Jitter Model and Signal Processing Techniques for Pulse Width Modulation Optical Recording

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ABSTRACT

This paper discusses a jitter model and signal processing techniques for data recovery in Pulse Width Modulation (PWM) optical recording. In PWM, information is stored through modulating sizes of sequential marks alternating in magnetic polarization or in material structure. Jitter, defined as the deviation from the original mark size in the time domain, will result in error detection if it is excessively large. This paper takes a new approach in data recovery by first using a high speed counter clock to convert time-marks to amplitude-marks, and uses signal processing techniques to minimize jitter according to the jitter model. The signal processing techniques include motor speed and intersymbol interference equalization, differential and additive detection, and differential and additive demodulation.

1 Introduction

Optical data storage is built upon many disciplines. Through the applications of these disciplines, storage densities and access speeds have been improved significantly [1]. In addition to the results that have provided shorter wavelength laser diodes, lighter optical heads, and better understanding of media, the use of signal processing techniques is also important in extracting information from noisy signals. As a result, this paper will study how data can be modulated, equalized, detected, and demodulated to achieve higher density storage.

Background

Since the magneto-optical (M-O) and phase change media have only two different polarizations or states, information can be stored only through modulating marks alternating in polarization or state. In this paper, pulse width modulation (PWM) is considered where marks of variable size according to the input signal are recorded.

In detecting a readback signal, the peak detection technique is commonly used [2][3]. That is, a signal of peaks at mark boundaries is first generated by a differentiator if necessary. To recover the original signal, a time window is used to decide whether a peak falls into or not. The time window is generally derived from the readback signal by a phase lock loop (PLL) [4].

Approach of This Paper

In this paper, a different approach is taken in recovering the original signal. First, mark boundaries are detected by methods such as the peak detection method described above. In the second step, instead of using the time window method, a high speed counter clock is used to quantize the mark size between two adjacent mark boundaries, as depicted in Figure 1. The counter output generates an integer number proportional to the time mark. In other words, this quantization step transforms the readback signal from time marks to amplitude marks, and signal processing techniques are subsequently used.

There are two important advantages of this quantization approach. First, it converts a time-mark signal to an amplitude-mark signal. As a result of this conversion, time domain noise—jitter—is at the same time converted to amplitude domain noise, which allows us to perform signal processing in the amplitude domain. Another advantage of this approach is that it provides a flexible and integrated implementation of various equalization, detection, and demodulation algorithms. This will become clear in the subsequent discussion.

One disadvantage of this approach is the added quantization error in the quantization step. However, if the clock is fast enough, this quantization error is negligible. For example, if the clock period is one nsec and mark sizes are multiples of the nsec, we have a signal to noise ratio $SNR = \frac{1}{\sqrt{1 + \frac{1}{16}}}$ = 56.8 dB for calculation. See (3) for example.

Jitter, defined as the total deviation away from the original mark size by all possible causes, is the time domain noise, similar to the amplitude noise in an amplitude modulated signal. There are various sources that contribute to the total jitter. This paper will establish a jitter model that translates all jitter sources into the total jitter, and study how the jitter can be reduced by signal processing.

![Figure 1: Quantization of Time Marks to Amplitude Marks](image)

2 Jitter Model

This section describes a jitter model based on which equalization, detection, and modulation techniques are described in the following sections. Although the model is not yet completely verified experimentally, it is formulated according to recent experiment and simulation studies [6][7][8].

1 If we assume the disk linear velocity is 4 m/sec, this 100 nsec time unit corresponds to 400 nm mark width. For a system using (2,7) RLL code, the minimum mark size is 1.2 um. If we compare this with a typical diffraction limit at 1.0 um, this 100 nsec is a reasonable assumption.

2 In optical recording, since there are many sources causing mark size deviation, jitter is also defined differently. For example, in peak detection, the deviation of a mark boundary is called peak shift [3], and jitter is one of the causes due to random noise. In this paper, for simplicity, jitter is the total result of all deviation causes, and each cause will be described in detail in the jitter model.
2.1 Write Process Jitter Model

In the write process, modulated input data is written onto a disk in the form of a sequence of time marks \( T_1, T_2, T_3, \ldots \), where each mark is the time duration of a mark. We can define \( T_0 = \sum T_i \) to be the starting time of mark \( j \).

When the input signal is recorded onto a disk, the spatial mark size \( W_s \), written corresponding to time mark \( T \), is

\[
W_s = \frac{T}{v} - A - B - T_0 \Delta v_s, \tag{2.1}
\]

where the disk is rotating at a nominal linear constant velocity \( v \), plus velocity jitter \( \Delta v_s \). In the equation, \( A \) is the jitter at the left hand side of the mark, \( B \) is at the right hand side, and \( T_0 \) is positive if it makes \( T \) smaller. Figure 2.

![Figure 2: Mark Size and Associated Jitter](image)

In Eq. (2.1) each \( \delta_i \) is due to three different jitter sources:

\[
\delta_i = \delta_{i1} + \delta_{i2} + \delta_{i3}, \tag{2.2}
\]

where

- \( \delta_{i1} \): Jitter due to random noise such as electronic noise and magnetic medium property fluctuation or defects. This first type of jitter is called noise jitter and often simply called jitter. This jitter has no correlation with the input signal and is independent of adjacent jitter of the same kind.

- \( \delta_{i2} \): Jitter due to laser power and/or beam width fluctuation or other similar mechanisms. This kind of jitter is called bit shift jitter. This jitter is shifted in different direction at the rising and falling edges of a mark in erase-and-write optical recording systems, where marks are "written" or "burned" only with even index marks. That is, the jitter sequence \( \delta_s(T_0) = \delta_s(T_0) = \delta_s(T_0) \) will be alternating in size. The magnitude of this jitter in general should be slowly varying and has strong correlation with adjacent ones.

- \( \delta_{i3} \): Jitter due to intersymbol interference (ISI). This jitter is a function \( f(\ldots T_{i-1}, T_i, T_{i+1}, \ldots) \) of adjacent time marks. This function can be linear or nonlinear of time mark sizes \( T_i \)'s. Physically, when a mark is being written, the longer the mark, the more heat is accumulated on the media, which results in this mark size dependent jitter.

2.2 Read Process Jitter Model

In the read process, the spatial mark size that is being read back can be similarly expressed as:

\[
W_r = W_s - \delta_s - \delta_s, \tag{2.3}
\]

where each jitter component has its similar counterpart described in the write process. Specifically:

\[\text{Appendix N}\]

- \( \delta_{r1} \): Noise jitter due to random receiver noise
- \( \delta_{r2} \): Peak shift jitter due to laser beam width fluctuation in the read process
- \( \delta_{r3} \): ISI jitter in the read process

Physically, this ISI jitter is due to the convolution of the laser beam width with a written mark size. The time mark read out will depend on the mark size recorded.

Including the motor speed jitter, we have \( T_j = T_i \Delta v_s - \Delta v_r = 1(\Delta v_s) = 1(\Delta v_r) \). Therefore, from Eqs. (2.1) and (2.3), we have:

\[
T_j = (\frac{V_0}{V_0/v})_j T_0 + (\Delta v)/v = \frac{1}{I_v} \left( \sum \gamma - \gamma_{i-1} \right) \tag{3.1}
\]

where \( (\Delta v)/v = \left( \Delta v_s + \Delta v_r \right) \) and \( \gamma = \gamma_0 = \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = \gamma_7 = \gamma_8 = \gamma_9 = \gamma_10 \). For convenience, we call \( \delta_1 \) the noise jitter, \( \delta_2 \) the bit shift jitter, and \( \delta_3 \) the ISI jitter.

3 Equalization Techniques

The objective of equalization discussed in this section is to restore the original mark size \( T_i \) from \( T_j \).

(i) Write Velocity Jitter Correction

The term \( T_j \delta v_s \) in Eq. (2.1) is the jitter caused by velocity fluctuation and is proportional to \( T_i \). In time-window-based peak detection systems where mark sizes are not quantized, this \( T_j \)-proportional jitter is not important since it can be compensated easily by a phase lock loop (PLL) in the read process. However, when time marks are quantized and converted into amplitude marks, it is more difficult to use a PLL. In the following we explain how velocity fluctuation can be compensated by using the servo voltage in the disk drive.

A circuit that removes motor speed jitter is depicted in Fig. 3. In the figure, a voltage signal \( v(t) \) that is proportional to the linear velocity of the disk with respect to the laser head is sent to an integrator. If the integrator is reset to zero at time \( t \), the voltage output \( U_i(t_{j+1}) \) of the integrator equals the spatial mark \( W_i \) at time \( t_{j+1} \), and the comparator output changes from "on" to "off".

This transition will reset the integrator, change the JK Flip-Flop state from on to off, and turn off the laser diode. Similar operation repeats from time \( t_{j+1} \) to \( t_{j+2} \).

![Figure 3: Circuit for Write Process Compensation](image)
Appendix N

With this compensation, the mark size error occurs
\[ \Delta \epsilon_j^m = \epsilon_j^m - \epsilon_j^m - \Delta \epsilon_j^m. \]

(iii). Read Process Equalization

The equalization in the receiver consists of two steps, as shown in Figure 4. The first step is to reduce the ISI jitter \( \Delta \epsilon_j \). One way to reduce ISI is to subtract each \( \Delta \epsilon_j \) by an amount of \( \Delta \epsilon_j \), where \( \Delta \epsilon_j = \epsilon_j^m - \epsilon_j^m - \Delta \epsilon_j^m \), and \( \epsilon_j^m \) is the known ISI function. If \( \epsilon_j^m \) cannot be exactly equal to \( \epsilon_j^m \), because we use \( \Delta \epsilon_j \) instead of \( \epsilon_j^m \), to estimate the ISI jitter. Better estimation can be obtained by using decision feedback equalization (DFE).

Neglecting the second order effect \( \Delta \epsilon_j \), and combining Eqs. (2.4) and (3.11), we have
\[ \Delta \epsilon_j = \frac{1}{\epsilon_j^m} \left( \epsilon_j^m - \frac{1}{\epsilon_j^m} \sum \Delta \epsilon_j \right). \]

The second step is to correct the motor speed jitter in the read process. To accomplish this, we also use the motor speed voltage signal to estimate the quantity \( \Delta \epsilon_j^m \), based on which, we have
\[ \Delta \epsilon_j^m = \frac{1}{\epsilon_j^m} \left( \epsilon_j^m - \frac{1}{\epsilon_j^m} \sum \Delta \epsilon_j \right). \]

After these two steps, jitter that is left includes only \( \Delta \epsilon_j \) and \( \Delta \epsilon_j^m \). The first one is purely random and has no correlation with adjacent ones. The second one is slowly varying and alternating in sign as a function of \( j \). Instead of equalizing this second jitter directly, the following detection techniques are used to make correct detection insensitive to this jitter.

![Figure 4: Block Diagram in Receiver Equalization and Detection](image)

4 Detection Techniques

The first method to recover the original mark size \( T_j \) from \( T_j^2 \) is called the Differential Interleaving Detection (DID). If we subtract \( T_j^2 \) from \( T_j^2 \), the difference is
\[ \Delta T_j = (T_j^2 - T_j^2) \approx \frac{V_c}{V_c} (T_j - T_j^2) - \frac{1}{V_c} (\Delta \epsilon_j - \Delta \epsilon_j^m - \Delta \epsilon_j^m). \]

where the term \( \Delta \epsilon_j - \Delta \epsilon_j^m - \Delta \epsilon_j^m \) is second order and may be neglected because of the strong positive correlation between \( \Delta \epsilon_j \) and \( \Delta \epsilon_j^m \).

\( \Delta T_j \) in Eq. (4.1) has only the random jitter. Comparing this with Eq. (3.3), this technique has a 30% power penalty. However, we may use maximum likelihood sequence detection (MLSD) to detect each \( \Delta T_j \) in a sequence of \( \Delta T_{j-1}, \Delta T_j, \Delta T_{j+1}, \ldots \) to avoid this penalty. With this differential interleaving method, if the first two mark sizes \( T_1 \) and \( T_2 \) are predefined, subsequent \( T_j \)'s can all be obtained from the differential terms.

In the case that the \( T_j \)'s are modulated, sifting in the encoded data, straightforward detection may have an error propagation problem. To solve this, a post-modulation method called Differential Interleaving Modulation (DIM) can be used as described in the next section.

The second method to recover the original mark sizes recorded is called the Additive Interleaving Detection (AID). This method first adds the two adjacent marks sizes read. That is
\[ T_j + T_{j+1} \approx T_j + T_{j+1} - \frac{V_c}{V_c} (T_j - T_j^2) - \Delta \epsilon_j - \Delta \epsilon_j^m - \Delta \epsilon_j^m. \]

Again, the term \( \Delta \epsilon_j - \Delta \epsilon_j^m \) is of second order and neglected.

From the detected \( T_j + T_{j+1} \), \( T_j, T_{j+1} \), and the \( T_j \) can all be recovered if the first \( T_j \) is predefined. This method has the same error propagation problem as DIM. If written marks are modulated according to \( \Delta T_j \), instead of \( T_j \), the problem completely removed, and this post-modulation is called Additive Interleaving Modulation (AIM).

5 Modulation Techniques

For a given modulation code that transmits an input sequence into a sequence of mark sizes \( S_j \), the objective of the post-modulation DIM or AIM is to translate \( S_j \) into \( T_j \). To do this, detection either \( \Delta T_j \) or \( T_j \) can be used directly to recover the original \( S_j \) without any error propagation. Without loss of generality, \( V_c = V_c \) is assumed in the following discussion.

(i). Differential Interleaving Modulation

For a given modulation code, assume each mark generates satisfies the following condition:
\[ 0 \leq S_{\text{min}} \leq S_j \leq S_{\text{max}}. \]

For DIM, we first define the initial values \( T_1 \) and \( T_2 \), and subsequent \( T_j \)'s after \( T_1 \) and \( T_2 \) are obtained as follows:
\[ T_j = \begin{cases} T_j + S_j, & \text{if } T_j + S_j \leq T_{\text{max}} \\ T_j + S_j - T_{\text{max}} + T_{\text{min}} - 1, & \text{if } T_j + S_j > T_{\text{max}} \end{cases} \]

where \( 0 \leq T_{\text{min}} \leq T_j \leq T_{\text{max}} \) for each \( j \).

To make the modulation rule self-consistent when \( T_1 = T_{\text{min}} \) and \( S_1 = S_{\text{max}} \), from the second part of Eq. (5.2), we need
\[ S_{\text{max}} + T_{\text{min}} - 1 \leq T_{\text{max}} \text{ or } T_{\text{max}} - T_{\text{min}} \leq S_{\text{max}} - 1. \]

3. By subtracting \( T_j \) on both sides of Eq. (5.2), we have:
\[ -\Delta T_j = T_{j+1} - T_j = \begin{cases} S_j, & \text{if } T_j + S_j \leq T_{\text{max}} \\ S_j - T_{\text{max}} + T_{\text{min}} - 1, & \text{if } T_j + S_j > T_{\text{max}} \end{cases} \]

We note that if \( T_j + S_j \leq T_{\text{max}} \) is true in recording, \( -\Delta T_j = T_{j+1} - T_j = S_j \geq S_{\text{min}} \), and if \( T_j + S_j > T_{\text{max}} \) is true in recording, by Eq. (5.3), \( -\Delta T_j = T_{j+1} - T_j = S_j - T_{\text{max}} + T_{\text{min}} - 1 \leq 0 \).

Therefore:
\[ -\Delta T_j = T_{j+1} - T_j = \begin{cases} S_j, & \text{if } -\Delta T_j \geq S_{\text{min}} \\ S_j - T_{\text{max}} + T_{\text{min}} - 1, & \text{if } -\Delta T_j \leq 0 \end{cases} \]

As a result, the differential pre-demodulation rule is:
and the original $S_c$ can be recovered by simple threshold detection from $S^c$. Here we see the condition in Eq. (5) also provides the error detection capability when $0 < \Delta \gamma < \Delta \gamma_{crit}$ happens.

6 Simulation Examples

Therefore, condition I. should be satisfied in order to have another condition for $T_{iT}$ and $T_{if}$. Note that when $S_i - T_i > 0$ is true, we have:

$$T_{iT} = \min \{S_i, T_{iT} - T_{if} = \min \{S_i, \Delta \gamma_{crit} + T_{iT} - T_{if} - \Delta \gamma_{crit}\}$$

Conditions (5.5) and (5.6) should be satisfied in order to have another condition for $T_{iT}$ and $T_{if}$. Note that when $S_i - T_i > 0$ is true, we have:

$$T_{iT} = \min \{S_i, T_{iT} - T_{if} = \min \{S_i, \Delta \gamma_{crit} + T_{iT} - T_{if} - \Delta \gamma_{crit}\}$$

As a result, with the two conditions (5.7) and (5.8), we can have the following AIM demodulation rule:

$$T_{iT} = \begin{cases} \Delta \gamma_{crit} + T_{iT} - T_{if} - \Delta \gamma_{crit} & \text{if } \Delta \gamma_{crit} + T_{iT} - T_{if} - \Delta \gamma_{crit} \\ \min \{S_i, T_{iT} - T_{if} = \min \{S_i, \Delta \gamma_{crit} + T_{iT} - T_{if} - \Delta \gamma_{crit}\} & \text{if } S_i - T_i > 0 \end{cases}$$

Again, if $S_{it} - T_{iT} < \Delta \gamma_{crit}$, $T_{iT} - T_{if} = \Delta \gamma_{crit}$, errors can be detected.

6 Simulation Examples

This section examines how data recovery is improved by using the signal processing techniques discussed earlier. To have a quantitative performance evaluation, we use the mark error ratio (MER) as the criterion, which is defined as the ratio of the number of misdetections to the total number of input marks.

In the following subsections, we first describe three different sets of the statistical parameters that are used in the computer simulation programs. These three sets are used to describe three different jitter scenarios. Next, we describe five different detection methods based on which MER is calculated. In simulation, each MER is obtained at a given signal to noise ratio (SNR), where SNR is defined as:

$$SNR = \frac{SNR}{RMS \text{ Jitter} \ of \ \gamma} = \frac{\Delta T \cdot V}{\sqrt{T_{iT} - T_{if} - \Delta \gamma_{crit} \gamma_{crit}}}$$

where $\Delta T$ is the unit of time. From this definition, we see that SNR here only includes noise jitter. At the end we will discuss the simulation results.

### Appendix A

#### 6.1 Statistical Parameters

In simulation, time mark sizes are $\Delta T_i$, where $\Delta T_i$ is chosen to be 100 nanoseconds, and $\gamma$ is uniformly distributed between [-10 and 10 ( exclusive) similar to the [0,1] code but not exact]. The disk linear velocity is set at 4 m/s, and in the both write and read process. For simplicity, the velocity fluctuation is in the write process is assumed to be perfectly done. In all simulation cases or assuming the velocity correction was done perfectly. Three different sets of parameters are tested to cover the following scenarios:

1. All velocity jitter, bit shift jitter, and ISI are significant.

   In this scenario, read velocity fluctuation range is set to be 0.1 m/sec, or 10% of the mean velocity. Velocity is maintained to be slowly varying within a time mark period.

   Bit shift jitter is set to have a mean shift 400 nm and represents approximately 20% of the laser beam width (assuming the diffraction limit is 1 mm), and the fluctuation of the shift is 800 nm, or approximately ±6% of the laser beam width. The bit shift jitter is also maintained to be slowly varying in a time mark period.

   ISI jitter is assumed to be essentially a linear function of the time mark written. The proportional constant is chosen to be 0.03 in this scenario. The detection performance is shown in Figure 5.

2. Only bit shift jitter is significant.

   In this scenario, velocity jitter is set to zero, and the ISI jitter is reduced from 0.03 in scenario 1 to 0.02. Other parameters are the same as in scenario 1. The detection performance is shown in Figure 6.

3. Only ISI is significant.

   In this scenario, velocity jitter is set to zero, and the bit shift jitter is reduced from ±60 nm in scenario 1 to ±30 nm, or ±1% of the laser beam width. Other parameters are the same as in scenario 1. The detection performance is shown in Figure 7.

#### 6.2 Detection Methods

Five detection methods are used in simulation. They are:

1. Basic Detection.

   The basic detection method is based on the threshold detection and uses no equalization other than compensating the average bit shift term $\Delta \gamma$. That is, for each detected mark size, $\gamma_i$, we subtract $2\Delta \gamma / V$ if $j$ is even and add the same amount if $j$ is odd.

2. Basic Detection plus ISI Equalization.

   In addition to the average bit shift compensation, this second detection method equals the ISI jitter.

3. Basic Detection plus ISI and Velocity Equalization.

   In addition to the basic detection and ISI equalization, this detection method equalizes velocity fluctuation.


   This detection method equals ISI and velocity fluctuation, but it does not cancel bit shift jitter in the rudimentary way of method 1. Instead, it uses the better differential detection method.

...
5. Additive Detection plus ISI and Velocity Equilization.

This detection method is almost the same as the last method except it uses additive detection rather than differential detection described in section 4.

6.3 Discussion

From the results, we may make the following observations.

1. The basic detection method is not an effective detection method if the noise jitter is dominated by other jitter. As shown in Figures 5 to 7, MER can not be effectively improved by increasing SNR. This indicates the importance of equalization.

2. Methods 2 and 3 perform almost the same if velocity fluctuation does not exist. These two methods perform equally as well as the DID and AID methods when gaussian noise dominates \( SNR < 12 \) (even better than DID).

3. Differential detection performs better than the first three detection methods, and is approximately 3 db poorer than additive detection. This is what we predicted before. But interestingly, when SNR is greater than 25 db, DID reaches an error floor if bit shift jitter is significant (see Figures 5,6). We do not see the similar floor when only ISI jitter is important (Figure 7). This error floor is likely due to the second order jitter effect that we have neglected, and this effect does not appear in the case of AID. When noise jitter dominates \( SNR < 12 \) in Figures 5-7), DID is not better than the other methods because of the extra 3db penalty.

4. Additive detection performs better in all cases, especially when all sources of jitter are important or when bit shift jitter is not negligible (see Figures 5-7).

7 Conclusion

This paper has introduced a jitter model and a quantization approach, based on which signal processing techniques in equalization, detection, and modulation were used to obtain better data recovery. From the simulation examples illustrated, we found that additive detection plus velocity and ISI equalizations performed best. If its smaller SNR to obtain the same mark error rate huge smaller sizes can be recovered and consequently a higher density can be achieved.

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References
