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 modulation.

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 it 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.

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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 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 this nsec, we have a signal to noise ratio SNR = (10 log (1/4)) = 50 dB for calculations, see [5] for example.

Jitter, defined2 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 can 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.

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]-[8].

1 If we assume the disk linear velocity is $v = 1$ 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 nm. If we compare this with a typical diffraction limit at 1 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 to a disk drive is in a sequence of time marks \( T_1, T_2, T_3, \ldots \), where \( T_i \) is the time duration of mark \( i \). We can define \( t_i = \frac{2i}{W} T_i \) to be the starting time of mark \( i \).

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

\[
W_y = W_y^* - \Delta W_y - \Delta W_y^* = T_i \Delta V_y^* \tag{2.1}
\]

if the disk is rotating at a nominal linear constant velocity \( V_y \) then velocity jitter \( \Delta V_y^* \). In the equation, \( \Delta W_y \) is the jitter at the left hand side of the mark, \( \Delta W_y^* \) is at the right hand side, and \( \Delta V_y^* \) is positive if it makes \( W_y \) smaller. Figure 2.

![Mark Size and Associated Jitter](image)

Figure 2: Mark Size and Associated Jitter

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

\[
\Delta W_y = \Delta W_y^{\text{J}} + \Delta W_y^{\text{S}} + \Delta W_y^{\text{L}}. \tag{2.2}
\]

where

- \( \Delta W_y^{\text{J}} \): 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.

- \( \Delta W_y^{\text{S}} \): 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 dots. This is the jitter sequence \( \{ \Delta W_y^{\text{S}}, \Delta W_y^{\text{S}}, \Delta W_y^{\text{S}}, \Delta W_y^{\text{S}} \} \) will be alternating in sign. The magnitude of this jitter in general should be slowly varying and has strong correlation with adjacent ones.

- \( \Delta W_y^{\text{L}} \): Jitter due to intersymbol interference (ISI). This jitter is a function \( f(1, \ldots, T_{i-1}, T_i, T_{i+1}, \ldots) \) 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:

\[
W_y^* = W_y - \Delta W_y^* - \Delta W_y^* \tag{2.3}
\]

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

\[ W_y \]

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- \( \Delta W_y^{\text{J}} \): Noise jitter due to random receiver noise
- \( \Delta W_y^{\text{S}} \): Peak shift jitter due to laser beam width fluctuation in the read process
- \( \Delta W_y^{\text{L}} \): 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 \( T_1 = W_y^* / V_y = T_y / T_y^* \approx \frac{W_y^*}{W_y^*} = \frac{W_y^*}{W_y^*} \). Therefore, from Eqs. (2.1 and 2.3), we have:

\[
T_2 = \left( \frac{W_y^*}{T_y^*} \right) T_1 + \frac{W_y^*}{T_y^*} \Delta V_y^* = \frac{1}{T_y^*} \sum_{i=1}^{n} \gamma_i + \gamma_i^* \tag{3}
\]

where \( \Delta V_y^* = \left( -\frac{\Delta V_y^*}{T_y^*} \right) + \left( \frac{\Delta V_y^*}{T_y^*} \right) \) and \( \gamma_i = \Delta W_y^* \). 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 \( T_y^* \) from \( T_y \).

(i). Write Velocity Jitter Correction

The term \( T_y^* \Delta V_y^* \) in Eq. (2.1) is the jitter caused by velocity fluctuation and is proportional to \( T_y \). In time-window-based peak detection systems where mark sizes are not quantized, this \( T_y \) 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 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 \( t_i \), the voltage output \( U_i(t_i) \) of the integrator equals the spatial mark \( W_y^* \) at time \( t_i \). And the comparator output changes from "0" to "1". 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 \( t_i \) to \( t_{i+1} \).

![Circuit for Write Process Compensation](image)

Figure 3: Circuit for Write Process Compensation

\[ \text{ORIGINAL PAGE IS OF POOR QUALITY} \]
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With this compensation, the mark size unchangeable becomes
\[
\Delta z_{e} = \Delta z_{t} - \Delta z_{s}
\]

(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 \( T_{j} \). One way to reduce ISI is to subtract each \( T_{j} \) by an amount of \( T_{j} \), where \( \Delta T_{j} = \sum_{j=1}^{i} \Delta T_{j} \) and \( \Delta T_{j} \) is the pre-known ISI function, \( \Delta T_{j} \) cannot be exactly equal to \( \Delta z_{t} \), because we use 4 times \( T_{j} \) instead of \( T_{j} \), to estimate the ISI jitter. Better estimation can be obtained by using decision feedback equalization (DFE)

Neglecting the second order effect \( \Delta z_{j} > -\Delta z_{j} \), and combining Eqs. (2, 4, and 3), we have

\[
T_{j} = T_{j} - \Delta T_{j} = \frac{1}{T_{j}} \sum_{j=1}^{i} \Delta T_{j} = \frac{\Delta T_{j}}{T_{j}}
\]

The second step is to correct the motor speed jitter in the read process. To accomplish this, we also use the motor servo voltage signal to estimate the quantity \( \Delta T_{j}/T_{j} \), based on which, we have

\[
T_{j} = T_{j} - \Delta T_{j} = \frac{1}{T_{j}} \sum_{j=1}^{i} \Delta T_{j} = \frac{\Delta T_{j}}{T_{j}}
\]

After these two steps, jitter that is left includes only \( \Delta z_{j} \) and \( \Delta z_{t} \). 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 \( T \). 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 of Receiver Equalization and Detection](image)

**4 Detection Techniques**

The first method to recover the original mark size \( T_{j} \) from \( T_{j}^{*} \) is called the Differential Interleaving Detection (DID). If we subtract \( T_{j}^{*} \) from \( T_{j}^{*} \), the difference is:

\[
\Delta T_{j} = (T_{j}^{*} - T_{j}^{*}) = (T_{j} - T_{j}^{*}) = \frac{1}{Z_{j}} (\Delta z_{j} - \Delta z_{j} + \Delta z_{j} - \Delta z_{j})
\]

where the term \( \Delta z_{j} - \Delta z_{j} \) is of second order and maybe neglected because of the strong positive correlation between \( \Delta z_{j} \) and \( \Delta z_{j} \).

\( \Delta T_{j} \) in Eq. (4.4) only has the random jitter. Comparing this with Eq. (3.3), this technique has a 3 db power penalty. However, we may use maximum likelihood sequence detection (MLSD) to detect each \( \Delta T_{j} \) in a sequence of \( \Delta T_{j}, \Delta T_{j}, \Delta T_{j}, \Delta T_{j}, \Delta T_{j}, \ldots \) to avoid this penalty. With this differential interleaving method, if the first two mark sizes \( T_{i} \) and \( T_{j} \) are predefined, subsequent \( T_{j} \)'s can all be obtained from the differential terms.

In the case that the \( T_{j} \)'s are modulated, detecting the unmarked data straightforward detection may give an error problem. To solve this, a post-modulation method named Differential Interleaving Modulation (DIM) can be used as described in the next section.

The second method to recover the original mark sizes recently called the Additive Interleaving Detection (AID). This method first adds the two adjacent mark sizes read. That is:

\[
\Delta T_{j} = T_{j}^{*} - T_{j}^{*} = \frac{1}{Z_{j}} (T_{j} - T_{j}^{*}) = \frac{1}{Z_{j}} (T_{j} - T_{j} - T_{j} - T_{j})
\]

Again, the term \( \Delta z_{j} - \Delta z_{j} \) is of second order and neglected.

From the detected \( \Delta T_{j}, T_{j}^{*}, T_{j}^{*}, T_{j}^{*}, \ldots \), the \( T_{j}^{*} \) can all be recovered if the first \( T_{j} \) is predefined. This method has the same error propagation problem as DID. 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 translates an input message into a sequence of mark sizes \( S_{j} \), the objective of the postmodulation DIM or AIM is to translate \( S_{j} \) into \( T_{j} \), so that at the detection either \( 
\Delta T_{j} \) or \( T_{j} \) can be used directly to recover to the original \( S_{j} \) without any error propagation. Without loss of generality, \( V_{m} = V_{m} \) is assumed in the following discussion.

(i) Differential Interleaving Modulation

For a given modulation code, assume each mark generated satisfies the following condition:

\[
0 < S_{min} - S_{j} < S_{max}
\]

For AIM, we first define the initial values \( T_{j} \) and \( T_{j} \), and subsequent \( T_{j} \)'s after \( T_{j} \) and \( T_{j} \) are obtained as follows:

\[
T_{j+1} = \begin{cases} T_{j} + S_{j}, & \text{if } T_{j} + S_{j} \leq T_{max} \\ T_{j} + S_{j} - T_{max} + T_{min} - 1, & \text{if } T_{j} + S_{j} > T_{max} \\ 0, & \text{if } T_{j} + S_{j} = T_{max} + T_{min} - 1 \end{cases}
\]

where \( 0 < T_{min} \leq T_{j} \leq T_{max} \) for each \( i \).

To make the modulation rule self-consistent when \( T_{j} = T_{max} \) and \( S_{j} = S_{max} \), from the second part of Eq. (5.2) we need

\[
S_{max} + T_{min} - 1 \leq T_{max} \leq S_{max} + T_{min} - S_{max} - 1
\]

By subtracting \( T_{j} \) on both sides of Eq. (5.2), we have:

\[
\Delta T_{j} = T_{j+1} - T_{j} = \begin{cases} S_{j}, & \text{if } T_{j} + S_{j} \leq T_{max} \\ S_{j} - T_{max} + T_{min} - 1, & \text{if } T_{j} + S_{j} > T_{max} \end{cases}
\]

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

Therefore:

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

As a result, the differential pre-demodulation rule is:

\[
0 < S_{min} \leq S_{j} \leq S_{max}
\]
and the original S can be recovered by simple threshold detection from \( e^* \). Here we see the condition in Eq. 5.5 also provides the error detection condition when \( 0 < \Delta T < S_{\text{min}} \) happens.

iii. Additive Interleaving Modulation

Assume the given condition code and the 10-bit AIM code allow the same condition in Eq. 5.1. The AIM true is described as follows:

\[
T_{\text{aim}} = \begin{cases} 
S_{\text{aim}} = S_{\text{min}} + S_{\text{max}} & \text{if } \Delta T < S_{\text{min}} \\
S_{\text{aim}} = S_{\text{max}} & \text{if } S_{\text{min}} \leq \Delta T \leq S_{\text{max}} \\
S_{\text{aim}} = S_{\text{min}} & \text{if } S_{\text{max}} < \Delta T
\end{cases}
\]

This definition makes sure \( T_{\text{aim}} \geq T_{\text{min}} \). To make sure \( T_{\text{aim}} \leq T_{\text{max}} \), we need the following two additional conditions. Substituting \( T_{\text{aim}} = T_{\text{min}} \) and \( S_{\text{aim}} = S_{\text{max}} \) in the first part of Eq. 5.5, we need

\[
S_{\text{max}} = S_{\text{min}} + S_{\text{max}} \quad \text{or} \quad S_{\text{max}} = T_{\text{max}} - S_{\text{min}}.
\]

(5.6)

In addition, to know whether \( S_{\text{aim}} = S_{\text{max}} \), or the threshold is true, we have the second part of Eq. 5.5:

\[
S_{\text{max}} = S_{\text{min}} + S_{\text{max}} \quad \text{or} \quad S_{\text{max}} = T_{\text{max}} - S_{\text{min}}.
\]

(5.7)

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

\[
T_{\text{aim}} = \begin{cases} 
S_{\text{aim}} = S_{\text{min}} + S_{\text{max}} & \text{if } \Delta T < S_{\text{min}} \\
S_{\text{aim}} = S_{\text{max}} & \text{if } S_{\text{min}} \leq \Delta T \leq S_{\text{max}} \\
S_{\text{aim}} = S_{\text{min}} & \text{if } S_{\text{max}} < \Delta T
\end{cases}
\]

(5.9)

Again, if \( S_{\text{aim}} - S_{\text{min}} < \Delta T < S_{\text{max}} - S_{\text{aim}} \), errors can be detected.

6 Simulation Examples

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

\[
\text{SNR} = \text{Unit Mark Size} = \frac{\Delta T W}{\text{RMS Jitter of } e^*}
\]

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.

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6.1 Statistical Parameters

In simulation, the mark sizes are \( \Delta T \), where \( \Delta T \) is chosen to be 100 nsec, and \( t \) is uniformly distributed between 0 and 5, similar to the (2,7,4) code but not exactly. The disk linear velocity is set at 4.0 m/sec in both the write and read process. For simplicity, the velocity fluctuation in the write process is assumed to be zero in all simulation cases or assuming the velocity correction can be done perfectly. Three different sets of parameters are selected to cover the following scenarios:

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

   In this scenario, the velocity fluctuation range is set to be 0.1 mm/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 2.00 nm and to represent approximately 20% of the laser beam width (assuming the diffraction limit is 1 µm), and the fluctuation of the shift is ±0.60 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 0.05 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 0.05 in scenario 1 to 0.02. Other parameters are the same as those 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 ±0.60 nm in scenario 1 to ±0.10 nm, or ±1% of the laser beam width. Other parameters are maintained to be 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 threshold detection and uses no equalization other than compensating the average bit shift term \( \delta_j \). That is, for each detected mark size, \( \Delta T_j \), we subtract \( 2\delta_j/V \) 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 provides the ISI jitter.

3. Basic Detection plus ISI and Velocity Equalization.

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


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

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. Its smaller SNR to obtain the same mark error rate means smaller sizes can be recovered and consequently a higher density can be achieved.

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References
