Reduced Complexity Viterbi Detection for Two-Dimensional Optical Recording

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Abstract — A novel data detection scheme is proposed for two-dimensional data storage systems. This scheme is designed to reduce the complexity of two-dimensional Viterbi detector by constraining intertrack interference to be causal and by exploiting the principle of decision feedback. Its application to the two-dimensional optical data storage system is investigated, and further simplifications are also developed.

Index Terms — Reduced Complexity, Two-Dimensional Recording, TwoDOS and Viterbi Detector.

I. INTRODUCTION

The continuously increasing demand for storage capacity in consumer electronics applications necessitates the rapid development of multidimensional (nD) data storage systems such as multichannel recording, multilayer recording, multiside development of multidimensional (nD) data storage (TwoDOS), which has been reported to achieve twice the areal density and ten times the performance, i.e. the probability of detection error. Although the example that we consider in this paper is two-dimensional (2D) in nature, the basic principles underlying the development of the proposed detector are applicable to higher dimensional data storage systems that may emerge in the future.

2D VD is of particular interest in our research work due to the wide application of 2D data storage systems. Moreover, research on reduced complexity 2D VD design will serve as the starting point for the development of reduced complexity nD VD. The 2D system concerned in this paper is the two-dimensional optical data storage (TwoDOS), which has been reported to achieve twice the areal density and ten times the data rate of 3rd generation blu-ray disc [6]. The basic idea of TwoDOS is to group $N$ tracks, with no guard-band within a group and one empty track between groups. Also, hexagonal bit cells are adopted to maximize the capacity of the disc. However, this recording format results in severe 2D ISI in TwoDOS readback signals. Therefore, parallel read-out with 2D partial response (PR) equalization and 2D VD become necessary to ensure reliable data recovery.

Since the complexity of 2D VD grows exponentially with both channel memory and number of tracks per group, the implementation of a full-fledged 2D VD is by far impractical for TwoDOS. The complexity can be reduced by shortening the channel along the track [7]. However, it is not enough if $N_e$ is large. For instance, in the current TwoDOS system where the number of tracks per group is eleven, even if we constrain the channel memory along the track to two, the number of states of full-fledged 2D VD becomes $2^{22}$. Some other techniques, such as decision feedback equalization VD (DFE-VD) [8] and stripe-wise VD (SWVD) [9], have been reported in literature to further reduce the complexity of 2D VD. The DFE-VD cancels some of the dominant intertrack interference (ITI) using decision feedback. Therefore, though it works well in systems with moderate ITI, its performance degrades much in TwoDOS due to the severe ITI. SWVD has better performance compared with DFE-VD since it uses all the dominant part of ITI in the detection process. The cancellation of the remaining ITI in SWVD is done using preliminary decisions (i.e. decision feedback) obtained through an iterative detection approach. However, the use of iterations increases complexity as well as latency. Our new proposal called fixed delay tree search with decision feedback VD (FDTS/DF-VD), on the other hand, is a non-iterative reduced complexity detector that can be applied to any 2D system.

This paper is organized as follows. In Section II, the discrete-time channel model of TwoDOS system is introduced. FDTS/DF-VD is described and analyzed in Section III, and techniques that improve its performance are presented in Section IV. Finally, Section V concludes the paper.

II. TWOADOS CHANNEL MODEL

![Fig. 1. Discrete-time channel model of TwoDOS system with partial response equalization and Viterbi detector.](image)

For the purpose of stating the main definitions and assumptions relevant to the derivations as well as for the sake of clarifying the notation, the discrete-time channel model of
TwoDOS system with PR equalization and VD is shown in Fig. 1. In the figure, $G_k$ ($k = 0, 1, \ldots, N_z - 1$) and $W_k$ ($k = 0, 1, \ldots, N_z - 1$) represent $N_z \times N_z$ coefficient matrices of PR target and equalizer, respectively. For the sake of simplicity, we do not show this figure in the delays (in number of bits) from channel input to equalizer output and detector output. In this paper, we assume that the channel response $H_k$ ($k = 0, 1, \ldots, N_z - 1$) is time-invariant, and the PR target $G_k$ is known. The channel is modeled using 2D Braat-Hopkins function with normalized cut-off frequency $\frac{1}{\sqrt{2}}$ [7]. The equalizer is designed using minimum mean-square error (MMSE) approach with 31 taps. The signal-to-noise ratio (SNR) is defined as

$$\text{SNR} = 10\log_{10} \left( \frac{\sum_{x,y} H^2_k(x,y)}{\sigma^2} \right)$$

where $\sum_{x,y} H^2_k(x,y)$ is the energy for a single spot with $H^2_k(x,y)$ being the symbol response in Cartesian coordinates, and $\sigma^2$ is the variance of the additive white Gaussian noise (AWGN) on each individual track. Then, the readback signal resulting from the parallel read-out at time index \(’n’\) is given by

$$z(n) = \sum_{k=0}^{N_z-1} H_k a(n-k) + \theta(n)$$

where $a(n) = [a_1(n), a_2(n), \ldots, a_{N_z}(n)]^T$, $a_k(n) \in \{-1, 1\}$ denotes the data bit written on the $k$th track, $\theta(n) = [\theta_1(n), \theta_2(n), \ldots, \theta_{N_z}(n)]^T$, $\theta_k(n)$ denotes the noise picked up from the $k$th track, $z(n) = [z_1(n), z_2(n), \ldots, z_{N_z}(n)]^T$, and $z_k(n)$ denotes the readback signal component from the $k$th track, for $k = 1, 2, \ldots, N_z$.

III. FDTS/DF-VD: A REDUCED COMPLEXITY DETECTOR FOR TWO DOS

A. Principle of FDTS/DF-VD

The concept of causal ITI, which means that ITI for a given track arises only from the tracks below it, was first used in multichannel DFE [4]. In this paper, we show that this concept can also be applied to reduce the complexity of 2D VD. For a causal ITI target, the 2D target response matrices are upper triangular and the diagonal elements of the first matrix $G_0$ are constrained to be 1. For example, if the target length along the track is $N_z = 3$ and number of tracks per group is $N_r = 3$, the target matrices can be written as

$$G_0 = \begin{bmatrix} 1 & \times & \times \\ 0 & 1 & \times \\ 0 & 0 & 1 \end{bmatrix}, \quad G_1 = \begin{bmatrix} \times & \times & \times \\ 0 & 0 & \times \\ 0 & 0 & 0 \end{bmatrix}$$

where \(‘\times’\) represents the elements that need to be optimized under a chosen criterion. As a starting point for our development, we first examine the suitability of the causal ITI target in TwoDOS. Fig. 2 shows the performance of full-fledged 2D VD for three different targets when $N_r = 3$ and $N_z = 5$. We use a fixed 2D target with elements [1 2] and 2D monic constrained target, which are reasonable targets discussed in [7] for TwoDOS, as reference targets. Observe that the causal ITI target outperforms all the other targets at every SNR. This manifests that it is reasonable to use the causal ITI target for TwoDOS. Based on this target, we propose some reduced complexity 2D VDs that are quite different from DFE-VD and SWVD since the latter two detectors suffer ITI from both lower and upper tracks.

![Fig. 2. BER performance of full-fledged 2D VD for different target constraints.](image)

![Fig. 3. Principle of FDTS/DF-VD with $N_r = 3$ and $N_z = 5$. The solid lines represent the input and output of sub-2D VDs, the dashed lines represent the feedback coming from the output of the previous sub-2D VDs.](image)
to one track except for the last sub-2D VD, whose outputs correspond to the top \( N_w \) tracks (See Fig. 3). Since in the cross-track direction we essentially use the principle of FDTS/DF [10], [11], we call this detector FDTS/DF-VD. Clearly, because we use the causal ITI target, the proposed detector is able to work satisfactorily dispensing preliminary decisions and iterations.

As our primary concern is to design a relatively simple detector that can be used in high-speed TwoDOS, we first examine the simplest FDTS/DF-VD (when \( N_w = 1 \)). We call this detector quasi-1D VD since each sub-2D VD reduces to a 1D VD, and its complexity grows exponentially with channel memory along the track while grows only linearly with \( N_w \). However, as shown in Fig. 4, quasi-1D VD provides a rather poor performance. With such large room for improvement in detection performance, it is certainly sensible to invest in more sophisticated detectors. Therefore, we investigate two factors that degrade its performance: target length and error propagation. As illustrated in Fig. 5, the bit error rate (BER) performance is not significantly improved by increasing the target length. Further investigations show that target response matrices \( G_s \) and \( G_t \) approach zero, thereby confirming that there is no need to increase the channel memory beyond two. Fig. 5 verifies this for the case of quasi-1D VD. It also shows that error propagation degrades performance by only 1dB when BER is \( 4 \times 10^{-4} \). Thus, target length and error propagation are not the primary causes of the poor performance of quasi-1D VD. In fact, the main reason is that quasi-1D VD ignores the signal energy embedded in the causal ITI terms, which are rather large for TwoDOS due to the absence of guard-band between tracks. Therefore, we should increase \( N_w \) in order to achieve better performance. Fig. 4 shows that setting \( N_w = 3 \) is enough to yield good performance. Although not shown here, we found that we can save another 1dB if there is no error propagation in this case.

![Fig. 5. BER performance of quasi-1D VD with different target lengths. "L4" and "L5" represent targets with length four and five, respectively, otherwise, the length is three. "No EP" means that error propagation is avoided by using the correct input bits to calculate the ITI. The equalizer length is 31 in all the simulations.]

### B. Performance Analysis of FDTS/DF-VD

The exact performance of FDTS/DF-VD is somewhat difficult to analyze because of decision feedback. However, as mentioned in the last subsection, error propagation degrades the performance by about 1dB. Therefore, we first investigate the FDTS/DF-VD that is free of error propagation. The effect of error propagation can be assessed through simulations.

Let \( \hat{a}(n) \) denote the detected data vector corresponding to \( a(n) \) and \( e(n) = (a(n) - \hat{a}(n))/2 \). Further, we define

\[
\hat{a} = [a'(n), a'(n+1), \ldots, a'(n+N_e-1)],
\hat{a}' = [a'(n), a'(n+1), \ldots, a'(n+N_e-1)],
\hat{a}'' = [a''(n), a''(n+1), \ldots, a''(n+N_e-1)].
\]

Then, \( \hat{a} \) is a 2D error event of length \( N_e \) if

1. \( e(n) \neq 0 \) and \( e(n+N_e) \neq 0 \),
2. the length of strings of zero vectors in \( e \) does not exceed \( N_e \), and
3. \( \hat{a}(n+i) = a(n+i) \) for \( -N_f \leq i < 0 \) and \( N_f \leq i \leq N_f + N_e - 1 \).

Here \( N_f \) is called the ‘error-free interval’ and \( N_f \geq N_e - 1 \). It should be noted that in the absence of propagation, only from \( k \)th to \( (k+N_e-1) \)th tracks may have errors for the \( (k+1) \)th sub-2D VD. Let \( W(e) \) be the number of error bits in the corresponding output track(s) of a sub-2D VD for the error event \( e \). Then, the bit error rate (BER) of the \( k \)th sub-2D VD at a particular time is given by

\[
P_e = \sum_{e} W(e) P(a) P(\text{error|a})
\]  

(3)

where \( E_s \) is the set of all possible error events, \( S_e \) is the set of all possible data patterns that support the error event \( e \), \( P(a) \) is the probability that the true recorded data is \( a \), and \( P(\text{error|a}) \) is the conditional probability that the VD detects \( a \) as the recorded data when the true recorded data is \( a \).
For notational convenience, \( a_j(n) \) and \((A \ast B)_n\) denote the \( j^{th} \) element of vector \( a_n \) and matrix \((A \ast B)_n\), respectively, where \( \ast \) denotes the 2D convolution operator given by 
\[
(A \ast B)_n = \sum_k A_{nk} B_{nk} \quad \text{and} \quad (A \ast B)_n = \sum_k A_{nk} B_{nk},
\]
unless specified otherwise. According to the principle of VD, \( P(\text{error}|a) \) can be upper-bounded by the probability that the metric corresponding to path \( \hat{a} \) is smaller than that corresponding to \( a \). That is
\[
\begin{align*}
&\sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} \left[ x_j(n+i) - (G \ast \hat{a})_{nk,j} \right]^2 \\
&< \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} \left[ x_j(n+i) - (G \ast a)_{nk,j} \right]^2
\end{align*}
\]
(4)
where \( k \) is the index of the sub-2D VD and \( x_j(n) \) is the equalizer output in the \( j^{th} \) track.
\[
x_j(n) = \sum_{i=0}^{N_2-1} W_{jk}(n-i) = \left[ (G + M) * a \right]_n + (W * \theta)_n
\]
(5)
where \( M \), \( a \), \( W \), and \( \theta \) denote the taps of the 2D ISI channel, i.e., \( M = (W + \mathbf{H}) \), \( a \) is a 2D white Gaussian noise vector with variance \( \sigma^2 \). Using (5), we can express (4) as
\[
d^2(e) + \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} \left[ (M * a)_{nk,j} + (W * \theta)_{nk,j} \right] < 0
\]
(6)
where \( d^2(e) + \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} \left[ (M * a)_{nk,j} + (W * \theta)_{nk,j} \right] \) and \( \hat{e}(n) = (G \ast e)_n \).

For given \( a \) and \( e \), the left hand side of the inequality in (6) is a Gaussian random variable with mean
\[
m_e = d^2(e) + \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} (M \ast \hat{e})_{nk,j} a_j(n+i)
\]
(7)
and variance
\[
\sigma^2_e = \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} (W \ast \hat{e})_{nk,j}^2.
\]
(8)
Thus, we get
\[
P(\text{error}|a) \leq Q(m_e / \sigma_e)
\]
(9)
where \( Q(\alpha) = \frac{1}{\sqrt{2\pi}} \int_{-\alpha}^{\infty} e^{-x^2/2} dx \) is the tail probability of Gaussian distribution. By substituting (9) into (3), we get the BER of the \( k^{th} \) sub-2D VD at a particular time as
\[
P_e^k \leq P \left( \sum_{j=0}^{N_1} \sum_{k=0}^{N_2-1} W_{jk}(e) P(a|\theta) Q(m_e / \sigma_e) \right).
\]
(10)

Based on the BER for the sub-2D VD given above, the BER of the FDTS/DF-VD in the absence of error propagation is upper bounded by the summation of the BERs of all the sub-2D VDs. As shown from (10), the presence of the residual ISI makes this analysis data-dependent in nature. Therefore, the complexity of exhaustive search over all possible input data patterns to compute the theoretical performance is prohibitively large. The usual practice is to assume that the residual is very small and to add it as part of the Gaussian noise [11]. In this paper, however, we will introduce a practical approach with significantly lower complexity to analyze systems that suffer severe residual ISI. As shown in (7), each input data bit corresponds to one unique element in \( (M \ast \hat{e})_k \). Consequently, we could only consider the bits whose corresponding element in \( (M \ast \hat{e})_k \) exceeds a given threshold in magnitude. The remaining bits are ignored since they have much less effect on the mean \( m_e \) (and hence the BER of the sub-2D VD). Then, we exhaustively search over all the possible data patterns of the bits under consideration to approximately compute the BER. Intuitively, the choice of the threshold is a trade-off between search complexity and BER accuracy. Our simulation results show that this method is able to evaluate different targets with acceptable computational complexity under a suitable threshold.
For a conventional causal ITI target, all of its 2D target response matrices are right triangular matrices and the diagonal elements of \( G_i \) are constrained to be 1s. This target makes a given track suffer ITI only from the tracks below it. However, the interferences from the tracks below are not equally significantly on the current track. For the channel under consideration, we found that only the two nearest tracks below the current track cause significant ITI. Therefore, in the target matrices, we only need to consider the elements that correspond to the two nearest lower tracks. All the remaining causal ITI terms can be constrained to be zero. For example, if target length is \( N_t = 3 \) and number of tracks per group is \( N_r = 5 \), the target matrices can be written as

\[
G_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad G_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},
\]

where ‘\( \times \)’ represents the elements that need to be determined.

We call this target truncated causal ITI target since it is essentially a causal ITI target with truncated channel memory across the track. This truncation leads to performance degradation of full-fledged 2D VD. However, it can make the FDTS/DF-VD suffer less error propagation effect since it prevents the error propagation from the lower tracks beyond the nearest two tracks. In other words, this target benefits FDTS/DF-VD by reducing error propagation at the cost of performance loss due to truncating.

As shown in [7], for a non-causal ITI target, assuming that ITI is only dependent on the relative separation between two tracks results in trivial performance loss while significantly reducing the complexity of target design. Therefore, to save complexity, we conduct an investigation on this assumption for causal ITI target. For example, if target length \( N_t = 3 \) and number of tracks per group \( N_r = 5 \), this simplified truncated target matrices can be written as

\[
G_0 = \begin{bmatrix} g_0 & g_1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad G_1 = \begin{bmatrix} 0 & g_1 & g_2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},
\]

In this case, the 1D vector target is \( g = [g_0, g_1, g_2, g_3, g_4, g_5, g_7]^T \), where \( g_i \) (\( i = 0, 1, ..., 7 \)) are the distinct non-zero elements in the target response matrices. This target has two advantages: First, it reduces the complexity of target design process shown in [7] since the target vector has only eight elements while the traditional causal ITI target has seventy-eight elements when \( N_t = 3 \) and \( N_r = 5 \). Second, it ensures that all the sub-2D VDs have equal noiseless output for a given state. Therefore, all the sub-2D VDs can share the same architecture to yield the noiseless output and this can be realized by a simple table look-up operation. However, since the assumption that the ITI is only dependent on the relative separation between tracks is not true in practice, this assumption additionally burdens the finite length equalizer and may lead to detection performance degradation.

![BER vs SNR in TwodoS with different targets.](image)

As illustrated in Fig. 7, both of the new targets degrade the performance of 2D VD. This is not expected, as already mentioned above. Fig. 7 also shows that these two new targets do not improve performance over that of conventional causal ITI target for the FDTS/DF-VD. The main reason is that the truncation performance loss nullifies the gains from error propagation reduction. However, simplified truncated causal ITI target result in lower complexity in the implementation of FDTS/DF-VD as well as in the process of target design. It also leads to reduction in error propagation. For this reason, simplified truncated causal ITI target is still preferable in TwoDOS system, and further research can be carried out to improve the detection performance and investigate its suitability on other 2D systems.

D. Further Reduction in FDTS/DF-VD

For the FDTS/DF-VD, adjacent two sub-2D VDs have \( N_r - 1 \) tracks in common. However, it is hard to tell which sub-2D VD is more reliable in detecting the bits of these tracks. For this reason and in order to further reduce complexity, we make each track correspond to one unique sub-2D VD. More specifically, the first sub-2D VD deals with the lowest \( N_r \) tracks and detected bits from these tracks are all
final decisions, the second sub-2D VD deals with the subgroup that is shifted up by $N_v$ tracks and detects all the bits in this subgroup. Same principles are applied to the third sub-2D VD and above. Note that the last sub-2D VD only deals with $N_v$, $N_v = N_v$ modulo $N_v$, tracks, as illustrated in Fig. 8. We call this detector reduced-complexity FDTS/DF-VD (RFDTS/DF-VD) since it uses less number of sub-2D VDs. From Fig. 4 we find that for the same $N_v$, RFDTS/DF-VD and FDTS/DF-VD perform almost comparably, whereas RFDTS/DF-VD significantly reduces the complexity compared to FDTS/DF-VD. Thus RFDTS/DF-VD is an attractive reduced complexity detector for TwoDOS. Further research is being carried out to reduce the performance loss of this detector compared to the full-fledged 2D VD.

IV. FDTS/DF-VD WITH GUARD-BAND

For the FDTS/DF-VD, error patterns show that most of the detection errors occur in the lowest track due to the minimum signal energy of the lowest subgroup. In addition, these detection errors make all the bit decisions in the upper tracks suffer from error propagation. To deal with this problem, we take the guard-band into consideration.

As a starting point, guard-bands are assumed to contain all '-1's in view of no pits in the guard-band. We normally do not take the effect of guard-bands into consideration since it can be perfectly canceled once we know the channel characteristics. Therefore, the assumption that guard-bands containing all '-1's will not affect the detection performance of full-fledged 2D VDs. Here, owing to the particular principle of FDTS/DF-VD, we assume that the bits in the guard also require to be detected. The already known information from the guard-band (contains all '-1's) makes the decisions on the guard-band free of errors. This error-free property conduces FDTS/DF-VD to suffer no error propagation from the lowest track (which are more likely to have errors for the conventional FDTS/DF-VD), and makes the bit decisions for the upper tracks more reliable. Therefore, the overall BER$^2$ performance for FDTS/DF-VD should be ameliorated. More specifically, for TwoDOS with $N_v$ tracks per group, we regard the number of tracks to be $N_v + 1$, and altogether $N_v + 1$ read-heads in the parallel readout system. Then we design causal ITI target for this $(N_v + 1)$-track system. In order to implement FDTS/DF-VD, we first use a 'fictitious' sub-2D VD to detect the lowest track (guard-band). This first sub-2D VD is actually not used in practice since the bits in the guard-bands are already known. Remaining sub-2D VDs process the other tracks and follow the same principle as the FDTS/DF-VD until all the tracks are detected.

Fig. 9 shows the BER performance for FDTS/DF-VD with or without taking the guard-band into account. As illustrated, the FDTS/DF-VD considering guard-band improves over that without considering guard-band by roughly 2dB when BER is $10^{-4}$. This shows that FDTS/DF-VD can displace full-fledged 2D VD. In fact, it is not the bit-decision process for guard-band that benefits the performance of FDTS/DF-VD. The essential factor for the performance improvement is the new designed target. The reason can be explained as follows. During the process of the target design, we also assume guard-band suffers ITI from each information track. Then, the total signal energy associated with each information bit increases due to the additional ITI from the guard-band. The increase in signal energy results in the improvement of effective SNR and thus leads to better detection performance for FDTS/DF-VD. This increase is more significant in the lowest information track since they are closest to the guard-band and their ITI terms in the guard-band are relatively large. As discussed earlier, the lowest information track is more liable to have errors in the FDTS/DF-VD due to its lowest signal power. The increase in signal energy due to guard-band makes the bit decisions for the lowest information track more credible and thus increases the overall detection performance of FDTS/DF-VD.

V. CONCLUSION

In this paper, we propose the reduce-complexity Viterbi-like detector for two-dimensional data storage systems by exploiting the causal intertrack interference target and decision feedback mechanism. This proposal is applied to two-
dimensional optical storage and its performance is analyzed with a reliable and simple method. Several techniques that further simplify the two-dimensional bit detectors are also introduced. The principle presented in this paper can be easily generalized for application to multi-dimensional data storage systems.

References


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