行政院國家科學委員會專題研究計畫成果報告

用於低複雜度最大可能序列估計之限制型決策迴授等化器

A Constrained Decision Feedback Equalizer for Low Complexity Maximum Likelihood Sequence Estimation

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一. 中文摘要

最大可能序列估測(MLSE)通常是利用 Viterbi 演算法(VA)來實現，而 Viterbi 演算法之複雜度是隨著通道的長度呈指數的增加。決策迴授等化器(DFE)可以用來縮短響應之長度。這種作法只會造成 MLSE 效能些微的損失，但其計算複雜度卻可有效地降低。然而在實際的應用上，結合 DFE 之 MLSE，其計算複雜度可能仍然很高。在本計畫裏，我們提出了一個限制型 DFE 進一步的降低 VA 之計算複雜度。其基本想法是在 DFE 的係數上面加一些限制，使得縮短之後的通道只具有離散的數值。這使得 VA 變得不需要乘法的運算，硬體的實現因而變得較容易。初步的研究顯示，我們所提出的方法既可以保有原來 MLSE 的效能又可以使得 VA 變得更有效率。利用這種結果我們接著研究 TCM 訊號之等化問題。我們將證明所提的方法可以大幅地降低此應用之計算複雜度。

關鍵詞：等化器，最大可能序列估測，決策迴授等化器，限制型決策迴授等化器

英文摘要

In high bit rate digital transmission, the intersymbol interference (ISI) effect is one of the impediments to the system performance. It is known that the maximum likelihood sequence estimator (MLSE) have superior performance to other methods. The MLSE is usually implemented by the Viterbi algorithm (VA) and its computationally complexity grows exponentially with the length of the channel response. With some performance reduction, a decision-feedback equalizer (DFE) can be used to shorten the channel response. This greatly reduces the computational requirement for the VA. However, for many real-world applications, the complexity of the DFE/MLSE approach may be still too high. In this project, we proposed a constrained DFE further reducing the computational complexity of the VA. The basic idea is to pose some constraints on the DFE such that the post cursors of the shortened channel response has only discrete values. As a result, the multiplication operations can be effectively replaced by shift operations making the VA almost multiplication free. This will greatly facilitate the real world applications of the MLSE algorithm. Primary study results show that while the proposed algorithm remains the original MLSE performance, the VA is much more efficient than the conventional approach. Using the proposed algorithm, we then further consider the equalization problem in trellis coded modulation (TCM) systems. We show that the computational complexity can be dramatically reduced.

Keywords: equalizer, MLSE, DFE, constrained DFE

二. 計劃緣由及目的

In high-speed digital transmission, the intersymbol interference (ISI) effect is one of the primary impediments to the system performance. Two approaches have been used to overcome the problem. One is the decision feedback equalization (DFE) and the other is the maximum likelihood sequence estimation (MLSE). It is well known that the MLSE can have much better performance than the DFE [1], however, the computational complexity is much higher. The MLSE is usually implemented using the Viterbi algorithm (VA) and the computational complexity of the VA grows exponentially with the length of the channel response. This greatly limits the real-time applications of the MLSE. Thus, a great deal of effort has been made to reduce the computational complexity of the VA.

An obvious method is to truncate the channel response. However, direct truncation will not give the optimal result. Qureshi and Newhall [2] proposed to place a linear equalizer before the VA. The equivalent channel response, which is the convolution result of the channel and the linear filter responses, can be shorter. Thus, the truncation then becomes much easier. Falconer, Magee [3], and Beare [5] used the same structure

but optimized the equivalent channel response using the MMSE and other criteria. Thus, the optimal shortened result can be obtained. To avoid noise enhancement introduced by the linear equalizer, Lee and Hill [4] adopted the DFE structure to shorten the channel response. The resultant precursors are truncated and the post cursors with small values are canceled using the tentative decisions from the DFE. This approach can effectively reduce the channel response length. Since only post cursors with small values are canceled, the error propagation effect is not significant. Other researchers attacked the problem
using the suboptimal search strategy in the VA. Foschini [6] proposed the reduced state algorithm which only searches the most probable states. Eyuboglu and Qureshi [7] used the VA with decision feedback into search the subset trellises, which are constructed using the set partitioning principle introduced by [10].

In this project, we consider the DFE/MLSE structure in [4]. We proposed a new DFE structure that can effectively reduce the computational complexity in the VA. The idea is to pose some constraints on the DFE coefficients such that the channel response used in the VA has only discrete values. As a consequence, the multiplication operations can be replaced by shift operations. This results in a VA almost multiplication-free making real-world implementation of the VA much more simpler. We called this a constrained DFE. The proposed algorithm is specially useful in equalizing the trellis coded modulation (TCM) signal. In the equalization of TCM signals, the delayed decision-feedback sequence estimation (DDFSE) is usually applied [12]. Being a special case of reduced state MLSE, the DDFSE utilizes a bank of DFE inside the VA. In this case, the proposed algorithm can dramatically reduce the computational complexity.

三. 研究方法及成果

A typical DFE structure is shown in Fig. 1. Symbols a(n)'s independently selected from a signal set with size S are transmitted through a time-dispersive channel. With a decision-feedback equalizer, we can shape the channel response into a shorter one reducing the VA complexity. Let F and B be the tap weight vectors of the feedforward and feedback filters, respectively. In the conventional DFE/MLSE algorithm, the feedback filter is further partitioned into two subfilters, i.e., $B=[B_1^T, B_2^T]^T$. Let F and B have their optimal values and G=C*F, where * denotes the convolution operation and C the channel response. It is known that the post cursors of the G equal B. In other words, the post cursors of G are canceled by the feedback filter B. If we partially cancel the post cursors using B_2 , the channel response becomes B_1. We can further truncate the precursors of G and this results in a shortened channel response as $\bar{C}=[\hat{c}_0, B_1^T]^T$ where $\hat{c}_0$ is the main cursor of the shortened channel response. This channel response is then used by VA. Usually, the length of $\bar{C}$ is much smaller than that of the original channel response C. This approach is depicted in Fig. 2. It is known that the hardware complexity for the multiplication operation is much higher than the addition operation. Thus, one possible complexity reduction method is to reduce the number of multiplications as much as possible. If we can make $\bar{C}=[\hat{c}_0, B_1^T]^T$ having discrete values, all the multiplications can be translated into shift operations and additions. We find that this is possible except for the main cursor. Thus, we propose to constrain the shortened channel response such that its post cursors only have discrete values. For simplicity, we let $b_i = q_i = \mathrm{sgn}(b_i)2^{k_i}$ where b_i is the i-th element of B_1 and k_i is an integer (possibly negative) and sgn (.) denotes the signum operator. In order words, we quantize b_i. Thus, implementation of b_i only requires a bit-shift. This will greatly reduce the computational complexity of the VA. Note that we cannot directly force b_i to q_i. This is because the post cursors generated by the feedforward filter cannot be perfectly canceled by the feedback coefficients q_i's. This problem can be alleviated by re-solving the optimal solution given the fixed q_i's resulting a constrained DFE. We will study this approach and explore the optimal quantization method. We then derived the optimal solution for the constrained DFE described above. Although the optimal coefficients of the constrained DFE can be found by solving the Wiener-Hoft equations, it requires the matrix operations which are not desirable in real-world implementation. Thus, an adaptive algorithm only requiring vector operations may be preferred. The least-mean-squared (LMS) algorithm [13] is a well known adaptive algorithm. It can find the optimal DFE solution recursively and at the same time keep track of the channel variation. We have performed simulations to demonstrate the performance of the proposed algorithm. Let the channel response be [0.2,1,0.7, 0.4,0.2,0.1,0.05]. Let the number of states in the VA is 16. The performance of the proposed algorithm is shown in Figure 3. As we can see that the performance of the proposed algorithm is slightly worse than the conventional one.

However, as Table 1 shows that the computational complexity of the proposed algorithm is significantly smaller than the conventional one.

四. 結果與討論

In this project, we have proposed a constrained DFE for reducing the computational complexity in the MLSE. The main idea is to let the equivalent channel seen by the VA become discrete. Thus, the BM computations in the VA algorithm is then become multiplication free. Simulations show that while the performance loss is small, the computation reduction is significant. The proposed algorithm is simple and easy to implement. It has great potential in real-world applications.

五. 參考文件

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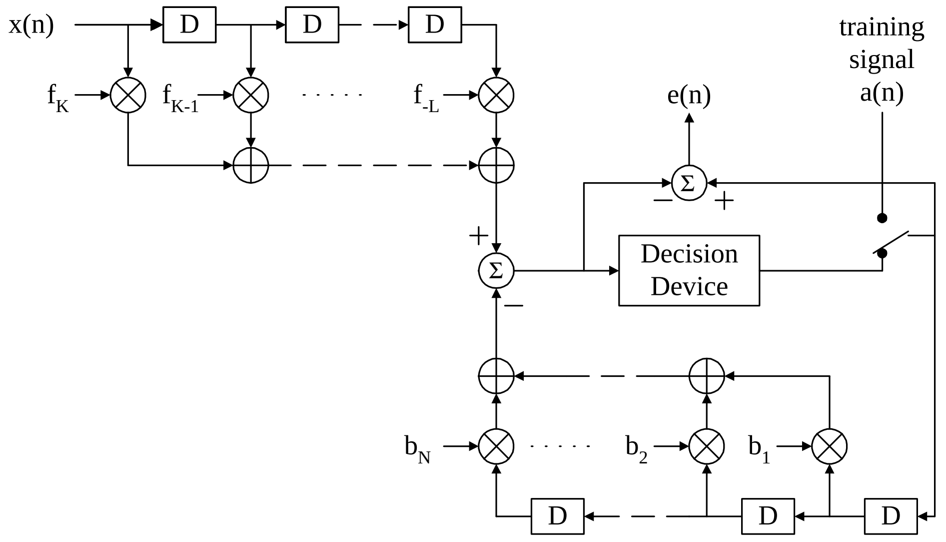

Figure 1. A typical DFE

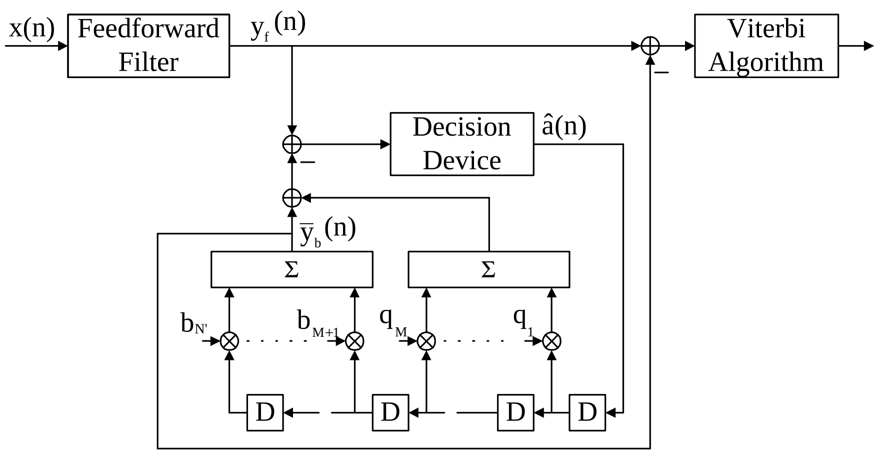

Figure 2. A DFE serving as the channel shortener

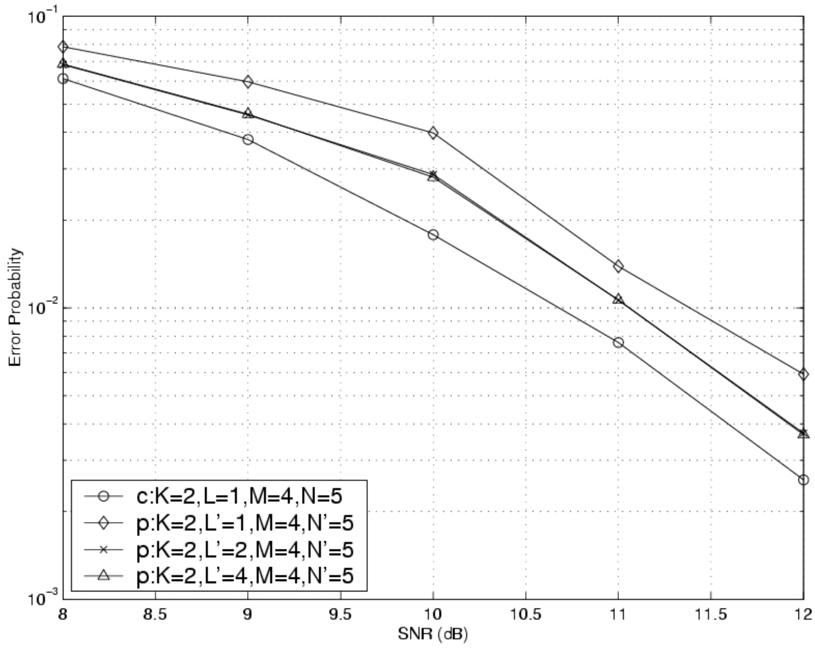

Figure 3. Error comparison for the conventional and proposed DFE/MLSE

Table 1. Computational complexity comparison for the conventional and proposed DFE/MLSE

Item	Conventional		Proposed		
	Multiplications	Additions	Multiplications	Additions	shift
Forward filter	4	3	5	4	0
Feedback filter	5	4	1	4	1
Branch metrics	80	80	16	80	64