A Fast Microtrack Simulator for High-Density Perpendicular Recording

Marcus N. Marrow, Michael K. Cheng, Paul H. Siegel, and Jack K. Wolf

***Abstract*—We present a fast waveform simulator based on the microtrack model for high-density perpendicular recording. The simulator characterizes dominant noise sources to create realistic recording outputs that allow useful evaluation of modern software channels. A novel model architecture was developed to overcome the computational burden due to the long perpendicular response. Speed and distortion tradeoffs are quantified and indicate that a throughput of 1 Mbps can be achieved with negligible distortion on a contemporary desktop computer.**

***Index Terms*—Data simulator, microtrack, perpendicular recording.**

I. INTRODUCTION

WE DEVELOPED a fast waveform simulator to facilitate the evaluation of modern signal detectors and error control codes with high-density perpendicular recording. The principle of the simulator is based on the microtrack model, discussed in Section II, that represents the physics of recording through the use of stochastic signal processing. The model accounts for the dominant noise source in current hard drives, media noise. However, extension of the model to perpendicular recording introduces a computational bottleneck due to the long transition response. In Section III, we present a novel architecture to overcome this challenge in which linearity of the component operations is exploited through operation reordering to significantly lower the model computational complexity. In particular, the repeated additions of the perpendicular transition response were reduced to a single convolution with an intermediate waveform consisting of the sum of shifted impulses. Furthermore, the above reconstruction filter was shortened by an order of magnitude by taking advantage of the dc-free nature of the intermediate waveform and splitting the filter into an accumulator and a filter representing the truncated derivative of the original response. In Section IV, we quantify distortion and speed tradeoffs. In Section V, we discuss how to incorporate dc noise, track curvature, and nonuniform track width effects in order to further increase the accuracy of the simulator.

II. MICROTRACK MODEL

The main source of distortion in magnetic recording is transition noise caused by the granularity of the media. Caroselli and Wolf [1], [2] introduced the microtrack model as an efficient approach to accurately simulate transition noise. The model divides the track along which the signal is written into N_t smaller "microtracks," each containing an ideal step response shifted from the center of transition as illustrated in Fig. 1. A mathematical description of the model output is given by

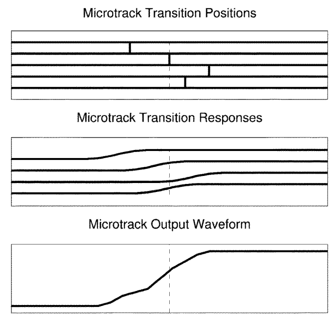

Fig. 1. Conceptual illustration of the microtrack model for a single transition with four microtracks. Dashed line marks the ideal center of transition.

$$s(t) = \frac{1}{N_t} \sum_{k=0}^{L-1} \sum_{i=0}^{N_t-1} a_k h(t - kT - \tau_{i,k}) \tag{1}$$

where $h(t)$ is the step response of a single microtrack, $\tau_{i,k}$s are i.i.d. random shifts of the kth transition on the ith microtrack track, and $a_k = u_k - u_{k-1}$ represents transitions in the user data u_k from a sector of length L and bit period T. The random shifts are drawn from a distribution derived from the average magnetization transition profile and given by

$$F(\tau) = P(x \le \tau) = \frac{1}{2}\left(1 + \tanh\left(\frac{2\tau}{\pi a}\right)\right). \tag{2}$$

The response $h(t)$, of length l_h bits, and model output $s(t)$ are typically sampled at a multiple X_s of the bit rate. Direct implementation of (1) would require the generation of N_t random numbers and $N_t \cdot l_h \cdot X_s$ additions per bit. This linear dependence of the channel response length causes a computational bottleneck when the model is applied to thin-film perpendicular media as the transition response is orders of magnitude longer than for longitudinal recording.

III. SIMULATOR ARCHITECTURE

A significant reduction in the model computational complexity can be achieved by reordering the operations in (1). Rather than adding long shifted responses, delta functions

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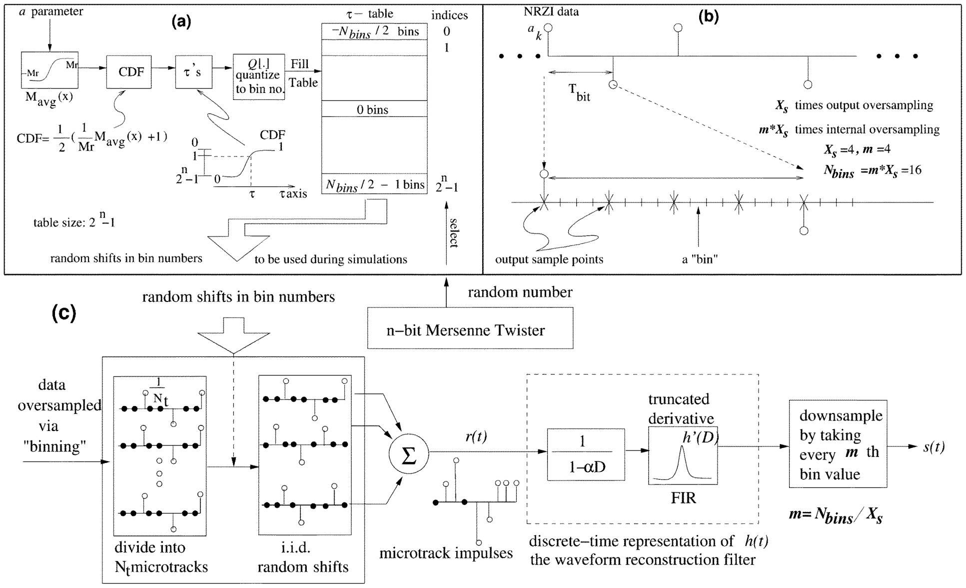

Fig. 2. (a) Create τ table, (b) oversample by "binning," and (c) simulator flow.

located at the shift centers are summed and a single final convolution is performed

$$s(t) = \underbrace{\left[\frac{1}{N_t}\sum_{k=0}^{L-1}\sum_{i=0}^{N_t-1} a_k \delta(t - kT - \tau_{i,k})\right]}_{r(t)} \otimes h(t) \qquad (3)$$

where $r(t)$ is the intermediate waveform. The number of operations per bit is reduced to $N_t + l_h \cdot X_s$. The operation reordering is depicted in Fig. 2. Given this reordering, the model implementation consists of the following tasks.

1) Generate uniform random numbers (URNs).
2) Convert the URNs to $\tau_{i,k}$ and shift the impulses.
3) Sum the impulses to form $r(t)$.
4) Convolve $r(t)$ with $h(t)$ to obtain $s(t)$.

The waveform $h(t)$ (and, hence, $s(t)$) is of finite duration and, thus, not band limited. Aliasing will be introduced by sampling. A higher sampling rate reduces this distortion, but also incurs a throughput penalty. Typically, $X_s = 4$ is sufficient to represent $s(t)$ at current recording densities. However, the intermediate waveform $r(t)$ has high frequency components and requires an internal sampling rate higher than X_s. Oversampling is performed by partitioning each bit period into N_{bins} discrete "bins." The number of time-quantization bins was constrained to be a multiple of the final sampling rate X_s to simplify the sampling rate conversion. During simulation, the Mersenne Twister algorithm, which has been shown [3] to have good statistical properties for long sequences, is used to generate uniform random numbers to index into a lookup table and pick out the shift value for each transition on each microtrack. As each bin has width $(1/N_{\text{bins}})$, the operation of summing each impulse to form $r(t)$ is equivalent in the discrete-time domain to incrementing the bin corresponding to the shift value $\tau_{i,k}$ by a quantity (N_{bins}/N_t). The final waveform is constructed by passing $r(t)$ through an accumulator and an FIR filter. The $F(\tau)$ lookup table is created by filling the entries with shifts derived from the distribution of (2). The simulator can be made more accurate by incorporating a perpendicular average transition profile obtained through theory or measurements. To increase the simulator speed, the shift values are first quantized into bin counts before populating the table. Monte–Carlo simulations were run to quantify the simulator speed and accuracy for a range of N_{bins}, as shown in Fig. 3. The accuracy was measured as the mean-square error (mse) with respect to a reference waveform generated with $N_{\text{bins}} = 128$. The average execution time spent in each task for the same simulation parameters is shown in Fig. 4.

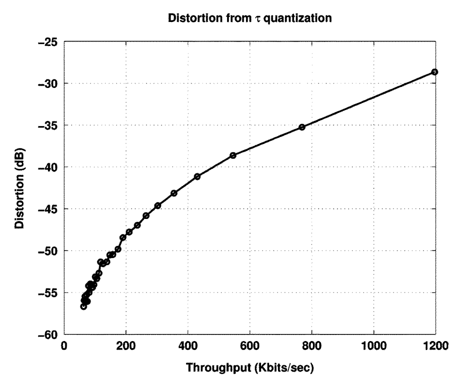

Fig. 3. Throughput versus distortion.

IV. Filter/Implementation Optimization

The transition response of thin-film perpendicular media is shown in Fig. 5 and is characterized by its long tails which results in the final convolution requiring significant computational effort. Direct truncation by a window $W[\cdot]$ of the response $h(D)$ causes large distortion. Its slow decay suggests

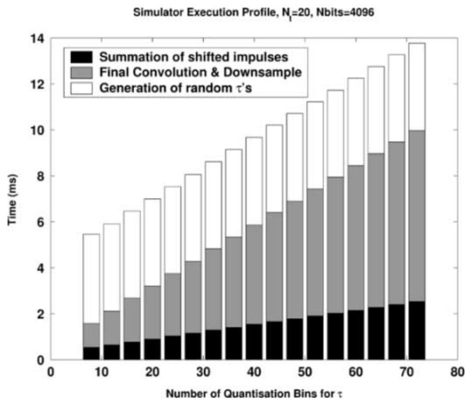

Fig. 4. Throughput versus internal sampling rate.

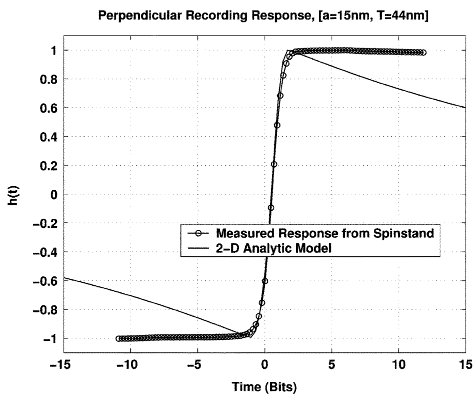

Fig. 5. Perpendicular recording response.

that shortening its discrete-time derivative, which has many near-zero coefficients, introduces less error

$$h(D) = \frac{1-D}{1-D}h(D) = \frac{h'(D)}{1-D} \tag{4}$$

$$\approx \frac{W[h'(D)]}{1-D} \tag{5}$$

A quantitative analysis was made of the truncation error by simulating random data sectors. The tails of the response predicted by a two-dimensional analytic model [4] fall faster than the response estimated from spin-stand data, which leads to larger truncation error. Decreasing the window length increases the simulator throughput at the expense of distortion, as seen in Fig. 6. Viewing the effect of truncating $h'(D)$ in the frequency domain reveals the elimination of the notch at dc. The error is reduced by further filtering with a high pass filter of the form $H(D) = (1 - D/1 - \alpha D)$ where α is close to 1, reintroducing the notch at dc which causes the droop in the truncated response. This filter requires no extra computation

$$h_\alpha(D) = \frac{1-D}{1-\alpha D} \cdot \frac{W[h'(D)]}{1-D} = \frac{W[h'(D)]}{1-\alpha D}. \tag{6}$$

The improved matching can be seen in Fig. 7 and the corresponding decrease in waveform distortion in Fig. 6. As the waveform is decimated by (N_{bins}/X_s) directly after the final convolution, the operations may be combined to eliminate redundant computations by only computing one in every (N_{bins}/X_s) outputs.

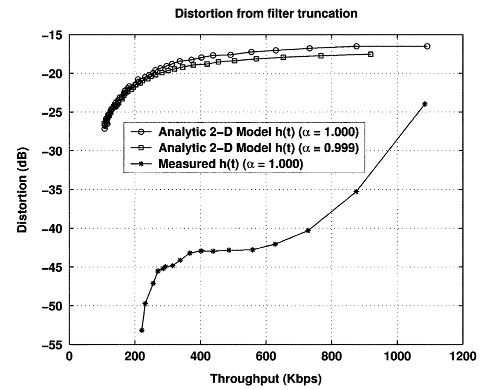

Fig. 6. Distortion versus throughput.

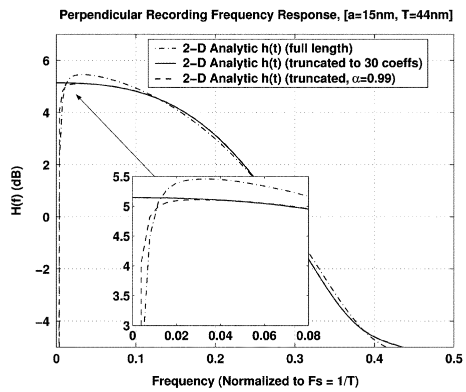

Fig. 7. Frequency response of truncated h(t).

V. Other Noise Effects

As the structure of the microtrack model is based on recording physics, additional media nonidealities can be included with minimal computational overhead. In particular, nonuniform track width and track edge curvature can be modeled by weighting the microtracks by a width profile w_k and shifting the microtrack transition locations by a track curvature profile c_k. Including these effects and modeling the dc noise as additive Gaussian noise produces the more realistic waveform

$$s(t) = \sum_{k=0}^{L-1} \frac{a_k w_k}{N_t} \sum_{i=0}^{N_t-1} h(t - kT - \tau_{i,k} + c_k) + n_{\text{dc}}(t). \tag{7}$$

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