REFERENCES

[1] G. C. Bacon and H. S. Hoagland, "High density digital magnetic recording techniques," *Proc. IRE*, vol. 49, Jan. 1961, pp. 258–267.
[2] J. C. Mallinson and C. W. Steele, "Theory of linear superposition in tape recording," *IEEE Trans. Magn.*, vol. MAG-5, Dec. 1969, pp. 886–890.
[3] E. Wong and J. C. Mallinson, "Noise whitening filters for digital recording," in *1970 Proc. INTERMAG Conf.*, Paper 12.6.
[4] Telemetry Standards IRIG 106-66.
[5] A. Miller, "Recording and/or reproducing system," U. S. Patent 3,108,261, Oct. 22, 1963.

On Optimal Processing of Digital Magnetic Recording Data

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An optimal processing of digital magnetic recording data based on a recent result in communication theory is discussed [1]. It is intended to indicate a promising direction in which the study of a higher density and more reliable recording may be pursued.

As far as the processing of the read back signal is concerned, a digital magnetic recording system is equivalent to a baseband data transmission system with correlative level coding. The correlative level coding is a technique recently developed in data communication systems in which a controlled amount of intersymbol interference is intentionally introduced in exchange for an improvement in the transmission rate [2]. In a magnetic recording system, on the other hand, the inherent differentiation operation in the readback process generates, in effect, a correlative level coded sequence [3].

First the problem of sequence decision, sampling and equilization is treated from the viewpoint of multiparameter estimation theory. It is shown that the maximum likelihood processor consists of a matched filter, sampler, equalizer and the sequence estimator. It is shown that for a better performance, a sequence decision should not be done on bit-by-bit basis as has been done in the conventional amplitude and peak detection methods.[1] The maximum likelihood decoding algorithm (often called Viterbi algorithm [4] in decoding of convolutional codes) recently developed by the present author [5], [6] and by Forney [7] will be discussed in this context. The decoding algorithm and its practical implementation are discussed. Expressions for the error probability are obtained and confirmed by computer simulations. It is shown that a significant improvement in the performance is achievable by the maximum likelihood decoding method. For example, under Gaussian noise assumption, the proposed technique can reduce raw error rates in the 10^{-3} to 10^{-4} range by a factor of 50 to 300. The improvement factor further increases for a higher SNR. These results indicate that this decoding method gains as much as 2.5–3.0 dB in SNR over the bit-by-bit detection method.

The structure of this maximum likelihood processor is further extended to the case in which the channel characteristic is unknown or time varying. An adaptive algorithm for adjusting simultaneously the sample instant and equalizer is discussed using the decision directed receiver approach.

The analysis and results obtained here are immediately extendable to the multilevel signaling [6] case which may be adopted in linear recording systems in the future development.

It is worthwhile to add a few remarks on amplitude detection versus peak detection. In the past decade or so the peak detection or sensing method has been playing a central role in digital magnetic recording systems. Various modulation or coding schemes have been developed in association with this specific detection method. There seem to be two major factors accounting for the preference for the peak detection method over the amplitude detection method. They are as follows.

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[1] The peak sensing or detection method is a readback detection technique [8] in which the presence or absence of a peak is sensed in each bit space. The presence of a peak in the read head output waveform corresponds to a saturation reversal in binary data stored on the magnetic surface.

1) The peak shift seems less sensitive to the so-called crowding effect (or intersymbol interference) than the amplitude information is.

2) The readback signal tends to suffer from the amplitude change due to variations of the systems, such as the change in flying height in magnetic disks. The conventional amplitude detection method is likely to break down in this environment, unless some automatic gain control is employed.

The peak detection method, however, seems to suffer an essential limitation as far as its potency for higher density recording is concerned. This is because the peak shift is a nonlinear function of both data sequences and the channel transfer function; thus it is extremely difficult to derive methods for any further processing. The amplitude detection method, on the other hand, allows equalization and other sophisticated processing techniques as will be discussed in the present paper, and may lead to a much higher density recording.

REFERENCES

[1] H. Kobayashi, "A simultaneous adaptive estimation and decision algorithm for carrier modulated data transmission systems," unpublished.
[2] A. Lender, "Correlative level coding for binary data transmission," *IEEE Spectrum*, vol. 3, Feb. 1966, pp. 104–115.
[3] H. Kobayashi and D. T. Tang, "Application of partial-response channel coding to magnetic recording systems," *IBM J. Res. Develop.* vol. 14, July 1970, p. 368.
[4] A. J. Viterbi, "Error bounds for convolutional codes and an asymptotically optimum decoding algorithm," *IEEE Trans. Inform. Theory*, vol. IT-13, Apr. 1967, pp. 260–269.
[5] H. Kobayashi, "Application of probabilistic decoding to digital magnetic recording systems," *IBM J. Res. Develop.*, Jan. 1971.
[6] —— "The correlative level coding and the maximum likelihood decoding,' presented at the 1970 IEEE Can. Symp. Communication, Nov. 1970.
[7] G. D. Forney, Jr., "Maximum likelihood sequence estimation of digital sequence in the presence of intersymbol interference," to be published.
[8] A. S. Hoagland, *Digital Magnetic Recording*. New York: Wiley, 1963.

New Coding Approach to Digital Magnetic Recording

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Normally the readback signal of a digital magnetic recording system contains, due to the inherent differentiation, three levels (i.e., the plus peak, zero, and minus peak), although the recorded data is binary and is represented by two opposite saturation states on the magnetic surface. This observation leads us to treat a magnetic recording channel as a linear system that possesses an inherent factor $(1 - D)$ in its transfer function, where D represents a unit time delay. Such a system is equivalent to the so-called partial-response channel which is widely used in high speed data communication systems [1].

In our earlier paper [2] it has been shown that the conventional nonreturn to zero IBM (NRZI) method of recording is equivalent to the precoding corresponding to the channel $(1 - D)$ which eliminates the error propagation. This new viewpoint has led to several important results.

An algebraic method of error detection and correction has been developed which is applicable in both amplitude and peak detection methods. The proposed error detection scheme [2], [3] takes full advantage of the redundancy inherent in the readback signal (see Fig. 1). In this system the detector (either amplitude or peak detection type) reduces the continuous analog waveform into a sequence of signals with three levels. This hard decision output is then fed to an inverse filter $1/(1 - D)$ and a decoder $[1 - D]_{\text{mod } 2}$. If any detectable error exists in this sequence, it can always be detected by tracking the existence of any illegitimate level in the inverse filter output sequence. This algebraic approach has been extended to more general decision schemes [3], in which the quantizer makes a soft decision including ambiguity zones (again either in amplitude or

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