Frame Synchronization for PPM-encoded Longitudinal Position Words in Magnetic Tape Storage

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Abstract—Frame synchronization is studied for pulse-position modulation-encoded longitudinal position (LPOS) words that are embedded in servo patterns written on tape. After introducing soft-output detection of LPOS symbols, the problem of LPOS frame synchronization using soft outputs from the LPOS detector is considered. An efficient LPOS frame-synchronization algorithm that is robust in the presence of transition noise found in magnetic recording channels is then proposed. Finally, the performance of hard-decision LPOS frame synchronization is compared by simulations with that of the proposed soft-decision algorithm, and a hardware implementation of the overall scheme is illustrated.

I. INTRODUCTION

Timing-based servo (TBS) [1] was first introduced in tape drive systems in 1995. In TBS systems, recorded servo patterns consist of magnetic transitions with two different slopes. The head position can be derived from the relative timing of pulses generated by a narrow servo head reading the servo patterns. TBS servo patterns also allow the encoding of additional longitudinal position (LPOS) information without affecting the generation of the transversal position-error signal (PES). LPOS symbols are encoded using pulse-position modulation (PPM). A critical issue in reliable LPOS detection is frame synchronization, i.e., the task of determining the position of the synchronization word in a stream of LPOS symbols received.

Various frame-synchronization techniques have been used in digital communication receivers [2]. In early work, the concept of the correlation decision rule was introduced. An optimum frame-synchronization algorithm for antipodal binary signals received in the presence of additive white Gaussian noise (AWGN) was proposed in [3]. Thereby the correlation decision rule was modified by an additive correction term that depends on the signal-to-noise ratio (SNR). Simulation results have demonstrated that the high-SNR approximation of the optimum algorithm in [3] performs very well [4]. Optimum frame synchronization for Gaussian channels with coherent and noncoherent phase demodulation was considered in [5].

In this paper, frame synchronization for LPOS words that are embedded in servo patterns written on tape is considered. A magnetic recording channel is characterized by disturbances that differ considerably from those of classical communication systems. In particular, the presence of transition noise may lead to nonnegligible performance impairment for the detection of PPM encoded symbols, as compared to systems that operate over AWGN channels. This performance impairment is especially severe if simple detection schemes based on the observation of the shifts of the dibit pulse peaks are adopted, as done in the case of legacy servo channels for tape drives. As the requirements in terms of track density become more stringent, more sophisticated signal-processing techniques that generate estimates for the operation of reel-to-reel and track-follow servomechanisms must be applied to servo channels in order to improve system reliability.

To obtain a reliable frame-synchronization algorithm for LPOS words, soft-output detection of LPOS symbols is introduced first. Then the discrete-time soft outputs generated by the detector are used to perform frame synchronization. A robust and computationally efficient soft-output frame-synchronization algorithm for LPOS words is proposed that outperforms hard-decision-based synchronization methods, and can readily be implemented in hardware, as demonstrated by a field-programmable gate array (FPGA) realization of the overall scheme.

The paper is organized as follows. The encoding of LPOS symbols in linear tape open (LTO*) format and the corresponding channel model are presented in Section II. The generation of soft decisions at the LPOS detector output and an LPOS frame synchronization algorithm using soft decisions from an LPOS detector are proposed in Section III. Section IV describes an efficient LPOS frame-synchronization algorithm for application in tape drive systems. Simulation results and a hardware realization of the overall scheme are presented in Section V. The paper concludes with Section VI.

II. ENCODING OF LPOS INFORMATION AND CHANNEL MODEL

The LTO consortium adopted the TBS approach and standardized a scalable dedicated servo pattern for LTO tape drives allowing backward compatibility [6]. In all LTO standards, four data bands are straddled by five servo bands, which are 186 µm wide. Therefore, for each data band there are two dedicated servo channels from which LPOS information as well as PES can be derived during write or read operations. About 84% of tape is reserved for recording data, whereas the remaining area is used for guard bands and dedicated servo bands. Fig. 1 depicts an LTO servo frame in any of the five servo bands, corresponding to one 200-µm period of the overall LTO servo pattern [6]. The LTO servo frame consists of four servo bursts. The A and B bursts have 5 servo stripes, whereas the C and D bursts have 4 stripes. Each servo stripe consists of two magnetic transitions, which are 2.1 µm apart and written with an azimuth angle of ±6°. In the absence of LPOS encoding, all the servo stripes within a servo burst are spaced at a distance of 5 µm from each other.
The positions of the second and fourth servo stripe in the A and B bursts of a servo frame are modulated to encode one bit of LPOS information, where the shift of the servo stripe position corresponds to ±0.25 μm. Fig. 1 shows the encoding of one LPOS bit in an LTO servo frame consisting of subframe 1, which contains A and B bursts, and subframe 2, which contains C and D bursts. In LTO, LPOS information is comprised within an LPOS word that consists of 36 servo frames, corresponding to a tape length of 7.2 mm. Each 36-bit LPOS word starts with a fixed 8-bit synchronization word, followed by 24 bits of LPOS information and 4 bits of manufacturing information. The fixed 8-bit sync word pattern is 10000000, where the symbol ‘1’ is written first, assuming forward tape motion. Note that sync words in an LTO servo band are periodically embedded into the LPOS data stream, where the sync word is always repeated after a distance of 7.2 mm, corresponding to the length of one LPOS word on tape.

The channel model is based on longitudinal magnetic recording, which is commonly used in tape storage. The characteristics of the dibit pulses, which originate from the servo stripes written with an azimuth angle of ±6°, differ considerably from the dibits obtained at the output of a read channel. In fact, data channel dibit pulses are obtained by reading magnetic transitions that are written perpendicularly to the direction of tape motion, i.e., with an azimuth angle of 0°. Assuming a Lorentzian response to a 0°-azimuth magnetic reading, the dibit response is given by

\[ g_d(x; \alpha, W, P, m) = h(x; \alpha, W, P) - h(x-m; \alpha, W, P). \]

Spatial quantities may be translated to temporal quantities through the tape velocity; accordingly by referring to a first-order position jitter and width variation model [8], the signal obtained by reading a transition is expressed as

\[ h(t; \alpha, W, P) + \zeta \frac{\partial h(t; \alpha, W, P)}{\partial t} + \zeta \frac{\partial h(t; \alpha, W, P)}{\partial P} + w(t), \]

where \( \zeta \) and \( \zeta \) are Gaussian random variables, which have variances \( \sigma_f^2 \) and \( \sigma_w^2 \), respectively, and are independently generated at each transition; \( w(t) \) is AWGN. The channel SNR is defined as

\[ \text{SNR} = \frac{E_d}{N_0 + M_0}, \]

where \( E_d \) denotes the dibit energy, \( N_0 \) is the one-sided AWGN power spectral density, and \( M_0/2 \) is the average energy of the noise associated with a transition. The relative contribution of transition noise to the total noise is characterized by the parameter \( \beta = M_0/(N_0 + M_0) \).

### III. LPOS Detection and Frame Synchronization

Consider two signals \( s^0(t) \) and \( s^1(t) \) in the interval \((0, T)\), representing the hypothesized LPOS symbol values 0 and 1, respectively, where \( T \) denotes the duration of a servo frame. Each of the two signals consists of 18 dipulses, as can be seen from Fig. 1, where the positions of 4 of the 18 dipulses are modulated depending on the LPOS symbol value. The interference between dipulses is assumed to be negligible, as the distance between servo stripes in an LTO servo frame is sufficiently large. It is also assumed that both signals are nonzero for a time interval equal to at most \( T \) seconds and have the same energy \( E_s \). The sequence of LPOS symbols is represented by

\[ q(t) = \sum_{k=-\infty}^{\infty} [a_k s^1(t-kT+T) + (1-a_k) s^0(t-kT+T)], \]

where \( a_k \) is a stream of binary i.i.d. random variables taking values 0 or 1. In the following, bipolar LPOS symbols are denoted by \( b_k = 2a_k - 1 \). The readback servo signal is expressed as

\[ r(t) = q(t) + n(t), \]

where \( n(t) \) is the noise signal including transition noise and AWGN, as discussed in Section II.

The detector for the binary modulated signals is ideally a linear filter characterized by the impulse response \( g(t) \), \( 0 \leq t \leq T \), followed by a sampler providing samples every \( T \) seconds. Clearly, such an approach using a detector filter with an impulse response that spans an entire servo frame is not practical, especially because in TBS systems individual dibits within a servo frame need to be identified to obtain information about PES and tape velocity. Nevertheless, this viewpoint turns out to be quite useful for the derivation of the efficient detection and frame.

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Fig. 1. Illustration of an LTO servo frame with the encoding of an LPOS bit.
synchronization scheme that will be presented in the next section. The soft output from an ideal LPOS detector, i.e., the sampled value at \( t = kT \), is characterized by

\[
x_k = x(kT) = \int_0^T g(t)q(kT-t)dt + \int_0^T g(t)\eta(kT-t)dt
\]

where

\[
x(t) = \int_0^T g(t)r(t-\tau)dt = \int_{-T}^0 g(t)\eta(t-\tau)r(\tau)dt.
\]

The mean values of the samples at the detector output, conditional on \( s^0(t) \) or \( s^1(t) \) being recorded within the symbol interval, are given by

\[
m^{0} = E[x_k | s^0] = \int_0^T g(t)s^0(T-t)dt,
\]

and

\[
m^{1} = E[x_k | s^1] = \int_0^T g(t)s^1(T-t)dt,
\]

respectively, where \( E \) denotes the expectation operator. Note that, in general, the variance of the sample \( x_k \) depends on the recorded symbol. To obtain a variance of \( x_k \) that is independent of the LPOS symbol, the impulse response of the detector filter is chosen as

\[
g(t) = c_1s^1(T-t) + s^0(T-t),
\]

where \( c \) is an arbitrary constant. This choice is further justified by the fact that \( g(t) \) represents the impulse response of an optimum detector filter in the presence of AWGN. In the following, \( c = 1/\sqrt{2E_s(1-\varphi)} \) is assumed, where

\[
\varphi = \frac{1}{E_s} \int_0^T s^0(t)s^1(t)dt,
\]

and \( E_s \) denotes the symbol energy. In this case,

\[
m^{1} = -m^{0} = \sqrt{E_s \frac{1-\varphi}{2}}.
\]

The variance of the sample \( x_k \) can be expressed as

\[
\sigma^2 = \frac{N}{2} \int_{-\infty}^{\infty} \left| G(f) \right|^2 df + K_1\sigma_1^2 + K_2\sigma_2^2,
\]

where \( G(f) \) is the Fourier transform of \( g(t) \), and \( K_1 \) and \( K_2 \) are constants obtained from the cross-correlation between the dibit response \( g_d(t) \) and the characteristic functions of the position jitter and width variation functions, respectively.

Assuming \( m^{1} > m^{0} \), the decision rule of the detector is

\[
x_k \leq \frac{m^{0} + m^{1}}{2} \Rightarrow \hat{a}_k = 0,
\]

\[
x_k > \frac{m^{0} + m^{1}}{2} \Rightarrow \hat{a}_k = 1,
\]

where \( \hat{a}_k \) denotes the hard decision at the detector output. Then the symbol error probability \( P_b \) at the detector output is

\[
P_b = \frac{Q \left( \frac{m^{0} - m^{1}}{2\sigma} \right)}{2},
\]

where

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-u^2/2} du.
\]

The soft output from the detector in the absence of noise can then be expressed as

\[
m_k = E[x_k | h_k] = b_k \sqrt{E_s(1-\varphi)}.
\]

Furthermore, the detection threshold is zero, which is obtained from the observation \( m^{0} + m^{1}/2 = 0 \).

Consider now a block of \( N \) soft outputs \( (x_0, x_1, \ldots, x_{N-1}) \) obtained from the LPOS detector described above. From the above analysis, the soft outputs can be represented as the sum of a signal term and a Gaussian noise term, i.e.,

\[
x_k = m_k + n_k,
\]

where on the data pattern \( m_k = b_k \sqrt{E_s(1-\varphi)} \), and \( n_k = p_k \sqrt{E_s(1-\varphi)} \) on the sync pattern. Here \( p_k \) are bipolar sync symbols assuming the values +1 or –1, and \( n_k \) independent Gaussian noise samples with standard deviation \( \sigma \). The detected soft-output block corresponds to \( L \) sync word symbols and \( (N-L) \) random binary data symbols. In the LTO standard, \( N = 36 \) and \( L = 8 \), and the sync word is defined by \( p_0 = 1 \) and \( p_i = -1 \) for \( i = 1, \ldots, 7 \). Furthermore, the 28-bit binary data sequence in an LPOS word consists of seven 14-ary symbols, where each 14-ary symbol is mapped into four binary symbols [6]. The sequence of LPOS data symbols is modeled as a sequence of equiprobable i.i.d. binary random variables here. This assumption enables the derivation of a simple optimum LPOS frame-synchronization algorithm and is justified because the LPOS symbols are initially unknown.

The approach described in [3] based on the mixed Bayes’ rule is used to derive the optimum LPOS frame-synchronization algorithm that maximizes the probability of correctly locating the LPOS sync word, which is periodically embedded into the LPOS data stream in the servo channel. For a detected block of soft outputs \( (x_i, x_{i+1}, \ldots, x_{i+32}) \) of length \( N+L-1=43 \) samples, the algorithm that estimates the best LPOS sync word location chooses the LPOS sync word location to be the value of \( n \), \( 0 \leq n < 36 \), which maximizes the statistic

\[
\sum_{i=0}^{7} p_i x_{i+n} - \sum_{i=0}^{7} \psi(x_{i+n}),
\]

where

\[
\psi(x) = \frac{\sqrt{E_s(1-\varphi)}}{\rho} \ln \left( \cosh \left( \frac{\rho}{\sqrt{E_s(1-\varphi)}} x \right) \right)
\]

and

\[
\rho = \frac{E_s(1-\varphi)}{2\sigma^2}.
\]
Approximating the convolution integral in the statistic by a sum that is to be minimized and dropping irrelevant terms in this sum would be very desirable because it would allow a simple and robust implementation of the LPOS frame-synchronization algorithm with digital logic. In this case, the statistic
\[ \sum_{i=0}^{N} \left| \sum_{j \in J} \mathbf{P}_j (\mathbf{s}^0_j - \mathbf{s}^1_j) \right| \]
where \( J \) denotes the set of indices \( j \), \( \mathbf{s}^0_j = s^0_j(jT' - (k + i + n - 1)T) \), \( \mathbf{s}^1_j = s^1_j(jT' - (k + i + n - 1)T) \), \( \bar{r}_j = r(jT') \), and \( T' \) is the sampling interval.

For a tape velocity \( v \), the signal samples \( \mathbf{s}^0_j \), \( \mathbf{s}^1_j \) and the received samples \( \bar{r}_j \) are spaced much closer to each other than \( T = 200 \mu m/v \), i.e., \( T' \ll T \). For example, a spacing of \( T' = 0.25 \mu m/v \) is a good choice for the LTO servo signal because the rate \( 1/T' \) is greater than the two-sided bandwidth of the servo signal, thus ensuring that the received signal can be reconstructed from its samples \( \bar{r}_j \) without loss of information, as required by the sampling theorem. Furthermore, only a few terms in the approximate statistic contribute significantly to the sum, thus the statistic can be efficiently computed by taking the sum over a subset \( J' \subseteq J \) of indices \( j \), i.e., the statistic to be minimized becomes
\[ \sum_{i=0}^{N} \left| \sum_{j \in J'} \mathbf{P}_j (\mathbf{s}^0_j - \mathbf{s}^1_j) \right| \]

The synchronous servo channel architecture proposed in [9] includes all elements needed to enable the generation of soft outputs with digital logic for a simple and robust implementation of the above soft-decision LPOS frame-synchronization algorithm. This architecture is based on the interpolation of the servo signal samples, which are provided by an analog-to-digital converter (ADC) at a fixed sampling rate, so that the interpolated signal samples are obtained at a predetermined fixed rate, independently of the tape velocity. Note that this predetermined fixed rate is defined in terms of samples per unit of length, as opposed to samples per unit of time, which is the measure of the ADC sampling rate. The resolution of the servo channel signal at the interpolator output is thus determined by the step interpolation distance \( \Delta x \), which is the minimum distance between samples at the interpolator output.
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noise introduces a performance loss of about 1 to 2 dB compared with the AWGN case.

Note that the results of Fig. 5 have been obtained by a soft LPOS detector employing a matched filter. Further results, not shown here, indicate that the proposed soft correlation method leads to considerably larger gains, on the order of several dB, if compared with legacy hard-correlation approaches, where hard decisions on LPOS symbols are based on the observation of the shifts of the peaks of modulated dibits.

![Fig. 5. Comparison of hard- and soft-decision correlation methods.](image)

The overall frame synchronization method, including a synchronous servo channel with soft LPOS detection, has been implemented in hardware using an FPGA, and tested using a tape drive during normal operation. Fig. 6 shows snapshots of four signals that were obtained from a hardware simulator employed to test the entire logic design, prior to running real-time experiments in a tape drive. Input to the simulator are servo signals captured from a tape drive with an ADC sampling rate of 16 MHz. From top to bottom, the four signals are (1) the sequence of detected LPOS binary symbols, (2) the corresponding values of 36-bit LPOS words obtained every 7.2 mm of tape, (3) the sequence of soft detector output values that are input to the soft correlator, and (4) the soft correlator output signal achieving maximum values in correspondence of the 8-bit sync word pattern. Note that in this case the sync word pattern is 00000001, because the readback servo signal is captured with the tape moving in backward direction.

![Fig. 6. Snapshots of signals from a hardware simulator.](image)

![Fig. 7. Correlation signal obtained during real-time operation of a tape drive.](image)

Fig. 7 shows the trace of a correlation signal from an oscilloscope during real-time operation of a tape drive, monitoring the operation of the soft correlator for LPOS frame synchronization. The cursor distance of 3.18 ms corresponds to the LPOS word length of 7.2 mm divided by the tape velocity of 2.26 m/s.

**VI. CONCLUSION**

A robust and efficient LPOS frame-synchronization algorithm that uses soft decisions from an LPOS detector has been presented. Reliable detection of LPOS words is essential for track-following and reel-to-reel servo mechanisms in tape drive systems. Simulation and experimental results have shown that the proposed soft frame synchronization algorithm significantly outperforms frame synchronization based on hard LPOS symbol decisions, as currently implemented in tape drives, and is suitable for practical applications.

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**REFERENCES**


