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Physically Based Information Science of Magnetic Recording I. Information Capacity of a Medium Model

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Abstract— **The data processing inequality of information theory states that no recording system using a medium can achieve a capacity greater than the capacity of the medium itself. We describe an efficient method for determining the storage capacity of a magnetic storage medium. We apply the method to a medium model consisting of a tessellation of magnetic "grains" and obtain a numerical measure of the storage capacity. We find that intergranular dipolar and exchange interactions reduce the storage capacity below that of a tesselation of non-interacting grains.**

I. Development

Most recording channel models approach the physical system as a "black box" characterized by its statistical properties. New codes and techniques for increasing the system's capacity are placed in this framework. In the alternative approach adopted here, we focus on a new physical model of the storage medium; other parts of the recording channel including the read/write transducers are modeled using standard techniques. This approach is expected to make possible the development of a more complete set of design rules. Our storage medium model is relatively simple, and computationally more tractable than more elaborate physical models in current use. It can be functionally incorporated into the information channel, and a framework developed in which other physical models can later be substituted. Novel signal processing techniques, including adaptive equalization, can be tested for the channel model. Here we examine the ultimate storage capacity of a medium model. The underlying assumption is that this limit is given by the number of different stable magnetic configurations of the medium. We shall show that interactions reduce the capacity below the superparamagnetic limit. There is at present no magnetic recording system that attempts to exploit the ultimate medium storage capacity. The approach described here can support the consideration of unconventional recording schemes.

II. Medium Model

Analysis of the ability of magnetic recording channels to store and retrieve information relies on a model of the physical systems under study. Models which reflect more accurately the underlying physical processes of recording system components should provide the means to achieve more accurate analysis of existing systems and improved design of coding, signal processing, and recording schemes. In [1], McLaughlin and Neuhoff present an analysis of a model based on a physical description of the readback process using conventional recording methods. They predict a potential increase in storage capacity up to a factor of 20 through selection of parameter values in their model. Storage capacity is expressed as the number of bits which can be reliably stored per unit of medium area. When storage and retrieval of data through the medium are viewed as transmitting data through a communications channel, this capacity corresponds to Shannon's channel capacity.

We seek knowledge through which greater capacity gains can be achieved through study of more sophisticated models of recording system components. In particular, we study a detailed physical model of magnetic recording media. By directly analyzing a model of the recording medium independent of any particular recording scheme, we seek the storage capacity of the medium itself. The data processing inequality of information theory [2] then assures us that no recording system using a medium can achieve a capacity greater than the medium's capacity. Thus, the medium storage capacity represents a fundamental limit. The ensuing challenge is to develop recording schemes to approach as nearly as possible the limits imposed by the underlying physics reflected in the medium model.

Much current research is dedicated to physically accurate medium models [3, 4]. These models are faithful, but their large computational demands make them difficult to incorporate into a broader recording channel model, and they provide detail that may not be essential to this functional role. Our simplified physical model has many of the characteristics needed to describe magnetic storage media. It is computationally tractable. We can establish a measure of its storage capacity, and it can be used to explore recording system performance, including systems comprising conventional components.

Like the physically more accurate models we use a planar tessellation of uniformly magnetized magnetic "grains." Each grain has a magnetic moment of the same

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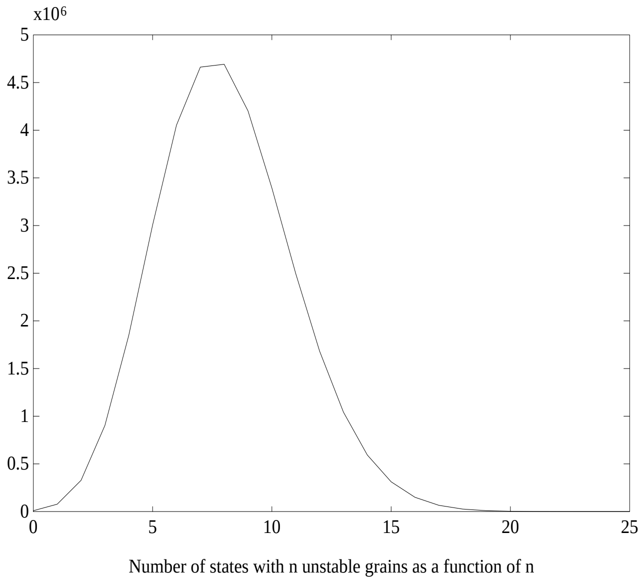

Fig. 1. Histogram of all states of one 25-grain patch

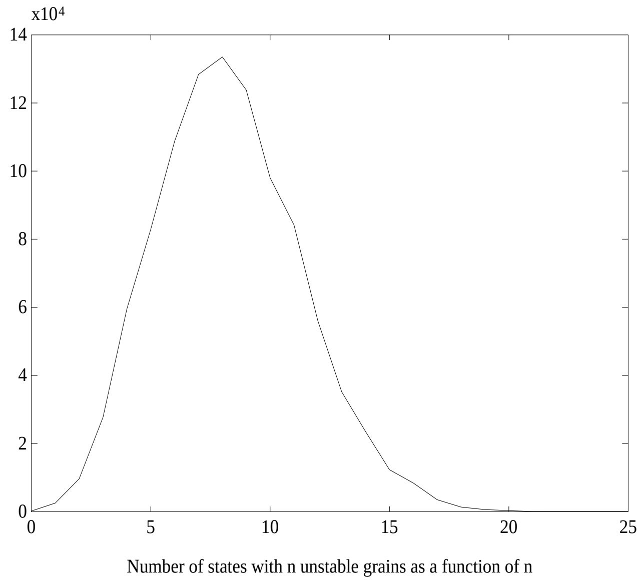

Fig. 2. Histogram of an ensemble of 10^6 25-grain patches

magnitude, but fixed in each grain at the time of fabrication is a magnetocrystalline anisotropy with random easy axis orientation. The grains interact through long range magnetostatic dipole-dipole and nearest neighbor exchange interactions. The results presented below are representative of typical longitudinal thin film recording media. An energy-minimizing annealing algorithm may be used to simulate the relaxation of an energized medium to one of its stable configurations. A detailed description of the medium model and of the annealing algorithm are presented in [5]. The stable configurations of the medium magnetization are reached when all the grains are stable against reversal. These states are local energy minima, stable at low temperature against transitions between minima. The number of stable configurations limits the medium's information capacity.

III. Simulation Examples

To illustrate the set of possible stable configurations we provide a series of examples. Consider a medium modeled as an assembly of N grains. Each grain has two possible stable states. In the absence of intergranular interactions the number of stable configurations of the assembly is 2^N. In principle, N bits of information may be reliably stored using these states, so the capacity of the medium is one bit per grain. For a more realistic medium model we add the intergranular interactions and compute the number of configurations which remain stable after the addition of the interaction energies. For a small number of grains this can be computed exactly. Fig. 1 displays data collected from a twenty-five grain assembly organized in a 5×5 array. This small assembly represents one small patch of a larger surface of a recording medium. In the presence of intergranular interactions, each grain "sees" an effective interaction field, generated by its environment, which may switch the orientation of the grain's magnetization if its initial assignment is unstable. For each of the 2^{25} possible initial assignments, we compute the number of grains whose assigned magnetization orientation is unstable against reversal. Fig. 1 is a histogram of these data. The stable states of the assembly are the 8860, or approximately 2^{13}, states indicated by the intercept of the plot with the ordinate axis (though this is hard to see in the figure due to linear scaling). These data indicate an upper limit of 13 bits of information which may be reliably stored on this medium, yielding a limiting capacity of 0.52 bits per grain for this medium. This limit is derived solely from the model of the recording medium. It does not depend on the particular recording or reading process used to store and retrieve information.

To characterize the storage capacity of media of more realistic size, we must perform simulations of larger patches, and average results from several patches from different locations on the media. Both of these goals are frustrated by computational demands of the medium model. As N increases, direct computation of all states is no longer feasible, as the number of states to test increases exponentially. We must turn to statistical methods to extract the information. Fig. 2 displays data collected from 10^6 randomly chosen states of a 5×5 patch. To simulate an average over several patches, a new set of easy axis orientations is generated for each random state. Not all states are tested, but this random sample yields 154 stable states, providing an estimate of the probability of a stable state of $154 \cdot 10^{-6}$. Computations similar to those above yield a similar limiting capacity of 0.49 bits per grain.

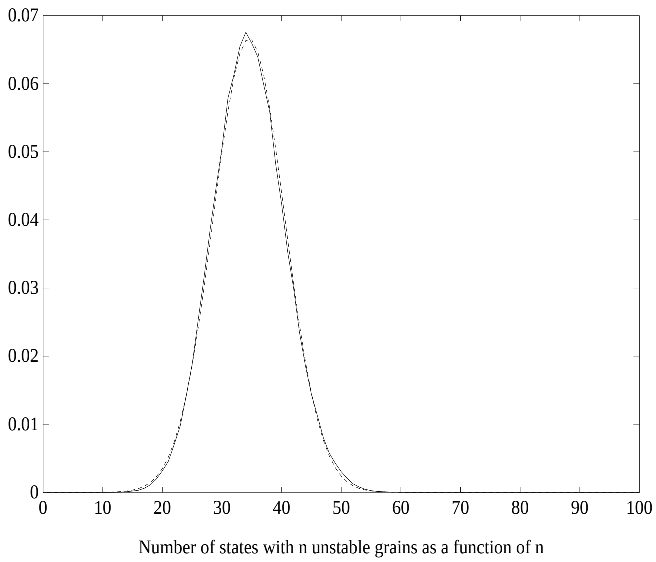

Fig. 3. Data from an ensemble of 10^6 100-grain patches: —— Data Histogram; - - - Gaussian Match

For simulations of larger patches there is another complication. The total number of states increases with increasing N at a greater rate than the number of stable states. Thus, the probability of a stable state decreases, so that more random states must be generated to calculate an accurate estimate of that probability according to the ratio method used above. For N as small as 100, the number of samples required makes this method no longer feasible. Instead, the estimate must be determined through an extrapolation method. This method determines the histogram of the number of unstable grains from sets of random magnetizations. As before, the ordinate axis intercept of the histogram is the number of stable configurations, but, for the relatively small number of states computed, the value of the histogram at that intercept is zero. However, the histogram can be fitted very well to a Gaussian probability density function through which one can estimate the value of the ordinate axis intercept, yielding the number of states with zero unstable grains. Fig. 3 displays both the histogram of data collected from 10^6 random states, averaging over several patches, and a Gaussian distribution function matched to the data. The Gaussian fit was chosen to have mean and variance equal to the sample mean and sample variance of the collected data. The histogram is scaled in the figure so as to match visually the Gaussian graph. In this example with dipolar and exchange interactions we found by extrapolation that 2^{72} of the 2^{100} possible states are stable, and we conclude that the limiting capacity of this medium is 0.72 bits per grain. Finite temperature induced jumps and random read/write and electronics noise will further reduce the capacity and are currently being investigated.

Even the 10×10 patch is very small on a scale of real media and may be expected to exhibit unphysical edge effects. To assess this effect we calculated a histogram like that of Fig. 3 for a 10×10 patch at the center of a 30×30 medium. The shape of the resulting histogram is similar to Fig. 3, but the peak is shifted to the right (to a larger number of unstable grains). This results in a reduction of the histogram's intercept, thus a further reduction of the storage capacity.

In the examples presented in this section, the capacity figures are computed through making a count of stable configurations. There is no simulation of the relaxation process of the medium by an annealing algorithm. For the arguments presented in this section, such direct simulation is unnecessary, since the annealing algorithm must terminate in a stable configuration. Direct simulation of relaxation will be helpful in determining how effectively proposed recording processes can approach the capacity limits presented here.

IV. Conclusions

A simple physically based magnetic medium model and a new analysis method have led to the computation of storage capacity values for small patches of a medium. The capacity values presented here are computed directly from the medium model. Further simulations are underway to extend these results to larger patches which might reasonably be considered to represent an entire medium. We have observed grain group phenomena; these effects remain to be quantified. Another phenomenon under investigation is the effect of finite temperature fluctuations on achievable storage capacity. The effect of particular recording schemes, physical properties of heads, data coding strategies, and equalization techniques are topics currently under study. We anticipate using similar physically based models for each component of magnetic recording systems. This medium model and analysis will be key components of a new framework of a finite state machine information channel model for the physical magnetic recording channel.

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