HIGH DENSITY PCM MAGNETIC TAPE RECORDING

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Summary. The Bell & Howell Enhanced-NRZ™ recording reproducing technique for bit packing densities up to 40,000 per track inch is described in this paper. Utilization of the pulse code modulation format of Enhanced-NRZ achieves this high density with a bit error rate of one in ten million. Bell & Howell's standard VR-3700B instrumentation tape recorder and wideband instrumentation recording tape are used. This same technique permits parallel recording of data rates up to 10 megabits per second at a tape speed of 120 in./s. The merits of the unique encoding/decoding method, factors affecting bit error rate, and future opportunities for development are discussed.

Introduction. The increasing use of digital computers, more precise transducers, telemetry links of greater bandwidth, and the advent of faster and more accurate analog-to-digital converters have all combined to require more performance from the instrumentation tape recorder. The increasing availability of data in digital form, the need for better signal-to-noise ratios than can be achieved with conventional analog recording techniques, and the need for computer compatibility of data place greater emphasis on digital tape recording. The parameters of greatest concern are typically data transfer rate, packing density on tape, and bit error rate.

Pulse-code modulation (PCM) recording is finding wide acceptance for critical digital applications; it permits both greater bandwidth and wider dynamic range than frequency modulation (FM), is not restricted to low frequencies as is pulse duration modulation (PDM), land does not share the amplitude sensitivity of pulse amplitude modulation (PAM)[1]. The PCM formats presently accepted by the Inter-Range Instrumentation Group (IRIG) are RZ, NRZ, and Bi-Phase. Of these formats, NRZ requires only half the bandwidth needed for the other two codes, but requires frequency response down to dc. Bi-Phase has the advantage that it is self-clocking; there is a transition for every bit cell.

Efforts to create a self-clocking code approaching the upper bandwidth requirement of NRZ have resulted in the Delay Modulation, or Miller code. For this code, transitions are required in the middle of the bit cell for a “one” or at the end of the bit cell for a “zero” - but only when followed by another “zero”. In comparing the recovery processes for Miller and Enhanced-NRZ (ENRZ) data, it is useful to refer to the "eye" pattern frequently used for system setup.[2, 3]

The eye pattern is generated by synchronizing an oscilloscope with the regenerated clock to display the output of the equalization amplifier. The result has the form of an eye (Fig. 1). The larger the eye, the more easily the reproduce detector or bit synchronizer can distinguish between a one and a zero. If the eye is partially closed or of small area due to inadequate signal amplitude or noise, the bit synchronizer may misinterpret the signal and bit errors will result.

Detection of Miller code requires that each bit cell be sampled in two positions (requiring regeneration of a double-frequency clock) to distinguish a one from a zero; ENRZ need be sampled in only one position. Representative oscilloscope photographs of the two are shown Fig. 2. It is evident that a much smaller decision area or eye is available for Miller code; the relative amplitudes are shown in Fig. 3. The requirement to sample at the 45° and 135° points of the waveform results in an amplitude only 0.707 of that available with ENRZ. The effect on SNR is

$$20 \log_{10} 0.707 = 3 \text{ dB}$$

a reduction of 3 dB. Examination of the theoretical curve for bit error rate versus SNR[4] shows that a reduction ml SNR of 3 dB corresponds to degradation of the theoretically achievable bit error rate by 3-4 orders of magnitude. In addition to the reduced amplitude available, the time during which the sample may be made is reduced by a factor of 2 with respect to ENRZ. The timing window is of course also degraded by bit jitter. The Miller code detector is uniquely dependent upon the occurrence of the sequence "101" within the data to achieve or recover synchronization.

Enhanced-NRZ Coding. The Bell & Howell Enhanced-NRZ format consists of adding a bit to each group of data bits to be recorded on one track. The bit added is a parity bit, such that the total number of "1"s recorded for the group with its parity bit is odd. For example, a parity bit may be added to each group of seven data bits. This enhancement of the raw data yields several advantages over straight NRZ encoding. First of all, it guarantees a transition rate in the recorded signal sufficient for maintaining phase lock in the detector tracking oscillator. Secondly, by means of parity check during playback, it gives a good indication of the accuracy with which the bits were recorded and reproduced. Thirdly, it makes it possible to determine when accurate bit count has been lost and, within a limited error boundary, reestablish the correct bit count and alignment of data bits at the system output. The extra bits inserted during the recording mode are deleted on playback prior to reformatting the data for output.

The addition of an odd parity bit after every seven data bits restricts the recorded bit pattern so that no more than 14 bit periods may elapse without a flux change, in the worst case. This brings the low frequency response requirement within the range of standard Direct reproduce electronics, while retaining the upper bandwidth capability of NRZ. The reduction in effective packing density due to the addition of the parity bits amounts to 14 percent: significantly less than the reduction occasioned by the use of Bi-Phase or Miller coding.

In addition to the higher achievable packing density, the parity bits provide an easy means of determining data accuracy on tape. A continuous running parity check is maintained, either during a read-after-write mode made possible by the normal instrumentation recorder head locations, or during a read-only mode. Either situation affords the user an output status line which may be monitored to determine the accuracy of data transfer for that particular recording. This ability to observe the recorded error rate, independent of the data being recorded, is unique to Enhanced-NRZ recording. It also minimizes the need for special error-checking test equipment in setting up or troubleshooting the record/reproduce electronics.

An additional advantage is that the decoder may be designed to recover from ±3 bits of slippage in the event of a severe dropout, based on the parity bits. Thus recovery to correct output synchronization may be made without waiting for special bit sequences or frame-sync words to occur in the input data.

The Record System. NRZ data and clock signal inputs are applied to the encoder (Fig. 4). These are normally TTL (transistor-transistor logic) levels, or low-level differential signals where either long cable runs or unusually noisy environments are expected. Input data rates can be as high as 3.5 megabits per second when recording at 120 in./s. The encoder separates the input serial bit stream into 7-bit words, performs odd parity determination for each word, reformats the data into 8-bit words, and outputs the result at 8/7 of the input bit rate. A phase-locked loop is used to generate the required output clock.

The encoder output drives a switching-type head driver. The use of saturation rather than biased recording not only improves the signal-to-noise ratio[5] but eliminates the high-frequency noise problems frequently encountered when cabling bias throughout a recording system. A potentiometer on the encoder board permits adjustment of the optimum record current.

Standard wideband instrumentation magnetic heads are used, providing 2 MHz response at 120 in./s for Direct recording. Recommended tape is 3M988 or 3M888. Satisfactory results may be obtained at packing densities up to 33,000 bits per track inch using tape as supplied by the manufacturer; higher densities usually require mechanical cleaning of the tape, even when new. Improvement in bit error rate of the order of 5:1 is frequently achieved by proper cleaning. The most effective “dry” cleaning technique, based on extensive experience at NASA Goddard, consists of scraping the oxide side of the tape with a razor blade and subsequently wiping both sides with a lint-free material.

The transport which has been used for the described performance is Bell & Howell’s VR-3700B, offering 9 bidirectional speeds from 240 to 15/16 in./s. Cumulative flutter over a 10 kHz bandwidth at 120 in./s is less than 0.11 percent peak-to-peak, minimizing the bandwidth required for the reproduce phase-locked loop in PCM recording. Very low dynamic skew minimizes the buffer size required for parallel recording.

The Reproduce System. The signal from the reproduce head is amplified by the same linear preamplifier normally used for Direct or FM recording, and applied to the PCM Reproduce Assembly. The entire reproduce electronics, consisting of the equalization amplifier, bit synchronizer, and decoder are mounted on a single plug-in printed circuit board compatible with the FM and Direct reproduce boards.

The equalization amplifier (patent applied for) was designed specifically for PCM reproduction and provides performance far superior to that obtained through the use of previous Direct reproduce amplifiers. It provides amplitude and phase equalization of the reproduced signal and has TTL output levels for application to the bit synchronizer. It is automatically switched by the transport through four tape speeds.

The bit synchronizer (patent applied for) is also switched through four speeds; it reconstructs the clock from the reproduced data, still at 8/7 of the input bit rate. It is a much-simplified version of the very complex and expensive bit synchronizers widely used in telemetry. Bell & Howell’s bit synchronizer has been tested and found to perform within 2 dB of the theoretical curve for bit error rate versus SNR.

The reconstructed data and clock from the bit synchronizer are applied to the decoder (Fig, 5) which determines word-sync, strips out the parity bits, and outputs data and clock at the original input bit rates.

The enhanced data is successively shifted through three 8-bit registers (S/R), where it is examined for correct parity in each bit position. When parity is satisfied in all three registers at once, the decoder assumes word-sync and extracts the parity bits. Word-sync is maintained until all three registers display parity failure simultaneously; this is taken to indicate that bit-slippage may have occurred (as during a severe and prolonged dropout in the tape). A “search” mode is then initiated to recover word-sync. As during initial acquisition, the criterion of three simultaneous “good” parities is used to resynchronize.

Each bit position is examined as the data is shifted through until this criterion is satisfied. If correct parity is found to reoccur at the original parity-bit position, no change in timing is made. If parity is reestablished at a different bit position, the output counter is resynchronized to the new position and correct data output follows. The parity-examine line is provided as an output to enable the user to monitor data quality.

A phase-locked loop is again used to give the output clock at 7/8 of the enhanced data rate from the tape. The data is present in parallel form in a register at the output of the parity-check registers; the reconstructed 7/8 clock shifts the data out serially without the parity bits. Data and clock are provided at the system output in either TTL or differential form, at the same rate as the input.

Performance. The coding and electronics described above give a bit error rate of one in ten million bits, at densities on tape up to 33,000 bits per inch per track. This same error rate has been achieved in the laboratory using cleaned tape at a packing density of 40,000 bits/in. Error rates are tested using a pseudorandom numeric (PN) sequence of sufficient length to include the worst case length enhanced sequence on tape without a flux change -- both for ones and zeros. Bit-by-bit comparisons are made of the reproduced data with the correct sequence. A pulse is generated for each incorrect comparison and output to a counter which accumulates total errors.

Parallel PCM Recording. Bell & Howell parallel PCM record/reproduce systems accept input data rates up to 10 megabits per second per charmer, NRZ. Each input channel is split up into three tracks on tape, as shown in Figs. 6 and 7. Data for each track, at one-third the input data rate, is then enhanced in the manner described above and recorded. A preamble PN sequence is recorded on each track for initialization of the output buffers.

In reproducing, each track is equalized, bit-synchronized, and decoded in the manner described above. The preamble sequence properly initializes each track buffer register; one track is selected as the master. The master clock is then used to drive a phase-locked loop (PLL) which regenerates the output clock at the original channel bit rate; this clock is then used to reformat each group of three tracks into deskewed output channels identical to the input data. The decoders in this application are modified to permit recovery of track sync in the same manner as used to establish word sync, in the event of dropouts.

This same approach may of course be used to accommodate even higher input data rates, utilizing more tape tracks per channel to maintain a constant track packing density.

Advantages of High Density Recording. Tape recording at the rates and densities described permits the use of standard instrumentation recorders and standard tape speeds for high data rate applications without the need for exotic, high-speed transport technology.

A significant increase in dynamic range with respect to Direct recording may be enjoyed; in contrast to signal-to-noise ratios of the order of 24 to 30 dB for a 2 MHz Direct system, PCM recording using an 8-bit analog-to-digital converter would give a dynamic range of 48 dB.

As an example of the reduction in storage requirement obtainable, a single 15-inch reel of 1-inch, 14-track instrumentation tape recorded at 33,000 bits/in. (Bell & Howell's present "standard product" density) would contain as much data as 300 full 8-inch reels of 9-track, 800 bit/in. computer tape.

Future Developments. Considerable improvement in system performance can be expected with the advent of cleaner tapes and more uniform coatings. One of the most significant limitations in present-day high density recording is in the area of tape dropouts -- as evidenced by the dramatic improvement resulting from mechanical cleaning. Bell & Howell is developing the capability to clean and certify tape at 30,000 to 40,000 bits/in. to satisfy the growing need in this area.

An opportunity for further increases in packing density lies in the use of Bell & Howell extended-bandwidth heads with high-energy tape.

Additional performance can be gained by the use of more sophisticated bit synchronizers to recover the data from tape, in applications where the considerable extra expense is justified.

Conclusions. A technique has been described for achieving extremely high longitudinal packing density of digital information on magnetic tape using EnhancedNRZ coding. Its advantages and limitations with respect to other coding formats have been discussed, and the transport and electronics in current use by Bell & Howell have been described. Some opportunities for further development have been mentioned.

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References

1. S.W. Athey, "Magnetic Tape Recording," NASA SP-5038, Washington, D.C., pp. 35-56; 1966.
2. R.W. Lucky, J. Salz, E.J. Weldon, Jr., "Principles of Data Communication," McGraw-Hill, Inc.; New York, N.Y., pp. 61-63; 1968.
3. W. R. Bennett, J. R. Davey, "Data Transmission, 11 McGraw-Hill, Inc.; New York, N.Y., pp. 119-120; 1965.
4. Ibid., p. 114.
5. Athey, Op. Cit., p. 34.

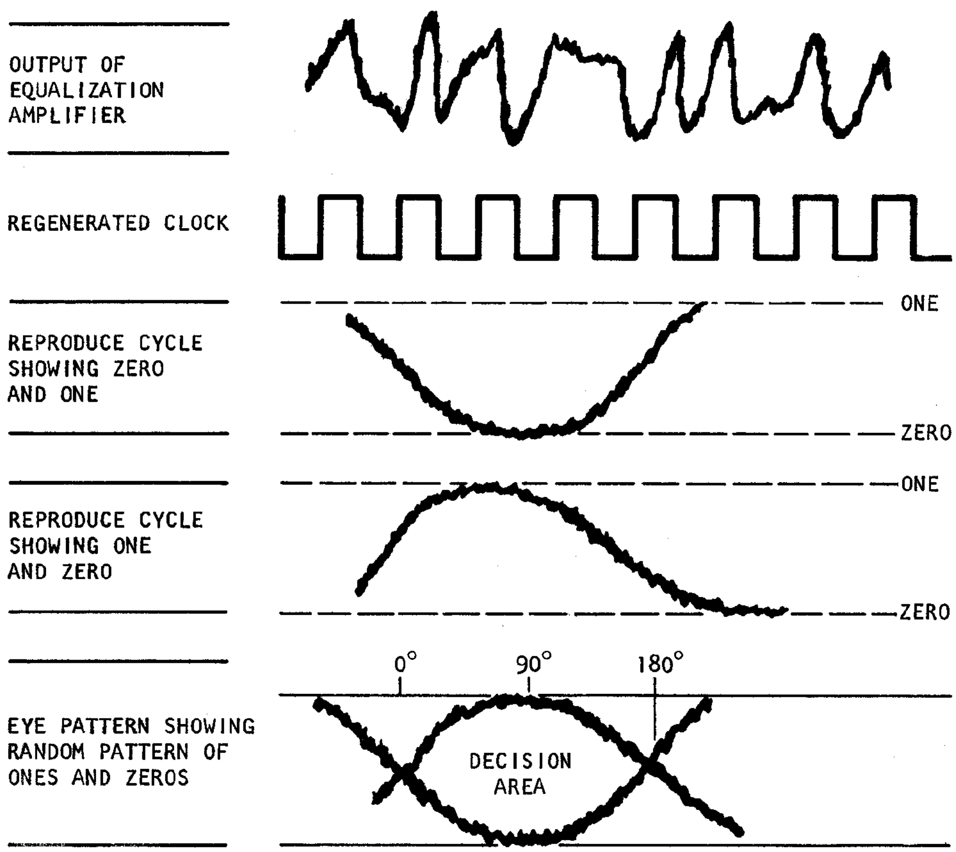
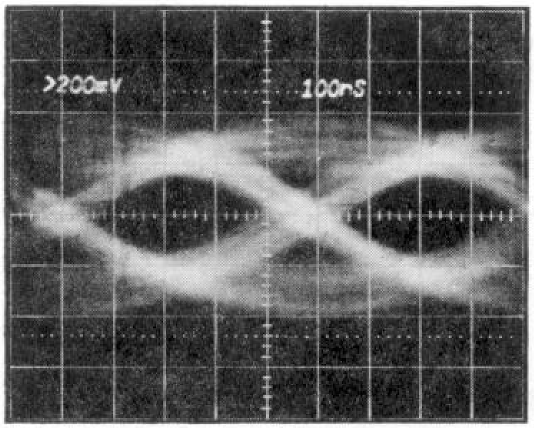


Fig. 1. NRZ or ENRZ Eye Pattern



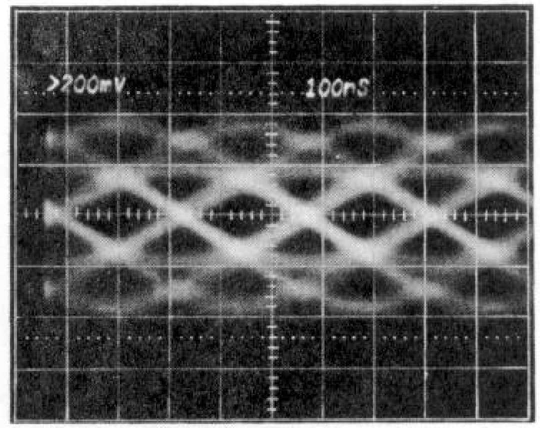


Fig. 2(a). Enhanced NRZ Eye Pattern **Fig. 2(b). Miller Eye Pattern**

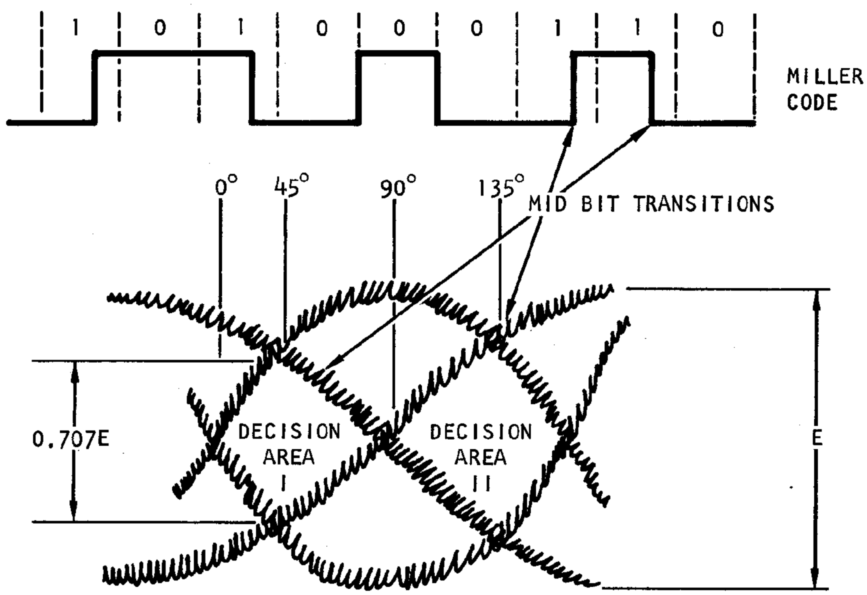


Fig. 3. Eye Pattern of Miller Code

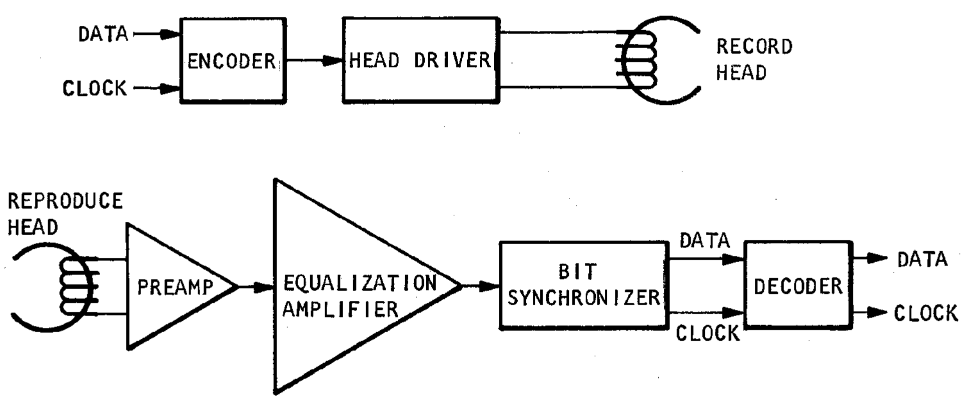


Fig. 4. PCM Record/Reproduce Electronics

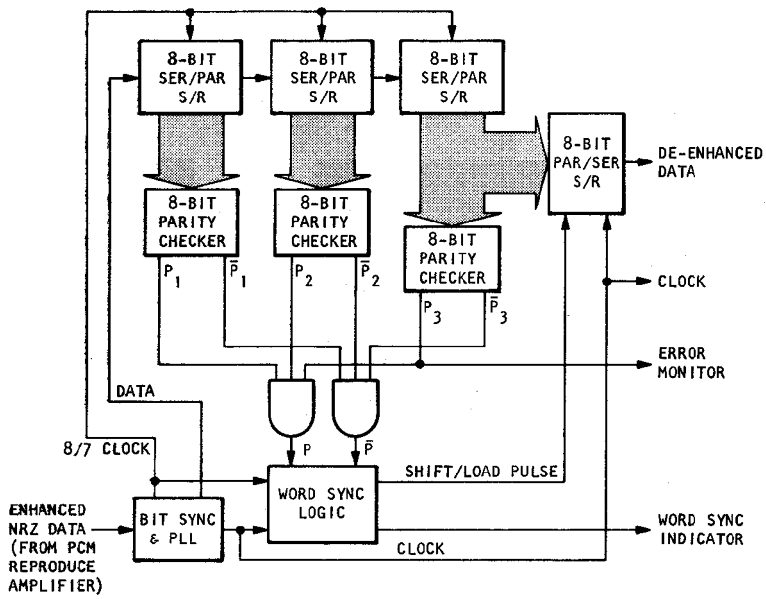


Fig. 5. Enhanced-NRZ Decoder

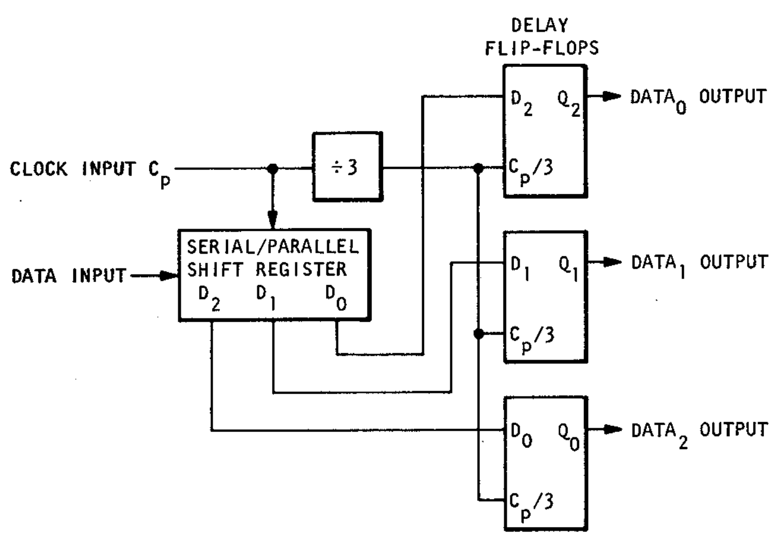


Fig. 6. Data-Channel to Three-Tape-Track Demultiplexer

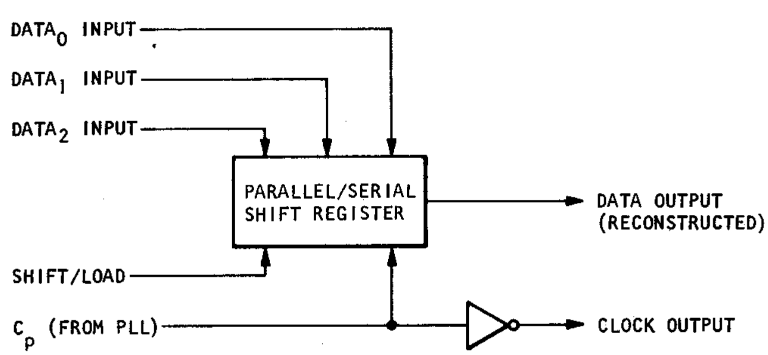


Fig. 7. Three-Tape-Track to One Data Channel Multiplexer