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다차원 신호공간 분할을 이용한 데이터 복원

Data Retrieval by Multi-Dimensional Signal Space Partitioning

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요 약

본 논문에서는 심볼 간의 간섭이 존재하는 채널에서 고정 지연 값을 가지는 트리검색 신호검출기의 효율적인 구성방법을 다룬다. 이 접근방법은 효율적인 다차원 신호공간 분할에 기반을 두고 있다. 다차원 공간에서의 Voronoi 다이어그램(VoD)과 Delaunay 분할 (DT)이 신호검출 알고리즘의 구현에 적용된다. 제안된 방식에서는 VoD/DT 에 포함되어 있는 기하학적인 정보를 활용하여 관찰된 순차적인 신호의 상대적인 위치가 결정되며 이러한 방식이 구현의 복잡도를 감소시키는 장점이 있음을 보인다. 구체적인 구성 절차가 심볼 간의 간섭이 존재하는 통신채널에서의 예를 가지고 논의되며 시뮬레이션 결과가 논의된다.

Abstract

This paper deals with a systematic approach for the construction of the fixed-delay tree search (FDTS) detector in the intersymbol interference channel. The approach is based on the efficient multi-dimensional space partitioning. The Voronoi diagram (VoD) and the Delaunay tessellation (DT) of the multi-dimensional space are applied to implement the algorithm. In the proposed approach, utilizing the geometric information contained in the VoD/DT, the relative location of the observation sequence is determined which has been shown to reduce the implementation complexity. Detailed construction procedures are discussed followed by an example from the intersymbol interference communication channel.

Key words : Tree search, Intersymbol interference, Voronoi diagram, Delaunay tessellation.

1. Introduction

The FDTS (Fixed Delay Tree Search) detection algorithm is the computationally efficient sequence detection algorithm using the depth limited lookahead tree [1]. The FDTS with depth τ detection compares a finite number $(\tau+1)$ of consecutive observation samples against all the possible noiseless signal sequences with the same length, chooses the one that best matches the observation, and identifies the decision bit associated with the chosen sequence. Several lookahead tree search type sequence detection methods have been reported which are based on the signal space concepts [2]-[4] but these are all limited to the developments in the lower dimensions. This is due to the difficulty in the visualization of the higher dimensional space. In this paper, a systematic approach is proposed for the construction of the FDTS using the efficient signal space partitioning. In this approach, utilizing the information contained in the VoD and the DT, the relative location of the observation sequence to the reference signals in the multi-dimensional space is found without any computational redundancy. The basic concepts of the VoD and the DT are briefly reviewed. The detailed construction procedure for detector is discussed followed by an example taken from the high density optical storage channel. The bit error rate (BER) simulation results are also presented.

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2. Voronoi Partitioning of the Signal Space

The VoD is the partition of the multi-dimensional signal space given some number of signal vectors according to the nearest-neighbor rule [5]. Each Voronoi region V_i, associated with the i^{th} signal vector, is the convex region which contains all points closer to the i^{th} signal than the Delaunay neighbors of the i^{th} signal. The i^{th} and j^{th} signals are called the Delaunay neighbors (DNs) to each other if their corresponding Voronoi regions V_i and V_j, intersect in a face. The half space H_{ij} and the bisector boundary B_{ij} are introduced to describe the Voronoi region V_i more specifically in terms of the relative placements of the i^{th} and j^{th} signals. The half space $H_{ij}(H_{ji})$ is defined as the locus of all points closer to the $i^{th}(j^{th})$ signal bounded by the hyperplane boundary B_{ij}. The function $h_{ij}(.)$, also called the discriminant function, can be used to determine whether an arbitrary observation vector $\mathbf{r}'_k$ is closer to the i^{th} signal than j^{th} signal:

$$h_{ij}(\mathbf{r}'_k) = \frac{1}{2}(\mathbf{y}'^{(i)}_k - \mathbf{y}'^{(j)}_k)\cdot \mathbf{r}'_k - \frac{1}{4}(\mathbf{y}'^{(i)}_k + \mathbf{y}'^{(j)}_k)\cdot(\mathbf{y}'^{(i)}_k - \mathbf{y}'^{(j)}_k) \quad (1)$$

where $\mathbf{y}'^{(i)}_k$ and $\mathbf{y}'^{(j)}_k$ are the i^{th} and j^{th} reference signals of our interest and '.' denotes the inner product operation in the signal space. If $\mathbf{r}'_k$ falls in $H_{ij}(H_{ji})$, $h_{ij}(\mathbf{r}'_k)$ is greater(or less) than zero. The Voronoi region V_i can be expressed in terms of H_{ij}'s as follows:

$$V_i = \bigcap_{j \in D_i} H_{ij} \quad (2)$$

where D_i is the set of indices whose elements correspond to all DNs of the i^{th} signal.

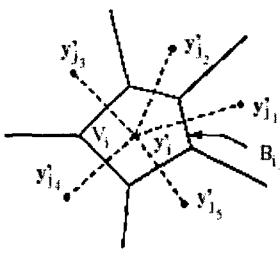

Figure 1. Voronoi region V_i and Delaunay neighbors (connected by dotted line segments) of the i^{th} signal ($D_i = \{j_1, j_2, j_3, j_4, j_5\}$).

3. Formulation of FDTS based on the VoD

In this section, The concept of the VoD/DT is applied to the construction of the FDTS with depth τ. For the channel model, it is assumed that noisy samples which experience the intersymbol interference (ISI) as well as the additive noise, are equalized as follows:

$$r_k = \sum_{i=0}^{\tau} f_i x_{k-i} + n_k = y_k + n_k \quad (3)$$

where f_k, x_k, n_k and y_k are the equalized channel impulse response, the binary channel input symbol, the noise and the signal sample, respectively. In the construction of the FDTS using the VoD/DT, the noiseless signal sample y_k is utilized as the reference signal. For this purpose, the modified signal $y_k'^{(i)}$ is defined as follows:

$$y'^{(i)}_{k-j} = \sum_{i=0}^{\tau-j} f_i x^{(i)}_{k-j-i}, \text{ for } 0 \le j \le \tau \quad (4)$$

where the superscript i is used to denote the i^{th} path in the look-ahead tree used for the original FDTS algorithm. A similar modification must also be made to the observation sequence, i.e., the modified observation sequence r_k' is defined as

$$r'_{k-j} = \begin{cases} r_{k-j}, & \text{for } j = 0 \\ r_{k-j} - \sum_{l=\tau-j+1}^{\tau} f_l \hat{x}_{k-j-l}, & \text{for } 1 \le j \le \tau \end{cases} \quad (5)$$

where past decisions $\hat{x}_{k-m}$'s, $m > \tau$, are utilized. The FDTS with depth τ compares the Euclidean distance between the observation vector $\mathbf{r}'_k=[r'_k, r'_{k-1}, \cdots, r'_{k-\tau}]$ and the $2^{\tau+1}$ possible reference signals $\mathbf{y}'_k=[y'_k, y'_{k-1}, \cdots, y'_{k-\tau}]$, identifying the signal vector which is closest to $\mathbf{r}'_k$ and releasing its associated $x_{k-\tau}$ value. The first step in the detector design is to find all possible reference signal vectors $y_k'^{(i)}$'s, i^{th} $1 \le i \le 2^{\tau+1}$ and to construct the VoD/DT on them. If the observation vector $\mathbf{r}'_k$ falls in one of the Voronoi regions associated with $x_{k-\tau} = 1$, the decision $\hat{x}_{k-\tau} = 1$ is made, otherwise $\hat{x}_{k-\tau} = -1$. But some of the DN pairs, (i, j) whose corresponding signals are in the same class are redundant if the new region V_i' formed after removing the half space H_{ij}, does not intersects with the region belonging to the other class. Then the decision rule for the estimation of the value of the delayed input symbol, $x_{k-\tau}$, can be expressed as follows:

$$\hat{x}_{k-\tau} = \begin{cases} 1 & \text{if } \mathbf{r}'_k \in \bigcup_i \left(\bigcap_{j \in D'_i} H_{ij} \right), 1 \le i \le 2^{\tau} \\ -1 & \text{otherwise} \end{cases} \quad (6)$$

where D_i' is a set of indices such that the i^{th} and j^{th} $(i \neq j)$ signals are the DNs of each other which do not satisfy the redundancy condition and the i^{th} reference signals, $1 \le i \le 2^{\tau}$, are assumed to be associated with $x_{k-\tau} = 1$.

The final step is to obtain the discriminant functions that correspond to the required boundaries and set up the logic rule that implements the decision rule in (6). It can be shown that τ multipliers are enough to implement the required discriminant functions.

4. Example and Simulation Results

As an example, the implementation of the FDTS with depth parameter $\tau = 3$ is considered for the ISI channel whose impulse response is given as $\{f_0, f_1, f_2\}=\{1, 2, 1\}$. This channel is called the class II partial response channel and often used in the high density optical recording channel [6]. It is assumed that the input binary data is encoded to have the $d=1$ minimum run length constraint.

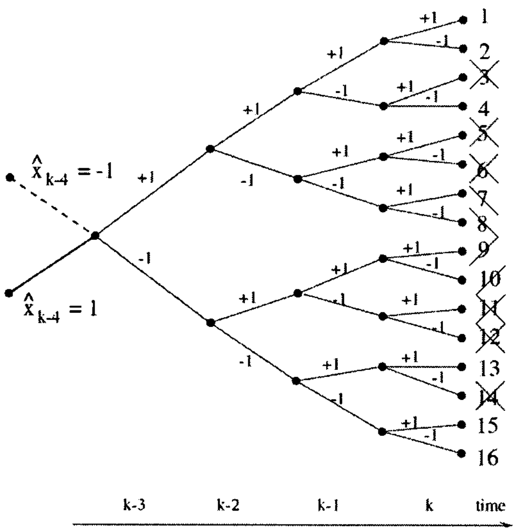

Fig. 2. Detection tree for $\tau=3$ and the $d=1$ constraint (code-violating paths are marked ''/'', ''\'' or ''x'').

Table 1. The DN pairs for (a) $x_{k-4}=1$ (b) $x_{k-4}=-1$

(a)

	1	2	4	7	8
1		X	X	X	
2	X		X	X	X
4	X	X		X	X
7	X	X	X		X
8		X	X	X	
13	O	O	O	O	O
15	O		O	O	
16		O	O		O

(b)

	9	10	13	15	16
1	O		O	O	
2		O	O		O
4	O	O	O	O	O
9		X	X	X	
10	X		X	X	X
13	X	X		X	X
15	X	X	X		X
16		X	X	X	

As the first step, the signal vectors that violate the code constraint should be excluded from the DT construction. In Fig. 2, the lookahead paths that correspond to the code-violating signals are marked ''/'' or ''\'' depending on the values of the previously detected symbol, $x_{k-4}=1$ or $x_{k-4}=-1$, respectively. The paths which violate the constraint regardless of the previously detected symbol are marked ''x''.

The next step is to find the DT on the 8 eligible reference signals $\mathbf{y}_k^{(i)}$'s in the 4-dimensional space for each case. The resulting DN pairs that do not satisfy the redundancy condition discussed in the previous section are summarized in Table 1. The row/column index pairs marked by ''o'' represent those of required DN pairs while the ones marked by ''x'' represent redundant DN pairs. Based on the required boundaries obtained from the DT and the redundancy test, the detection rule can be set up in terms of the discriminant function shown in (1):

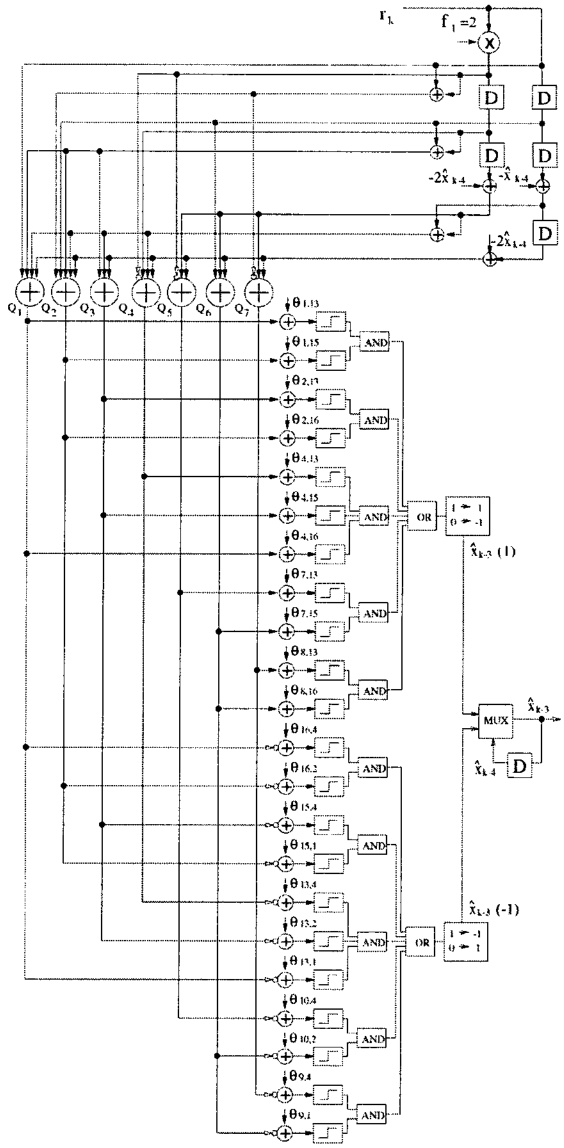

Figure 3. Signal space FDTS detector for the channel $\{f_0, f_1, f_2\}$={1, 2, 1} (the white arrow heads with small circles at the input of the adder represent the subtraction, while dark ones represent the addition).

$$\hat{x}_{k-3}=\begin{cases}1 & \text{if } (h_{1,13}>0 \cap h_{1,15}>0) \\ & \cup (h_{2,13}>0 \cap h_{1,16}>0) \\ & \cup (h_{4,13}>0 \cap h_{4,15}>0 \cap h_{4,16}>0) \\ & \cup (h_{7,13}>0 \cap h_{7,15}>0) \\ & \cup (h_{8,13}>0 \cap h_{8,16}>0) \\ -1 & \text{otherwise}\end{cases} \quad (7)$$

for $\hat{x}_{k-4}=1$ and

$$\hat{x}_{k-3} = \begin{cases} -1 & \text{if } (h_{9,1} > 0 \cap h_{9,4} > 0) \\ & \cup (h_{10,2} > 0 \cap h_{10,4} > 0) \\ & \cup (h_{13,1} > 0 \cap h_{13,2} > 0 \cap h_{13,4} > 0) \\ & \cup (h_{15,1} > 0 \cap h_{15,4} > 0) \\ & \cup (h_{16,2} > 0 \cap h_{16,4} > 0) \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

for $x_{k-4} = -1$. Fig. 3 shows the block diagram of the detector which implements the detection rule (6) and (7). In this implementation, to reduce the pairwise add operation, the intermediate variable Q_i's, $1 \leq i \leq 7$ are introduced. These variables represent common terms in h_{ij}'s used in the decision rule. the fact $h_{ij} = -h_{ji}$ is utilized to reduce the hardware complexity. The upper and the lower half block after the Q_i's generate the conditional estimates of x_{k-3} given $\hat{x}_{k-4} = 1$ and -1, respectively. Also note that the detection value $\hat{x}_{k-4}$ from the previous symbol period is needed only at the last stage of the decision.

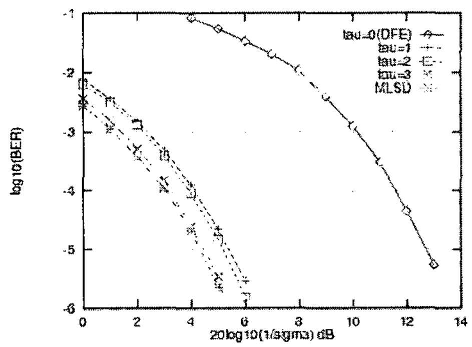

Fig. 4. Bit error simulation for the channel $\{f_0, f_1, f_2\} = \{1,2,1\}$.

This type of implementation makes the high speed pipelining of the detection procedure possible. The θ_{ij} represent the threshold values for each h_{ij}. These threshold values are terms in (1) which are independent of the observation sequence. The BER simulation results (Fig. 4) in which additive white Gaussian noise with variance σ^2 is assumed, show that this detection scheme performs comparable to the maximum likelihood sequence detection (MLSD) [7].

5. Conclusion

A systematic method is proposed which reduces the implementation complexity of the FDTS without any performance degradation. This approach is based on the efficient multi-dimensional signal space partitioning using the concept of VoD/DT. The implementation example is presented to illustrate the construction procedure. Also, utilizing the parallel nature of the detection process, the possibility of the pipelining of the procedure is presented for the high speed implementation without significant increase of the hardware complexity. BER simulation results verify the near optimum performance of the resulting detector in the high density channel.

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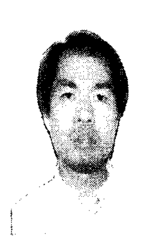

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