded on tape contains more bits than the users bits. In order to preserve the timing the modified data must be clocked at a rate proportionately higher than the unmodified user data. This is called "stuffing the data" and the added control bits are called "overhead".

The prospective user of HDDR should be aware that almost every manufacturer utilizes a different coding or data modification scheme. The number of check bits and the frame lengths differ as well. When calculating the format for a given HDDR system the user must know the overhead for that system when computing the tape speed/number of data channels combination. TABLES 2 and 3 address some of these codes.

ERROR CORRECTION

The parity or cyclic redundancy check words provide for a means of detecting errors and giving a measure of confidence to the user of the system. However, the errors are not corrected. Yet, it is possible to not only detect errors but to correct some, if not all of them. The actual correction is accomplished by changing an incorrect one to a zero, and vice versa. When the parity or check word for a group of data bits flags it to be incorrect the user still does not know which bit (or bits) in the group is in error. The simplest method of isolating the faulty bit is by means of comparing it with a column parity or check word. As each byte of data is clocked into the formatter or encode circuits, a parity or check word is assigned to it and recorded on a separate channel of the recorder. (For purposes of this paper a byte includes all of the data bits in parallel channels). During reproduction, the check word for the column as well as the check words for each channel are examined. If one track is in error, the column check should indicate which bit is in error. More complicated techniques may be utilized to correct errors in more than one channel at a time.

The encoding process then, may include a further modification of the data to ensure that not only is there confidence in the reproduced data, but also a means of correcting some errors in the data.

RECORDING

At the present state of the art most HDDR systems are hybrids. That is, they are a mixture of existing tape recorders and "wrap-around" processors. The processor provides the data modification, data playback, and error detection and correction. The modified data is recorded and reproduced on a standard wideband direct instrumentation recorder. Although the record and reproduce heads may be constructed to ensure more precisely uniform outputs, and head drivers substituted for the regular record amplifiers, the recording and reproducing function is rather straightforward as direct recording goes. The reproduced data is first equalized to optimize the decision area for the bit detector. This may be accomplished in the reproduce section of the recorder itself or in the processor. Some tape recorders are not limited to 7 or 8 speeds, but adjust automatically to the data rate provided to run at a speed which gives the best packing density. Such systems make maximum use of the tape running time available.

DECODING

The equalized data are generally applied to the decoder and the bit synchronizer. The bit synchronizer, locked in with the data, becomes the reproduce clock. This is not the final output clock, however, as it is running at the higher frequency rate, that of the modified and stuffed data. In the decoding process, the modified data is checked for parity, and decoded and clocked into the buffer where it remains until the output clock releases it to the user. When error correction is utilized the data is routed through those circuits before being returned to the user.

OUTPUT CLOCKING

The data clocked into the buffer are at the higher clock rate for modified data. The output clock is generated in another phase locked loop tuned to the original frequency of the user clock. It is locked onto the data by the sync or deskewing word which occurs once for each frame. As an alternative the user may provide an external clock in order to keep the data output exactly in phase with his processing equipment. Although the range of increase or decrease may be limited for most equipments, the data rate may be changed to provide some flexibility during processing. Some tape systems permit a wide change of data rate on playback. All HDDR systems permit changes of 2X, 4X, 8X, or 1/2, 1/4, 1/8 etc, within the limits of the recorder itself.

REFORMATTING

This is usually a user provided device. It is desirable for the user to understand the particular HDDR system needs before he designs or purchases a formatter/reformatter. The tables included in this memorandum are designed by the author to simplify the determination of whether or not a format change is required or if a given HDDR system can handle the user's data rate.

DETERMINATION OF BIT RATES FOR HDDR

If you are a potential user of HDDR, you can use the following tables to determine either the tape speed necessary to record a given data rate, or the maximum data rate available at a given tape speed. TABLE 1 lists the maximum number of millions of transitions (megatransitions) which can be read at the standard tape speeds in inches per second (IPS) for channel availability of 1 to 42 Tracks (TKS). For example, reading the left column (# TKS) you can see that for one channel or track the maximum mumber of megatransitions which can be read at 1.875 IPS is 0.063. At 60 IPS the maximum number of megatransitions is 2.000 (2 million transitions per second). Reading down the left column, you will see that 0.875 megatransitions per second can be read at 1.875 IPS if the data is spread out over 14 tracks. Reading across the 14 track line under the 120 IPS column indicates that a total of 56 Megatransitions per second can be read at that speed. TABLE 2 lists the overhead factor for each manufacturer. Since each manufacturer adds control bits to the data, a percentage of the transitions available must be used for these "overhead bits". Therefore, the total number of transitions must be reduced by the overhead factor in order to determine how many are left over for user data. TABLE 3 relates transitions to bits for different codes. In most codes a transition represents one bit. However, a transition could represent more bits (as in 3PM Coding).

PROCEDURES FOR USING THE TABLES

If you know the data rate you can use the tables to determine the necessary tape speed of the recorder for various track formats. Or, if you have a particular HDDR system available you can determine the maximum data rate it can handle. The following procedures and examples explain how.

A. To determine the tape speed/parallel track combination for a given user data rate.

1. Divide your data rate in Megabits per second by the overhead factor of the code in the system you will be using to record the data. See Table 2.

Example: If your data rate is 375 Kilobits per second and you will be using a DataTape HDDR system, the code is ENRZ, which has an overhead factor of .824. Dividing the .375 megabits by this factor equals .455 megabits. This is the total number of user bits plus overhead bits which have to be recorded in the one second time frame.

2. Determine from TABLE 3 the number of transitions per bit for the code being used. Multiply this number by the total number of bits per second from STEP 1. The result is the total number of transitions in millions per second.

Example: Using the .455 Megabits from the example in STEP 1, the code bit/transition factor for ENRZ is 1. So, the total number of transitions is .455 Million per second (Megatransitions).

3. Using TABLE 1 locate the lowest tape speed for TK #1 which has greater than the total number of transitions you calculated from STEP 2.

Example: The maximum number of megatransitions at 7.5 IPS is .250, and at 15 IPS is .500. Since .455 megatransitions is greater than that possible at 7.5 IPS you would have to use 15 IPS tape speed to record ENRZ.

Note! If the data rate you used in the example represents one line of a parallel output device such as an 8 bit A/D converter you might use 8 tracks of the recorder at 15 IPS. As an alternative you can take the total throughput which in the example would be 375 Khz multiplied by 8 bits . Then, using this throughput (3 Megabits) you can determine a format from the tables which would allow better utilization of the tape. The more tracks you use, the lower the tape speed needs to be in order to handle all of the data.

B. To determine the maximum user data rate for a given tape speed/track usage combination:

1. Using TABLE 1 find the tape speed and count down the number of tracks being used to format the data. You can now read the number of transitions per second in millions which the recorder can resolve.

Example: At a speed of 30 IPS and 12 Tracks a total data rate of 12 million transitions per second could be resolved.

2. Divide the number of transitions in millions per second by the code bit/transition ration from TABLE 3. The result is the total number of bits which can represented per second on tape.

Example: If Randomized NRZ is used the code bit/transition ratio is 1, so 12 Megabits per second could be recorded.

3. Multiply the answer from STEP 2 by the code overhead factor from TABLE 2. The result is the number of user bits per second which can be recorded for the given tape speed and format.

Example: With Randomized NRZ, the overhead factor is .969 so 12 Megabits multiplied by this factor equals 11.6 Megabits, which is the user data limit.

TABLE 1

MEGATRANSITIONS PER SECOND*

	TAPE SPEED IN INCHES PER SECOND (IPS)						
# TKS	1.875 IPS	3.75 IPS	7.5 IPS	15 IPS	30 IPS	60 IPS	120 IPS
1	0.063	0.125	0.250	0.500	1.000	2.000	4.000
2	0.125	0.250	0.500	1.000	2.000	4.000	8.000
3	0.188	0.375	0.750	1.500	3.000	6.000	12.000
4	0.250	0.500	1.000	2.000	4.000	8.000	16.000
5	0.313	0.625	1.250	2.500	5.000	10.000	20.000
6	0.375	0.750	1.500	3.000	6.000	12.000	24.000
7	0.438	0.875	1.750	3.500	7.000	14.000	28.000
8	0.500	1.000	2.000	4.000	8.000	16.000	32.000
9	0.563	1.125	2.250	4.500	9.000	18.000	36.000
10	0.625	1.250	2.500	5.000	10.000	20.000	40.000
11	0.688	1.375	2.750	5.500	11.000	22.000	44.000
12	0.750	1.500	3.000	6.000	12.000	24.000	48.000
13	0.813	1.625	3.250	6.500	13.000	26.000	52.000
14	0.875	1.750	3.500	7.000	14.000	28.000	56.000
15	0.938	1.875	3.750	7.500	15.000	30.000	60.000
16	1.000	2.000	4.000	8.000	16.000	32.000	64.000
17	1.063	2.125	4.250	8.500	17.000	34.000	68.000
18	1.125	2.250	4.500	9.000	18.000	36.000	72.000
19	1.188	2.375	4.750	9.500	19.000	38.000	76.000
20	1.250	2.500	5.000	10.000	20.000	40.000	80.000
21	1.313	2.625	5.250	10.500	21.000	42.000	84.000
	16 HR	8 HR	4 HR	2 HR	1 HR	0.5 HR	0.25 HR
	TAPE RUNNING TIME (9200 FT REEL)						

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* Based on 33,333 transitions per inch for a 2 MHz Recorder

TABLE 1 (CONT.)

MEGATRANSITIONS PER SECOND*

	TAPE SPEED IN INCHES PER SECOND (IPS)						
# TKS	1.875 IPS	3.75 IPS	7.5 IPS	15 IPS	30 IPS	60 IPS	120 IPS
22	1.375	2.750	5.500	11.000	22.000	44.000	88.000
23	1.438	2.875	5.750	11.500	23.000	46.000	92.000
24	1.500	3.000	6.000	12.000	24.000	48.000	96.000
25	1.563	3.125	6.250	12.500	25.000	50.000	100.000
26	1.625	3.250	6.500	13.000	26.000	52.000	104.000
27	1.688	3.375	6.750	13.500	27.000	54.000	108.000
28	1.750	3.500	7.000	14.000	28.000	56.000	112.000
29	1.813	3.625	7.250	14.500	29.000	58.000	116.000
30	1.875	3.750	7.500	15.000	30.000	60.000	120.000
31	1.938	3.875	7.750	15.500	31.000	62.000	124.000
32	2.000	4.000	8.000	16.000	32.000	64.000	128.000
33	2.063	4.125	8.250	16.500	33.000	66.000	132.000
34	2.125	4.250	8.500	17.000	34.000	68.000	136.000
35	2.188	4.375	8.750	17.500	35.000	70.000	140.000
36	2.250	4.500	9.000	18.000	36.000	72.000	144.000
37	2.313	4.625	9.250	18.500	37.000	74.000	148.000
38	2.375	4.750	9.500	19.000	38.000	76.000	152.000
39	2.438	4.875	9.750	19.500	39.000	78.000	156.000
40	2.500	5.000	10.000	20.000	40.000	80.000	160.000
41	2.563	5.125	10.250	20.500	41.000	82.000	164.000
42	2.625	5.250	10.500	21.000	42.000	84.000	168.000
	16 HR	8 HR	4 HR	2 HR	1 HR	0.5 HR	0.25 HR
	TAPE RUNNING TIME (9200 FT REEL)						

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* Based on 33,333 transitions per inch for a 2 MHz Recorder

TABLE 2

CODE OVERHEAD FACTOR

MANUFACTURER	CODE	EFFICIENCY
Ampex	Miller/Miller^2	1.000*
Fairchild/Weston	Randomized NRZ	0.969
Datatape	ENRZ	0.824
Honeywell	Pseudo Random Odd Parity	0.833
Thorn EMI	3 PM Format A	0.909
Thorn EMI	3 PM Format B	0.933

*Miller and Miller^2 coding requires a separate track of the recorder for overhead bits.

TABLE 3

TRANSITIONS/CODE BIT

CODE	T/B
Miller/Miller^2	1
Randomized NRZ	1
Enhanced NRZ	1
Pseudo Random Odd Parity	1
3 PM Format A or B	0.67

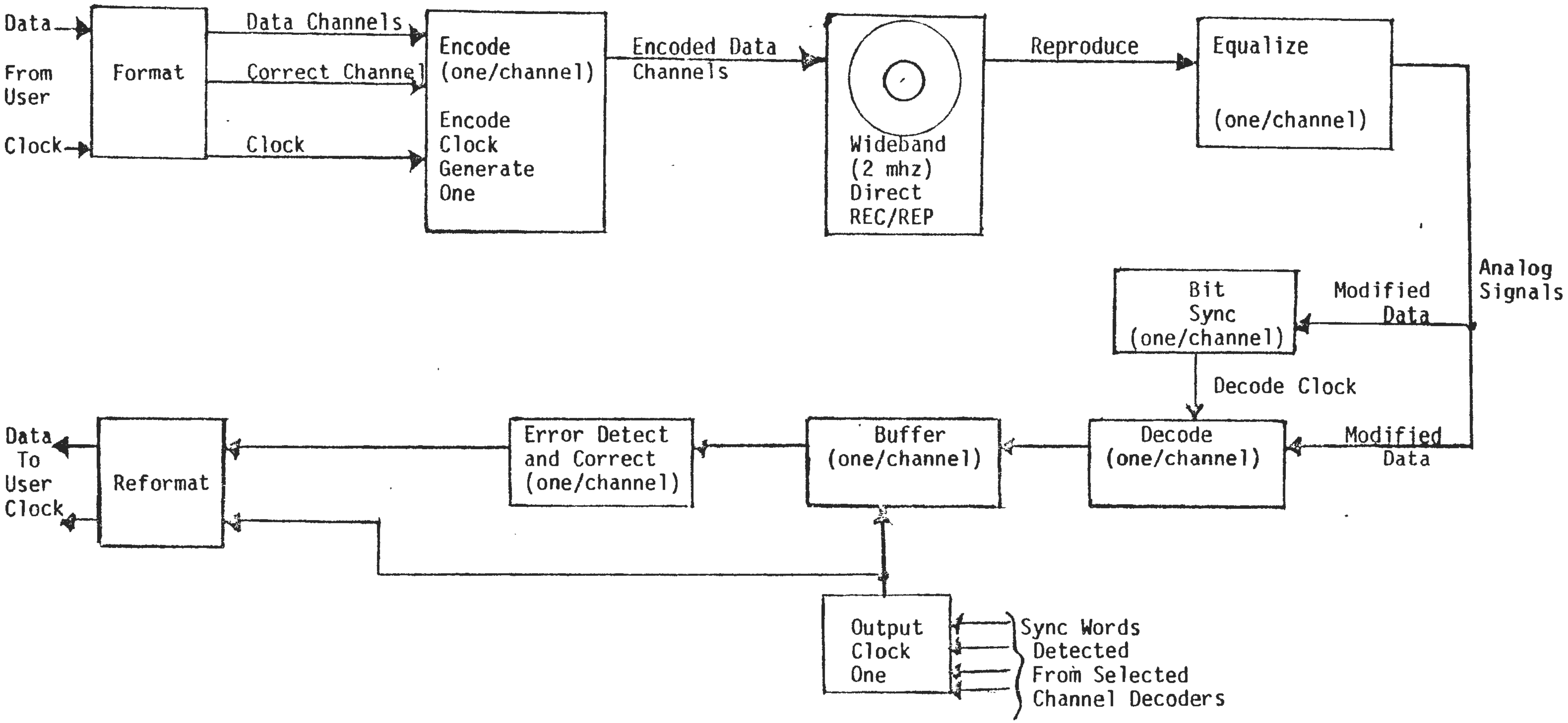

FIGURE 1 - TYPICAL HDDR SYSTEM FUNCTIONS