

Synchronization and Detection for Two-Dimensional Magnetic Recording

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Abstract — The subject of this project is *two-dimensional signal processing* — the joint processing of multiple readback waveforms from neighboring tracks so as to recover the recorded user bits. Two-dimensional signal processing promises significant increases in areal density, in part because it facilitates the elimination of guard band inefficiencies, in part because it enables shingle writing strategies, and in part because it enables the use of larger and more sensitive read heads. The combination of shingle write recording and two-dimensional readback detection is known as two-dimensional magnetic recording (TDMR). Before the promises of TDMR can become a practical reality, however, further advances in signal processing algorithms are required.

This research proposal describes a research project that explores two fundamental questions:

- How best to performing timing recovery (downtrack) and position recovery (crosstrack)? This is the 2-D extension of the timing recovery problem. The challenge is to achieve reliable performance with reasonable complexity despite the low SNR expected for a TDMR system.
- How best to implement a soft-output channel detector that efficiently accounts for both the intersymbol interference and the intertrack interference? The challenge is to find the right balance between performance and complexity, since the optimal 2-D soft-output detector is prohibitively complex.

We choose to focus on these two questions for two reasons:

- Synchronization and detection algorithms are often the bottleneck to either the performance achieved by the read channel, or to its overall complexity.
- We are interested in the *interaction* between synchronization and detection, with the hope that a practical synchronization strategy will be able to exploit the error-control coding in an iterative setting to improve performance.

Our aim is to develop synchronization and detection strategies that have reduced complexity and yet are capable of approaching the performance of optimal strategies (which are prohibitively complex).

I. RESEARCH DESCRIPTION

1. Introduction

A. The 2-D Advantage

A conventional 1-D readback strategy uses a single read head that is carefully aligned to the center of the track to avoid interference from neighboring tracks. See Fig. 1-a. To avoid excessive intertrack interference, the size of the read head is typically smaller than the track width, which prevents the read head from capturing all of the signal energy from the desired track. In contrast, a 2-D readback strategy jointly and simultaneously processes the readback waveforms from multiple neighboring tracks [1–5]. These multiple waveforms may arise from an array of read heads, roughly one for each track, or they may arise from a single read head that makes multiple passes over neighboring tracks in multiple revolutions. Either way, a key advantage of 2-D processing is that it relaxes the severe size, SNR, and read-tracking constraints of a 1-D system. A 2-D system can use a read head that is comparable in size to the track width, and enjoy the resulting increase in SNR. See Fig. 1-b. A 2-D system has relaxed tracking requirements during the readback process, since any energy from the desired track not captured by one head will be captured by a neighboring head. In effect, the 2-D signal processing can compensate electronically for a fair amount of sloppiness in readback tracking. Finally, another benefit of 2-D processing is that enables an increase in areal density by eliminating the guard bands between tracks. In summary, a 2-D system is able to *embrace* ITI rather than avoid it. Just as there was a significant increase in areal density when peak detection strategies (which avoid ISI) were replaced by PRML strategies (which embrace ISI), so too can we expect a similar jump in areal density when 1-D strategies (which avoid ITI) are replaced by 2-D strategies (which embrace ITI).

B. Project Scope and Relationship to Other Projects

This project is limited to the signal processing tasks of synchronization and detection during readback. As such, this project will not attempt to design two-dimensional error-control or run-length-limited codes, for example, nor will it develop new models for the TDMR channel. Instead we will coordinate with the investigators of other projects, as well as with other ASTC members,

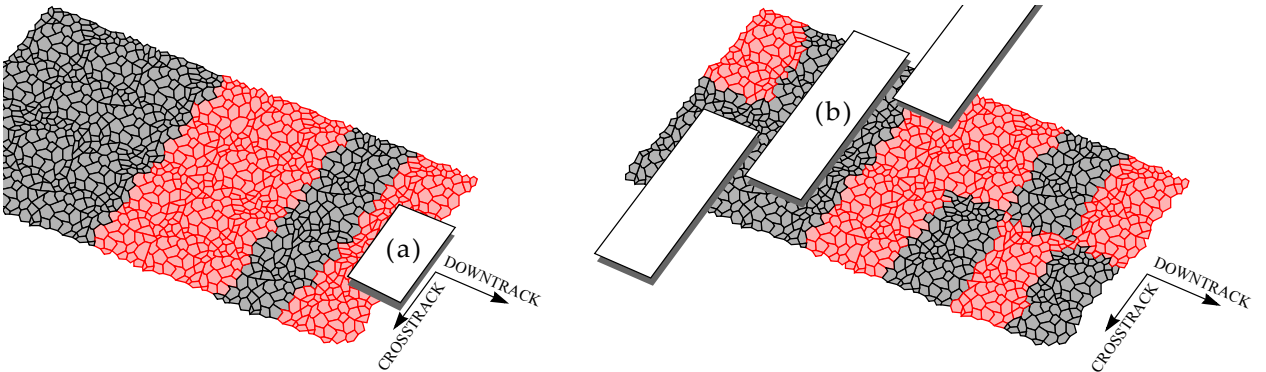


Fig. 1. With 2-D signal processing, a small read head (a) that is carefully aligned with the center of the track can be replaced by multiple read heads (b) that can be larger and more loosely aligned. Dimensions are exaggerated. (In practice the read-head array might be virtual — implemented using multiple passes of a single read head.)

and use the best-available codes and models in our research [6–8]. As models are refined and improved we will incorporate these changes into our simulation platform.

2. Research Tasks

A. Synchronization at Low SNR

In a conventional 1-D readback channel, *timing recovery* is the process of synchronizing the sampling times of the analog readback waveform to align with the positions of the pulses. Timing recovery today is more difficult than it once was, primarily because — thanks to modern error-control codes such as LDPC codes — the operating SNR is smaller than ever before. In prior work, the PI and colleagues developed a variety of *iterative* timing recovery strategies that are able to exploit the presence of the error-control code to improve timing recovery performance at low SNR [9–20].

In this project we will study the 2-D analog of the timing recovery problem. On the magnetic medium itself, the two dimensions (downtrack and crosstrack) are roughly interchangeable, especially when the bit-aspect ratio approaches one: we can expect that neighboring bits in the crosstrack direction will interact in the same way as neighboring bits in the downtrack direction. However, the proposed TDMR readback process — involving either an array of heads or multiple passes from a single head — will destroy this symmetry. Specifically, in producing a set of readback waveforms, one for each head, the TDMR readback process fundamentally *discretizes* the crosstrack dimension but not the downtrack dimension. If the read heads are not perfectly positioned in the first place (as is the case in Fig. 1-b), then synchronizing the sampling times of each waveform will not be enough to compensate. What is needed is a strategy for jointly choosing the sampling times of the A/D converters (one for each head) and interpolating the resulting sequences along the spatial dimension.

Conceptually one can formulate a strategy by thinking of the 2-D synchronization problem as an exercise in image processing. Indeed, a recent experimental demonstration of the TDMR concept used magnetic-force microscopy images as an alternative to an array of read heads for readback [21]. Such an MFM image is what would also arise from a dense array of small read heads (one for each row of pixels), when each readback waveform is oversampled with a sampling rate chosen so that each square pixel corresponds to a corresponding square on the medium. When the pixel size is small relative to the size of a bit cell, such an image represents a 2-D signal that is oversampled in both dimensions, so that the samples are sufficient to represent (in a Nyquist sampling theorem sense) the underlying 2-D analog readback waveform:

$$r(t_1, t_2) = \sum_m \sum_n a_{m,n} g(t_1 - mT_1 - \tau_{m,n}^{(1)}, t_2 - nT_2 - \tau_{m,n}^{(2)}) + n(t), \quad (1)$$

where:

- t_1 represents the downtrack dimension, t_2 represents the crosstrack dimension
- $a_{m,n} \in \{\pm 1\}$ is the m -th information symbol in track n
- $g(t_1, t_2)$ is the 2-D pulse shape, after a matched filter
- T_1 is the bit period and T_2 is the track period
- $(\tau_{m,n}^{(1)}, \tau_{m,n}^{(2)})$ is the position offset of the $(m, n)^{\text{th}}$ pulse

- $n(t)$ is the matched-filtered additive noise.

If there were no timing offsets ($\tau_{m,n}^{(i)} = 0$), we would want to sample the $(m, n)^{\text{th}}$ pulse at $t_1 = kT_1$ and $t_2 = jT_2$. This would amount to sampling the 2-D surface along the rectangular lattice $\{(kT_1, jT_2): k, j \in \mathbb{Z}\}$. Taking into account the timing offsets, however, the optimal sampling times for the $(m, n)^{\text{th}}$ pulse are $t_1 = kT_1 + \tau_{m,n}^{(1)}$ and $t_2 = jT_2 + \tau_{m,n}^{(2)}$. The problem is that the offsets $(\tau_{m,n}^{(1)}, \tau_{m,n}^{(2)})$ are not known and must be estimated.

As a part of this project we will investigate a 2-D PLL, which will accumulate (and filter) estimates of residual timing error from “past” pulses to produce an estimate of the timing offset for the current pulse. Causality is not uniquely defined on the plane, and hence there are some choices to be made. For example, if only a single read head is used for readback, but with multiple passes, then it would make sense to let the crosstrack dimension take precedence over the downtrack dimension, so that the timing offsets for the current track would benefit from the history of not only the previous samples of the current track, but also all of the samples of the previous tracks. On the other hand, if the read-head array is not virtual, then it would make sense to let the downtrack dimension take precedence over the crosstrack dimension, so that the timing offsets for the current set of samples (one for each read head) could take advantage of all of the previous samples from all of the read heads.

The natural ordering of time in the 1-D setting simplifies the PLL design. The only degrees of freedom are the timing-error detector and the loop filter. A 2-D PLL will need not only a 2-D timing-error detector (see [22]) and a loop filter, but also a strategy for ordering different points in the plane. The first multidimensional PLL was proposed by the PI and his colleague in the context of multiuser detection [23][24]. The setting was different, and the aim was a multidimensional extension of the carrier recovery problem rather than the timing recovery problem, but we nevertheless are hopeful that our experience with higher-dimension extensions of the PLL will prove to be useful in the proposed research.

The 1-D PLL enjoys many advantages, including its effectiveness, robustness, and low complexity. The PLL is widely used and is a true workhorse. We are hopeful that at least some of these attributes will be retained as the PLL is extended to two dimensions.

2-D Interpolative Synchronization

As a part of this work we will examine batch signal processing strategies that do not synchronize the A/D converter clock directly, but instead sample asynchronously (across both dimensions) and use 2-D synchronization along with interpolation to arrive at the synchronized samples. This is the 2-D analog of interpolative timing recovery [25]. The interpolative approach is especially advantageous when the pulse shape is bandlimited and the asynchronous samples are taken at a high enough rate to ensure that the Nyquist sampling theorem is satisfied, so that they capture everything desired about the recorded bits. In other cases, a nominal level of synchronization may be necessary to avoid a performance loss. A key advantage the interpolative approach is that it opens the door to 2-D iterative synchronization, a 2-D extension of 1-D iterative timing recovery [9–20].

Scan Alignment

A virtual read-head array must contend with the *misalignment* problem, in which the alignment between the readback waveforms from multiple passes of the read head are not fully synchronized. At one level this problem can be dealt with implicitly with any generic

synchronization strategy, including the 2-D PLL. However, there may be performance and complexity advantages to an explicit scan alignment step. We will explore this possibility and evaluate the potential performance gains.

B. Soft-Output Detectors for Iterative Processing

One scan with an array of M read heads will produce a set of M readback waveforms $\{r^{(1)}(t), \dots, r^{(M)}(t)\}$. A perfectly synchronized linear model for the i -th waveform is:

$$r^{(i)}(t) = \sum_m \sum_n a_{m,n} h_{i,n}(t - mT) + n^{(i)}(t), \quad (2)$$

where:

- $a_{m,n} \in \{\pm 1\}$ is the m -th information symbol in track n
- $h_{i,n}(t)$ is the readback pulse at head i due to a transition on track n
- $n^{(i)}(t)$ is the additive noise for the i -th waveform

Sampling the i -th readback waveform at the bit rate will produce a discrete-time model:

$$r_k^{(i)} = \sum_m \sum_n a_{m,n} h_{i,n}(kT - mT) + n_k^{(i)} \quad (3)$$

or in matrix form:

$$\mathbf{r}_k = \sum_m \mathbf{H}_k - m \mathbf{a}_m + \mathbf{n}_k, \quad (4)$$

where $\mathbf{r}_k = [r_k^{(1)}, \dots, r_k^{(M)}]^T$, $\mathbf{n}_k = [n_k^{(1)}, \dots, n_k^{(M)}]^T$, $\mathbf{a}_m = [a_{m,1}, \dots, a_{m,N}]^T$, and where $\mathbf{H}_k$ is a matrix whose entry in row i and column j is equal to $h_{i,j}(kT)$, i.e., the k -th sample of the readback pulse at head i due to a transition on track j .

In (4) we recognize the familiar multiple-input multiple-output (MIMO) channel model that arises in a variety of applications, including wireless communications using antenna arrays [26]. There are well-established strategies for hard-output [27][28] and soft-output [29–31] detection of MIMO channels, some of which were developed by the PI and his colleagues, and we intend to leverage our prior work in this area. However, there are important distinctions that make the TDMR model unique:

- The $M \times N$ channel matrix $\mathbf{H}_k$ will have more columns than rows. It will thus be underdetermined. For example, if each read head captures energy from not only the primary track but also from the L neighboring tracks on both sides, so that the ITI span is $2L + 1$, then the dimensions of the $M \times N$ channel matrix will satisfy $N = M + 2L$. The implication is that we cannot expect to reliably recover the recorded bits from all of the tracks based on just one scan of the read head array. Only the center track or tracks will be reliably decodable.
- The information recorded on a single track will impact multiple scans of a read-head array.

For these reasons, we should not look at the model of (2) or (4) in isolation, since this would limit performance. Instead, for best performance we should exploit the observations from multiple scans of the read-head array when making decisions. This observation is not substantially different from the observation that decisions in a 1-D ISI channel should not be made on a

sample-by-sample basis, but instead should be based on a large window of observations, and ideally on the entire observation sequence. A key distinction is that the 1-D maximum-likelihood sequence detector is implementable with reasonable complexity, in the form of the Viterbi algorithm. In contrast, the 2-D maximum-likelihood detector is conceptually well-understood but is an NP-complete problem [32]; there is no known algorithm for efficient implementation.

There has been more than two decades of progress on the 2-D equalization problem. Early work on multi-track detection focused on reduced-complexity hard-output detectors [33–37]. Chen and Chugg proposed to view the 2-D channel as the serial concatenation of two 1-D channels, and to use iterative detection techniques analogous to those used for decoding of serially concatenated turbo codes [38]. Their algorithm had high complexity but good performance. Wu *et al.* took a similar approach and developed a reduced-complexity row-column iterative detector for the special case when the 2-D ISI channel is *separable* into a concatenation of 1-D channels [39]. Unfortunately, the 2-D ISI experienced in a TDMR system will not be separable. Ozaki *et al.* proposed an ITI cancellation strategy in the single-read-head scenario, in which soft information from a previously decoded track is stored and used to cancel interference on a neighboring track [40]. Fujii and Shinohara recently proposed an iterative ITI cancellation strategy for the multi-track scenario [41].

The 2-D detection in TDMR problem shares many similarities with page detection in two-dimensional optical storage, but there is also a key difference: In 2-D optical storage, the detector generally has access to an image representing the entire page of storage. In stark contrast, it is not practical for a TDMR detector to scan the entire disk before making decisions. Rather, practical constraints will force a TDMR system to make decisions about the bits stored on a single track based on only a handful of readback waveforms, possibly with the aid of soft information stored about neighboring tracks that were previously decoded [40][41].

Our plan of attack for the soft-output detection problem is to take full advantage of prior work [33–46]. There are already several candidate algorithms on the table, and we suspect that a winning strategy will need to incorporate many of the approaches already developed in prior work. At this stage we suspect a combination of soft or hard intertrack cancellation along with a reduced complexity soft-output detector such as the soft-feedback equalizer [47–49] will achieve good performance with reasonable complexity. We will implement an iterative detector that iterates between the soft-output detector and an error-control decoder in a turbo-like fashion. Of particular interest to us is the concept of *iterative synchronization*, whereby soft information from the soft-output detector is used to improve the initial timing estimates and resynchronize the original samples through interpolation.

We have some experience with iterative synchronization in the 1-D setting [4–20]. At the same time, the community has long recognized the challenges of 2-D detection. While it is difficult to imagine a provably optimal solution, our aim is to explore the gains that might be attained by iterative synchronization in the 2-D setting, and to develop practical algorithms with low complexity. Our previous record along these lines is good and we are inspired by the challenge of the problem.

Related Issues

The performance of 2-D detection will be highly dependent on the size, geometry, and spacing of the read-head array. At the same time, the best design for the array geometry will depend in part on how the 2-D signal processing performs. We thus hope to get feedback on the geometry to

facilitate our algorithm development, and we likewise hope that our algorithms may prove useful in the design of the array geometry. We may even want to consider a “shingle read” strategy to complement the shingle write strategy, where the read head width is much wider than the track width, and where there is significant overlap between neighboring heads (say 80% or more instead of the 20% or so shown in Fig. 1-b).

The problem of target design for TDMR is an important one that will significantly impact both performance and complexity. For example, because of the clear performance and complexity advantages to a separable 2-D target, one might pose the target design problem as one of finding the 2-D separable target that is closest to the underlying 2-D channel model, so that equalization to the nearest separable target would incur minimal noise enhancement. Our project is not directly concerned with the target design problem [50], but at the same time the best choice for a target will depend in part on how the 2-D detector will be implemented.

3. Likely Outcomes

This project will support one graduate research assistant for one year. We expect to produce the following outcomes:

- a simulation platform for studying signal processing strategies in two-dimensional magnetic recording
- synchronization strategies and algorithms for two-dimensional magnetic recording
- soft-output detection strategies and algorithms for two-dimensional magnetic recording
- iterative synchronization strategies that jointly perform the tasks of synchronization and detection
- presentations at ASTC quarterly meetings
- one or more conference or journal publications

II. RESOURCES REQUIRED

As outlined in the budget, this project supports one GRA student for 12 months and the PI for one month. No other personnel will be charged. The research will be performed using Georgia Tech computers and other resource. The work will be theoretical in nature, with some algorithm development and computer simulations. No experimental equipment or resources are required.

III. RESOURCES OTHER THAN ASTC FUNDING DEDICATED TO PERFORM PROJECT

The PI has no existing grants or contracts that are concerned with the tasks described in this proposal.

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V. RESOURCES REQUESTED FROM ASTC AND HOW THEY WILL BE UTILIZED

1. Funding

Barry (1 month)	\$11,184
GRA (12 months)	\$23,700
Total Personnel Services	\$34,884
Fringe 26.1% Faculty	\$ 2,919
Health Insurance Support 0.8% GRA	\$ 190
Total: PS and Fringe:	\$37,993
Materials and Supplies	\$ 2,000
Travel	\$ 4,000
Total Direct Costs	\$43,993
Overhead (57.1%)	\$25,120
Tuition for GRA	\$12,364
TOTAL	\$81,476

2. Budget Justification

A. Senior Personnel — Professor Barry requests 1 month of salary for the project.

B. Other Personnel — The remaining portion of the labor costs is dedicated to providing support for one Graduate Research Assistant (GRA). The GRA direct costs include a monthly stipend, fringe benefits and tuition. The ECE GRA salary rate at the PhD level at 33% time is \$1,316.65 per month.

C. Fringe Benefits — A fringe benefit rate of 26.1% has been applied to Prof. Barry's salary. Health Insurance has been applied to the GRA salary at 0.8%.

D. Supplies and Materials — The budget includes \$2,658 for conference registration fees which are between \$400 and \$900, depending on the event, sponsors, and organizers.

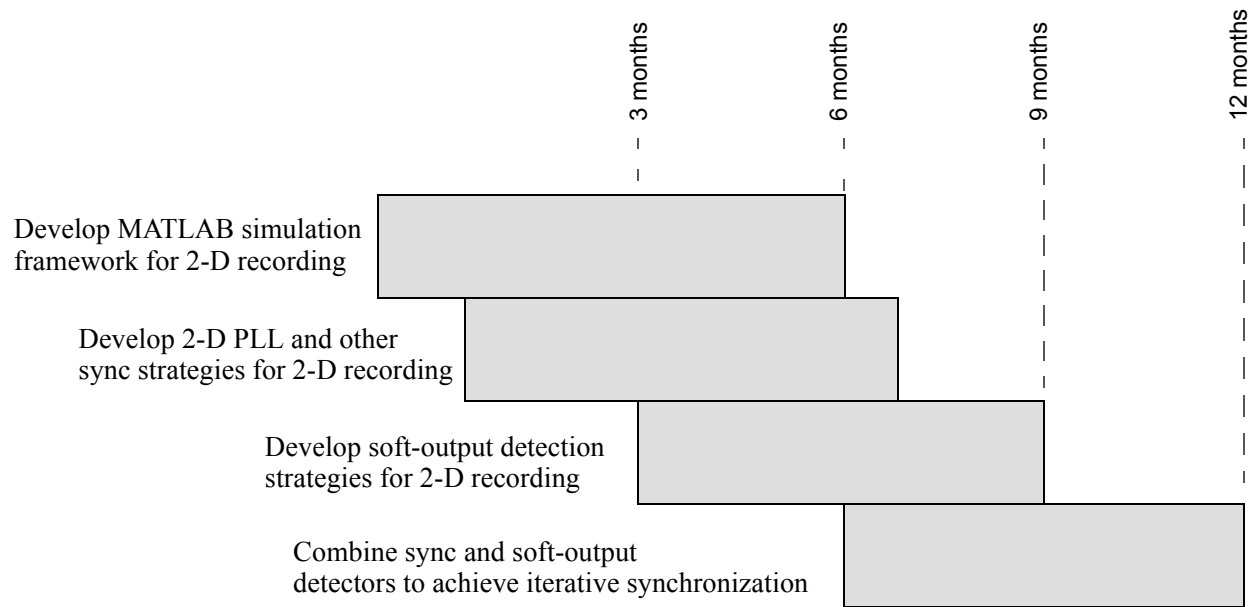
E. Travel — The travel budget includes \$4,000 for the personnel to attend the quarterly ASTC meetings. Students will present research results in conferences and workshops.

F. Tuition — The full-time graduate student tuition at Georgia Institute of Technology is currently at \$1,030.32 per month. The rate follows the percentage of effort by the GRA for the 12 months of the academic year.

G. Facilities and Administration Expense Rate (Overhead) — Georgia Institute of Technology and ONR have negotiated the indirect cost recovery rate of 57.1% for industry grants. This rate is assessed over all direct costs except for tuition.

VI. TIME LINE

This 12-month project involves four tasks. A tentative schedule is shown below.



VII. BIOGRAPHICAL SKETCH

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EDUCATION

Ph.D. in Electrical Engineering, University of California at Berkeley, 1992
M.S. in Electrical Engineering, University of California at Berkeley, 1987
B.S. in Electrical Engineering, State University of New York at Buffalo, 1986

ACADEMIC APPOINTMENTS

Georgia Institute of Technology, Assistant Professor, 1992 — present
University of California at Berkeley, Research Assistant, 1988 — 1992
University of California at Berkeley, Graduate Student Instructor, 1986 — 1987

INDUSTRY EXPERIENCE

IBM T. J. Watson Research Center, Hawthorne, NY, Summer 1990
Bell Communications Research, Red Bank, NJ, Summers 1987 and 1988
General Dynamics, Pomona, CA, Summer 1986
Hughes Aircraft Company, Fullerton, CA, Summer 1985
General Motors — Chevrolet, Buffalo, NY, Summer 1984

RELATED PUBLICATIONS

P. Kovintavewat and J. R. Barry, *Iterative Timing Recovery: A Per-Survivor Approach*, VDM Verlag, 2009.

E. Chesnutt, R. Lopes, and J. R. Barry, “Beyond PRML: Linear-Complexity Turbo Equalization Using the Soft-Feedback Equalizer,” *International Magnetics Conference (Intermag 2005)*, pp. 1599-1600, Nagoya, Japan, April 4-8, 2005.

P. Kovintavewat and J. R. Barry, “Interpolated Timing Recovery,” chapter, *CRC Handbook on Magnetic Recording*, CRC Press, 2004.

J. R. Barry, A. Kavcic, S. W. McLaughlin, A. Nayak, and W. Zeng, “Iterative Timing Recovery,” *IEEE Signal Processing Magazine*, pp. 89-102, January 2004.

J. R. Barry, E. A. Lee, D. G. Messerschmitt, *Digital Communications, Third Edition*, Boston: Kluwer Academic Publishers, 2003.

A. Nayak, J. R. Barry, and S. W. McLaughlin, “Joint Timing Recovery and Turbo Equalization for Coded Partial Response Channels,” *IEEE Transactions on Magnetics*, Vol. 38, No. 5, pp. 2295 - 2297, September 2002.