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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.

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 (or 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's period is one nsec and mark sizes are multiples of 100 nsec,[1] we have a signal to noise ratio $SNR = 10\log_{10}(\ldots)$ = [illegible] db (for calculation, see [5] for example).

Jitter, defined[2] 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.

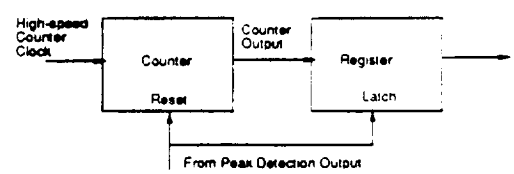

Figure 1: Quantization of Time Marks to Amplitude Marks

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 4 m/sec, this 100 nsec time unit corresponds to 400 nm mark unit. For a system using (2,7) RLL code, the minimum mark size is 1.2 μm. If we compare this with a typical diffraction limit at 1 μm, 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: $\ldots, T_{j-1}, T_j, T_{j+1}, \ldots$, where T_j is the time duration of mark j. We can define $t_j = \sum_{i=0}^{j-1} T_i$ to be the starting time of mark j.

When the input signal is recorded onto a disk, the spatial mark size W_j^w written corresponding to time mark T_j is:

$$W_j^w = T_j V_w - \delta_j^w + \delta_{j+1}^w + T_j \Delta V_w. \quad (2.1)$$

if the disk is rotating at a nominal linear constant velocity V_w plus velocity jitter ΔV_w. In the equation, δ_j^w is the jitter at the left hand side of the mark, δ_{j+1}^w is at the right hand side, and δ_j^w is positive if it makes W_j smaller. Figure 2.

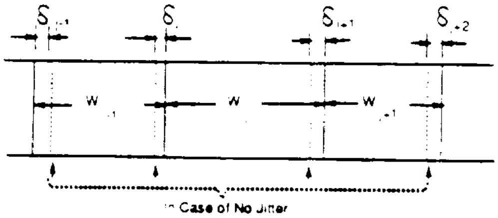

Figure 2: Mark Size and Associated Jitter

In Eq. (2.1), each δ_j^w is due to three different jitter sources.

$$\delta_j^w = \delta_{1,j}^w + \delta_{2,j}^w + \delta_{3,j}^w, \quad (2.2)$$

where

$\delta_{1,j}^w$: 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.

$\delta_{2,j}^w$: 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 indexes. That is, the jitter sequence $(\delta_{2,j-1}^w, \delta_{2,j}^w, \delta_{2,j+1}^w)$ will be alternating in sign. The magnitude of this jitter in general should be slowly varying and has strong correlation with adjacent ones.

$\delta_{3,j}^w$: Jitter due to intersymbol interference (ISI). This jitter is a function $f(\ldots, T_{j-1}, T_j, T_{j+1}, \ldots)$, of adjacent time marks. This function can be linear or non-linear of time mark sizes T_j'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:

$$W_j^r = W_j^w - \delta_j^r + \delta_{j+1}^r, \quad (2.3)$$

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

$\delta_{1,j}^r$: Noise jitter due to random receiver noise.

$\delta_{2,j}^r$: Peak shift jitter due to laser beam width fluctuation in the read process.

$\delta_{3,j}^r$: 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 $T_j^r = W_j^r/(V_r - \Delta V_r) \approx (W_j^r/V_r)(1 + \Delta V_r/V_r)$. Therefore, from Eqs. (2.1) and (2.3), we have

$$T_j^r = \left(\frac{V_w}{V_r}\right)T_j + \left(\frac{V_w}{V_r}\right)\left(\frac{\Delta v}{v}\right)T_j - \frac{1}{V_r}\sum_{i=1}^{3}(\delta_{i,j} - \delta_{i,j+1}), \quad (2.4)$$

where $(\Delta v/v) = (-\Delta V_r/V_r) + (\Delta V_w/V_w)$ and $\delta_{1,j} = \delta_{1,j}^w + \delta_{1,j}^r = \delta_{laser,j} + \delta_{media,j} + \delta_{receiver,j}$, $\delta_{2,j} = \delta_{2,j}^w + \delta_{2,j}^r$, and $\delta_{3,j} = \delta_{3,j}^w + \delta_{3,j}^r$. For convenience, we call $\delta_{1,j}$ the noise jitter, $\delta_{2,j}$ the bit shift jitter, and $\delta_{3,j}$ the ISI jitter.

3 Equalization Techniques

The objective of equalization discussed in this section is to restore the original mark size T_j from T_j^r.

(i). Write Velocity Jitter Correction

The term $T_j \Delta V_w$ in Eq. (2.1) is the jitter caused by velocity fluctuation and is proportional to T_j. 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_j, the voltage output $U_j(t_{j+1})$ of the integrator equals the spatial mark W_j at time t_{j+1}, 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_{j+1} to t_{j+2}.

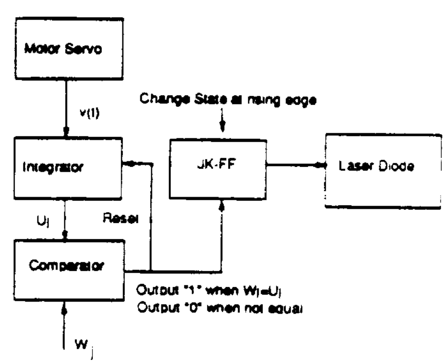

Figure 3: Circuit for Write Process Compensation

With this compensation, the mark size written becomes

$$W_j^w = W_j - \delta_j^1 - \delta_{j-1}^2. \quad (3.1)$$

(ii). 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 $\delta_{1,j}$. The way to reduce ISI is to subtract each T_j^r by an amount of $\delta_{1,j}^r / V_r$, where $\delta_{1,j}^r = f(\ldots, T_{j-1}^r, T_j^r, T_{j+1}^r, \ldots)$ and $f(\cdot)$ is the pre-known ISI function. $\delta_{1,j}^r$ cannot be exactly equal to $\delta_{1,j}$ because we use T_j^r 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 $(\delta_{3,j} - \delta_{3,j}^r)$ and combining Eqs. (2.4 and 3.1), we have

$$T_j^{r,1} \approx (\frac{V_w}{V_r}) T_j (1 - \frac{\Delta V_r}{V_r}) + (\frac{1}{V_r}) \sum_{i=1}^{2} (\delta_{i,j} - \delta_{i,j+1}) \quad (3.2)$$

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 $\Delta V_r / V_r$, based on which, we have:

$$T_j^{r,2} \approx (\frac{V_w}{V_r}) T_j + (\frac{1}{V_r}) \sum_{i=1}^{2} (\delta_{i,j} - \delta_{i,j+1}) \quad (3.3)$$

After these two steps, jitter that is left includes only $\delta_{1,j}$ and $\delta_{2,j}$. 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.

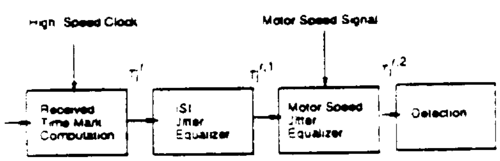

Figure 4: Block Diagram in Receiver Equalization and Detection

4 Detection Techniques

The first method to recover the original mark size T_j from $T_j^{r,2}$ is called the Differential Interleaving Detection (DID). If we subtract $T_{j+2}^{r,2}$ from $T_j^{r,2}$, the difference is:

$$\Delta T_j = (T_j^{r,2} - T_{j+2}^{r,2}) \approx (\frac{V_w}{V_r})(T_j - T_{j+2}) - \frac{1}{V_r}(\delta_{1,j} - \delta_{1,j+2} - \delta_{1,j+1} + \delta_{1,j+3}), \quad (4.1)$$

where the term: $\delta_{2,j} - \delta_{2,j+2} - \delta_{2,j+1} + \delta_{2,j+3}$ is of second order and maybe neglected because of the strong positive correlation between $(\delta_{2,j}, \delta_{2,j+2})$ and $(\delta_{2,j+1}, \delta_{2,j+3})$.

ΔT_j in Eq. (4.1) has only the random jitter. Comparing this with Eq. (3.3), this technique has a 3db power penalty. However, we may use maximum likelihood sequence detection (MLSD) to detect each ΔT_j in a sequence of $(\ldots, \Delta T_{j-2}, \Delta T_j, \Delta T_{j+2}, \ldots)$ 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 according to the input 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 mark sizes read. That is:

$$\Xi T_j \stackrel{def}{=} T_j^{r,2} + T_{j+1}^{r,2} \approx (\frac{V_w}{V_R})(T_j + T_{j+1}) + (\frac{1}{V_r})(-\delta_{1,j} + \delta_{1,j+2}) \quad (4.2)$$

Again, the term $\delta_{2,j} - \delta_{2,j+2}$ is of second order and neglected.

From the detected $(\ldots, \Xi T_{j-1}, \Xi T_j, \Xi T_{j+1}, \ldots)$, the T_j can all be recovered if the first T_1 is predefined. This method has the same error propagation problem as DID. If written marks are modulated according to ΞT_j instead of T_j, the problem is 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 ΔT_j or ΞT_j can be used directly to recover the original S_j without any error propagation. Without loss of generality, $V_r = V_w$ is assumed in the following discussion.

(i). Differential Interleaving Modulation

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

$$0 < S_{min} \le S_j \le S_{max}. \quad (5.1)$$

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:

$$T_{j+2} = \begin{cases} T_j + S_j, & \text{if } T_j + S_j \le T_{max} \\ T_j + S_j - T_{max} + T_{min} - 1, & \text{if } T_j + S_j > T_{max}, \end{cases} \quad (5.2)$$

where $0 < T_{min} \le T_j \le T_{max}$ for each j.

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:

$$S_{max} + T_{min} - 1 \le T_{max} \quad \text{or} \quad T_{max} - T_{min} \le S_{max} - 1. \quad (5.3)$$

By subtracting T_j on both sides of Eq. (5.2), we have:

$$-\Delta T_j = T_{j+2} - T_j = \begin{cases} S_j, & \text{if } T_j + S_j \le T_{max} \\ S_j - T_{max} + T_{min} - 1, & \text{if } T_j + S_j > T_{max} \end{cases}$$

We note that if $T_j + S_j \le T_{max}$ is true in recording, $-\Delta T_j = T_{j+2} - T_j = S_j \ge S_{min}$, and if $T_j + S_j > T_{max}$ is true in recording, by Eq. (5.3), $-\Delta T_j = T_{j+2} - T_j = S_j - T_{max} + T_{min} - 1 \le 0$. Therefore:

$$-\Delta T_j = T_{j+2} - T_j = \begin{cases} S_j, & \text{if } -\Delta T_j \ge S_{min} \\ S_j - T_{max} + T_{min} - 1, & \text{if } -\Delta T_j \le 0. \end{cases}$$

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

$$S_j^r = \begin{cases} -\Delta T_j^r & \text{if } -\Delta T_j^r \geq S_{min} \\ -\Delta T_j^r + T_{max} - T_{min} + 1 & \text{if } -\Delta T_j^r \leq \ldots \end{cases} \quad (5.4)$$

and the original S_j can be recovered by simple threshold detection from S_j^r. Here we see the condition in Eq. (5.3) also provides the error detection capability when $0 < -\Delta T_j^r < S_{min}$ happens.

(iii). Additive Interleaving Modulation

Assume the given modulation code and the post AIM code follow the same condition in Eq. (5.1). The AIM rule is described as follows:

$$T_{j+1} = \begin{cases} S_j - T_j + T_{min} & \text{if } S_j - T_j \geq 0 \\ S_j - T_j + T_{min} + T_{max} - S_{min} & \text{if } S_j - T_j < 0. \end{cases} \quad (5.5)$$

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

$$S_{max} - T_{min} + T_{min} = S_{max} \leq T_{max}. \quad (5.6)$$

Substituting $(S_j - T_j)$ with -1 in the second part of Eq. (5.5), we need

$$-1 + T_{min} + T_{max} - S_{min} \leq T_{max} \quad \text{or} \quad T_{min} \leq S_{min} + 1 \quad (5.7)$$

In addition, to know whether $S_j - T_j \geq 0$ or $S_j - T_j < 0$ is true in recording to select the right equation from Eq. (5.5) for data recovery, we should have another condition for T_{min} and T_{max}. Note that when $S_j - T_j < 0$ is true, we have: $\min(T_j + T_{j+1}) = \min(S_j + T_{max} + T_{min} - S_{min}) = T_{max} + T_{min}$, and when $S_j - T_j \geq 0$ is true, $\max(T_j + T_{j+1}) = \max(S_j + T_{min}) = S_{max} + T_{min}$. Therefore, condition (5.6) should be modified as:

$$T_{max} > S_{max} \quad (5.8)$$

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

$$S_j^r = \begin{cases} \Sigma T_j^r - T_{min} & \text{if } \Sigma T_j^r \leq S_{max} + T_{min} \\ \Sigma T_j^r - (T_{min} + T_{max} - S_{min}), & \text{if } \Sigma T_j^r \geq T_{min} + T_{max} \end{cases} \quad (5.9)$$

Again, if $S_{max} + T_{min} < \Sigma T_j^r < T_{min} + T_{max}$, 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 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.

$$SNR \equiv \frac{\text{Unit Mark Size}}{\text{RMS Jitter of } e_j} = \frac{(\Delta T)V_r}{\sqrt{\sigma_{laser}^2 + \sigma_{media}^2 + \sigma_{receiver}^2}}$$

where ΔT 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.

6.1 Statistical Parameters

In simulation, time mark sizes are $i\Delta T$, where ΔT is chosen to be 100 nsec. and i is uniformly distributed between 3 and 5 (similar to the (2,7) code but not exactly). The disk linear velocity is set at 4.0 m/sec in the both write and read process. For simplicity, the velocity flucution 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, read velocity fluctuation range is set to be ±0.4 m/sec, or 10% of the mean velocity. Velocity is maintained to be slowly varying within a time mark period.

Bit shift jitter (δ_j^r) is set to have a mean shift 200 nm to represent approximately 20% of the laser beam width (assuming the diffraction limit is 1 μm), and the fluctuation of the shift is ±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 ±60 nm in scenario 1 to ±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 $\overline{\delta_2}$. That is, for each detected mark size, T_j^r, we subtract $2\overline{\delta_2}/V_r$ 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 equalizes 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.

4. Differential Detection plus ISI and Velocity Equalization.

This detection method equalizes 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

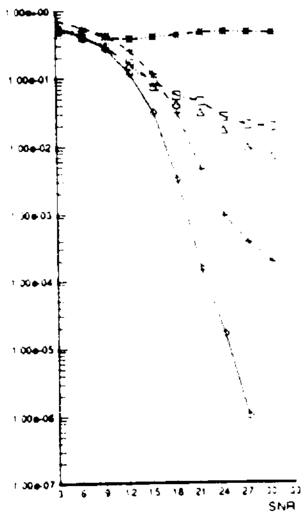

Figure 5: Mark Error Rate of scenario 1

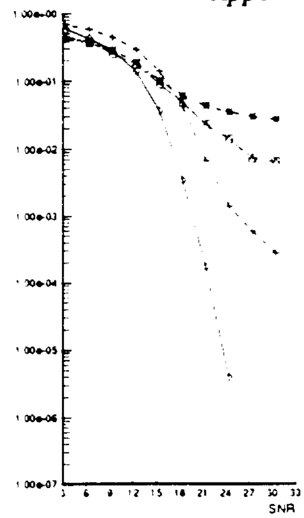

Figure 6. Mark Error Rate of scenario 2

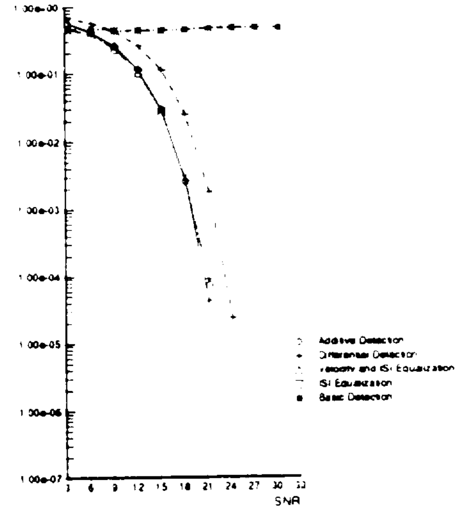

Figure 7: Mark Error Rate of scenario 3

(DID) to cancel the jitter.

5. **Additive Detection plus ISI and Velocity Equlization.**

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 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 implies smaller sizes can be recovered and consequently a higher density can be achieved.

8 Acknowledgement

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