

Comparison of Two Blind Sequence Estimations

T.Furuya+, Y.Sato+, N.Kajihara*, S.Nakaya*, T.Yamauch*, T.Inuo*, T.Higuchi-
+:Toho University, *: RWCP -NEC Lab., -: Electrotechnical Laboratory

Address:

Tatsumi FURUYA
Information Sciences
Toho University
2-2-1 Miyama, Funabashi-shi,
Chiba-ken 274-8510
Japan

Phone +81-474-72-8227

Fax +81-474-74-6821

Email furuya@is.sci.toho-u.ac.jp

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1. Introduction

The development of adaptive receivers is important in digital mobile communication technology. This paper examines the adaptive receiver that is used for frequency selective fading channels. In mobile communication, there are two kinds of channel impairments. First, the channel is very rapidly time-varying, and second, it suffers an occasional null spectrum in the transmission band. Consequently, the receiver in mobile communication must meet the following requirements: (1) The channel response should be identified (not equalized). If the channel has a null spectrum in its transmission band, the conventional transversal equalizer cannot realize its inverse. The transmitted sequence estimation through blind channel identification is called blind sequence estimation. (2) The channel identification should be accomplished in a short time. (3) Both channel response and the transmitted sequence must be jointly estimated. This requirement leads us to a dilemma of the so-called "Blind Problem" in which the sequence estimation is never successful without the knowledge of the channel response, but the channel response cannot be estimated without referring to the transmitted sequence.

In order to solve these requirements, two kinds of blind Viterbi algorithms have been proposed: (1) The explicit blind Viterbi algorithm (EBV) for slowly time-varying case and (2) the implicit blind Viterbi algorithm (IBV) for fast time-varying case. The EBV estimates the channel response first, then estimate transmitted sequence by the use of the estimated channel response. So, the error rate of the EBV is low and the estimation rate is slow. The IBV estimates transmitted sequence without estimating the channel response. So, the error rate of the IBV is high and the estimation speed is high. This paper shows the quantitative comparison of the algorithms, including the error rates, the estimation speed and their hardware volume. In the next chapter we briefly summarize the algorithms, and chapter 3 shows their performance of those algorithms.

2. Two Blind Viterbi Algorithms

The Viterbi algorithm coupled with blind channel identification solves the blind problem described above. The key ideas for solving problem are listed as follows:

- (1) Consider all possible candidates for the currently transmitted subsequence.
- (2) Define a cost function to estimate that the candidate was actually transmitted. Note that any a priori information of the channel response is not available.
- (3) Select the most probable time-series candidate.

All possible sequences are represented as a trellis graph of (short-term) candidate

sequence(item (1) above). An example of the trellis graph is shown in figure 1. Each node of the graph corresponds to a short-term transmitted sequence. An estimated long-term sequence is a concatenation of the most probable short-term sequences. The Viterbi algorithm could be the best solution for selecting the most probable candidate(item(3) above). The cost values (item (2) above) is the probability of the continuation of two short-term sequences. The cost is called “branch metric”, assigned to each link of the trellis graph. The cost value of the EBV is different from the cost value of the IBV.

2.1 Blind sequence estimation

Assuming the time-invariant channel, consider the time average of the squared error

$$J_R = \sum_{k=0}^R (\hat{y}_k - y_k)^2. \quad (1)$$

The received signal y_k and its replica \hat{y}_k are given by

$$y_k = \sum_{n=0}^{N-1} a_{k-n} h_n + n_k \quad (2)$$

and

$$\hat{y}_k = \sum_{n=0}^{N-1} \hat{a}_{k-n} \hat{h}_n \quad (3)$$

where n_k is additive white Gaussian noise and mark $\hat{}$ denotes the estimate. Note that

J_R is a joint function of (R+N-1)-dimensional candidate vector

$$\hat{\mathbf{a}}_R = (\hat{a}_R, \hat{a}_{R-1}, \dots, \hat{a}_1, \dots, \hat{a}_{1-(N-1)})^T \quad (4)$$

and N-dimensional vector

$$\hat{\mathbf{h}} = (\hat{h}_0, \hat{h}_1, \dots, \hat{h}_{N-1})^T \quad (5)$$

If the received signal ends at time R, the best solution of the blind sequence estimation can be stated as, “For all possible (R+N-1)-dimensional candidate vectors $\hat{\mathbf{a}}_R$, calculate

a minimum of J_R in relation to the vector $\hat{\mathbf{h}}$. Among them, select a pair of $\hat{\mathbf{a}}_R$ and $\hat{\mathbf{h}}$

giving the smallest quantity of $\min J_R$. However, this numerical effort is in proportion to the exponent of the whole observation time R. Therefore, in a real situation where time R is not truncated, such an exponential increase of calculations is prohibitive. A strategy of on-line blind sequence estimation like the Viterbi algorithm should be introduced by segmenting J_R into short intervals. For mobile communications, the length of the segment should be as short as possible in order to adapt to a rapidly time-

varying channel. Provided that the estimation of the current channel response is completed by use of a finite number of received signals, $y_R, y_{R-1}, \dots, y_{R-(M-1)}$, such procedures can be categorized into two types, as follows.

Define a short time-average of the squared error

$$J_k(M) = \sum_{i=0}^{M-1} (\hat{y}_{k-i} - y_{k-i})^2 \quad (6)$$

Note that this criterion contains the $(M+N-1)$ -dimensional transmitted vector

$$\mathbf{a}_k(M) = (\hat{a}_k, \dots, \hat{a}_{k-(M-1)}, \dots, \hat{a}_{k-(M-1)-(N-1)})^T \quad (7)$$

Type1 : Explicit Blind Sequence Estimation

For each $(M+N-2)$ -dimensional candidate vector

$$\hat{\mathbf{a}}_{k-1}(M-1) = (\hat{a}_{k-1}, \dots, \hat{a}_{k-(M-1)}, \dots, \hat{a}_{k-(M-1)-(N-1)})^T \quad (8)$$

estimate $\hat{\mathbf{h}}$ so that

$$J_{k-1}(M-1) = \sum_{i=0}^{M-2} (\hat{y}_{k-1-i} - y_{k-1-i})^2 \quad (9)$$

is minimized. By using $\hat{\mathbf{h}}$, calculate the present squared error $(\hat{y}_k - y_k)^2$ for all possible present N -dimensional vectors $\hat{\mathbf{a}}_k(1) = (\hat{a}_k, \hat{a}_{k-1}, \dots, \hat{a}_{k-(N-1)})^T$ following from $\hat{\mathbf{a}}_{k-1}(M-1)$. Totally, we calculate the same number of the present squared errors corresponding to all possible $(M+N-1)$ -dimensional candidate vectors $\hat{\mathbf{a}}_k(M)$. As in the Viterbi algorithm, regarding $\hat{\mathbf{a}}_k(M)$ as a trellis state and $(\hat{y}_k - y_k)^2$ as branch-metric of the branch leading to the state $\hat{\mathbf{a}}_k(M)$, we can perform the path selection. The branch-metric is the cost value that shows the possibility of a short-term sequence.

Type 2 : Implicit Blind Sequence Detection

Minimize $J_k(M)$ in relation to $\hat{\mathbf{h}}$ for all possible $(M+N-1)$ -dimensional candidate vectors $\hat{\mathbf{a}}_k(M)$. Let each minimum be a branch-metric leading to the corresponding trellis state $\hat{\mathbf{a}}_k(M)$. Note that the estimate $\hat{\mathbf{h}}$ is not needed in an explicit form.

2.3 Algorithms

As the Viterbi algorithm is the most popular algorithm for sequence estimation, we use it for the blind sequence estimation. Both blind Viterbi algorithms (EBV and IBV) consist of the following two steps:

Step 1: Calculate the branch-metrics from the received data.

Step 2: Search the most probable path (Viterbi algorithm).

The branch-metrics are calculated as follows.

In the case of the EBV, estimate $\hat{\mathbf{h}}$ by the use of the Kalman filter.

The equations of the Kalman filter are as follows.

$$\hat{\mathbf{h}}_k = \hat{\mathbf{h}}_{k-1} + \mathbf{k}_k (Y_k - \hat{\mathbf{a}}_k^H \hat{\mathbf{h}}_k^H) \quad (10)$$

$$\mathbf{k}'_k = \mathbf{P}_k \hat{\mathbf{a}}_k \quad (11)$$

$$\mathbf{P}_{k-1} = \mathbf{P}_k - \frac{\mathbf{k}'_k \mathbf{k}'_k{}^H}{1 + \hat{\mathbf{a}}_k^H \mathbf{k}'_k} + \mathbf{Q}_k \quad (12)$$

$$\mathbf{k}_k = \frac{\mathbf{k}'_k}{1 + \hat{\mathbf{a}}_k^H \mathbf{k}'_k} \quad (13)$$

By using the $\hat{\mathbf{h}}_k$ in each node, calculate two replicas corresponding to two diverging branches, respectively. For each branch, calculate the branch-metric $(\hat{y}_{k+1} - y_{k+1})^2$.

In the case of the IBV, we define a matrix \mathbf{A}_k

$$\mathbf{A}_k = \begin{bmatrix} \mathbf{a}_k^T \\ \mathbf{a}_{k-1}^T \\ \vdots \\ \mathbf{a}_{k-N+1}^T \end{bmatrix} \quad (14)$$

$$\hat{\mathbf{y}}_k = \hat{\mathbf{A}}_k \hat{\mathbf{h}}_k \quad (15)$$

In the simplest case,

$$\hat{\mathbf{A}}_k = \begin{bmatrix} \hat{a}_{k-2} \hat{a}_{k-3} \\ \hat{a}_{k-1} \hat{a}_{k-2} \\ \hat{a}_k \hat{a}_{k-1} \end{bmatrix}, \quad \hat{\mathbf{h}}_k = \begin{bmatrix} \hat{h}_0^k \\ \hat{h}_1^k \end{bmatrix}, \quad \mathbf{y}_k = \begin{bmatrix} \hat{y}_{k-2} \\ \hat{y}_{k-1} \\ \hat{y}_k \end{bmatrix}$$

The branch-metric of the IBV is obtained by a formula

$$\mathbf{y}_k^T (\hat{\mathbf{A}}_i \mathbf{A}_i^- - \mathbf{I})^T (\hat{\mathbf{A}}_i \mathbf{A}_i^- - \mathbf{I}) \mathbf{y}_k \quad (16)$$

where \mathbf{A}_i^- is Moor-Penrose general inverse of $\hat{\mathbf{A}}_i$.

The equation $(\hat{\mathbf{A}}_i \mathbf{A}_i^- - \mathbf{I})^T (\hat{\mathbf{A}}_i \mathbf{A}_i^- - \mathbf{I})$ can be calculated a priori, so the branch-metric is quickly obtained. The branch-metrics of above simplest channel model is as follows:

$$\begin{aligned} bm0 &= bm15 = (y_k - y_{k-1})^2 / 3 + (y_{k-1} - y_{k-2})^2 / 3 + (y_{k-2} - y_k)^2 / 3 \\ bm1 &= bm14 = (y_{k-1} - y_{k-2})^2 / 2 \\ bm2 &= bm13 = (y_{k-1} + y_k)^2 / 2 \\ bm3 &= bm6 = bm9 = bm12 = (y_{k-2} + y_k)^2 / 2 \\ bm4 &= bm11 = (y_{k-1} + y_{k-2})^2 / 2 \\ bm5 &= bm10 = (y_{k-1} + y_{k-2})^2 / 3 + (y_{k-1} + y_k)^2 / 3 + (y_{k-2} - y_k)^2 / 3 \end{aligned} \quad (17)$$

3. Comparison of the EBV and the IBV

We evaluate the performance of two blind Viterbi algorithms in terms of the error rate and the blind sequence estimation speed. The assumptions are as follows:

(1) The channel is the two-ray model with time-variant. The channel response is represented as

$$h_0 = \cos \theta, \quad h_1 = \sin \theta$$

(2) Binary both side band amplitude modulation.

(3) $N=2, M=3$ in equation (7). Therefore, the total number of possible branches is 16.

(4) The error rate is measured after differential decoder.

3.1 Error rate

Figure 2 shows the error rate performances when the channel response is varied (θ : 0 degree~360 degrees). The EVB has the advantage of the IBV. Especially, if the SNR greater than 18 dB, there is no error in the EBV. Figure 3 shows the relation between θ and the error. Most errors happen at degree 0, 45, 90, 135, 180,....(i.e., at 45 x n). At these degrees, equation (15) has not unique solution.

3.2 Estimation speed

We measured the estimation rate and the hardware volume by implementing the algorithms on a field programmable gate array (FPGA: Altera10K100). The hardware is

designed so that every equation is calculated by the use of integer numbers. The received signals are digitized to eight-bits integers.

The blind estimation hardware consists of the following two parts:

- (1) Blind part: This part calculates branch-metrics. The blind part of the EBV is different from that of the IBV.
- (2) Viterbi part: This is common to both blind Viterbi algorithms. This part is designed based on the trace forward method proposed by the paper [3].

The main circuit of the blind part of the EBV is the Kalman filter. In order to get the h_0 and h_1 , we have to repeat the Kalman operation (equation 10~13) two times. The two cycles are executed at two nodes of the trellis graph. Equation (17) is the blind part of IBV. Table 1 shows the comparison of the estimation speed and hardware volume. The EBV1 in the table 1 uses a hardware in which the Kalman filters are implemented by perfectly parallel circuits. On the other hand, the Kalman filter in the EBV2 is executed by a 100 MFLOPS-DSP. The table shows that IBV is three times faster than the EBV1, and hardware volume is about 1/7 that of the EVB.

Table 1 Estimation rate and Hardware volume of blind part

	IBV	EBV1(parallel)	EBV2(by DSP)
Rate(Mbps)	11.16	3.85	0.71
Hardware(Logic)	1	7.2	1.5

4. Conclusion

We showed a quantitative evaluation of two blind sequence estimations for the simplest model. In our simulation, the IBV is faster than the EVB. However, the error rate of the IBV is worse than the EBV. Hardware volume is a serious problem. If we want to realize the same estimation rate for more complicated channel models (e.g. , for a five-ray model), a large amount of circuits is necessary. Especially for the EBV, the hardware for the Kalman filter would be incredibly large ($O(n^2)$). On the other hand, the hardware volume of the IBV would not increase so drastically ($O(n)$). For high-speed digital mobile communication, we believe that the development of a method for lowering the error rate for the IBV will be the best way to solve the blind problem.

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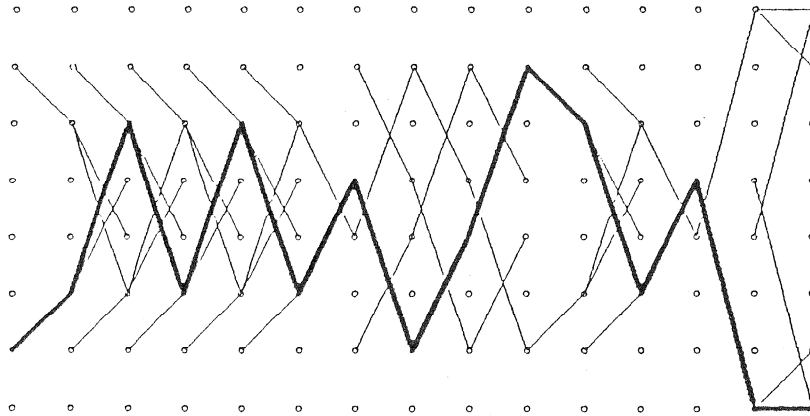


Figure 1 Trellis graph for $(h_0, h_1) = (1, 0.5)$.

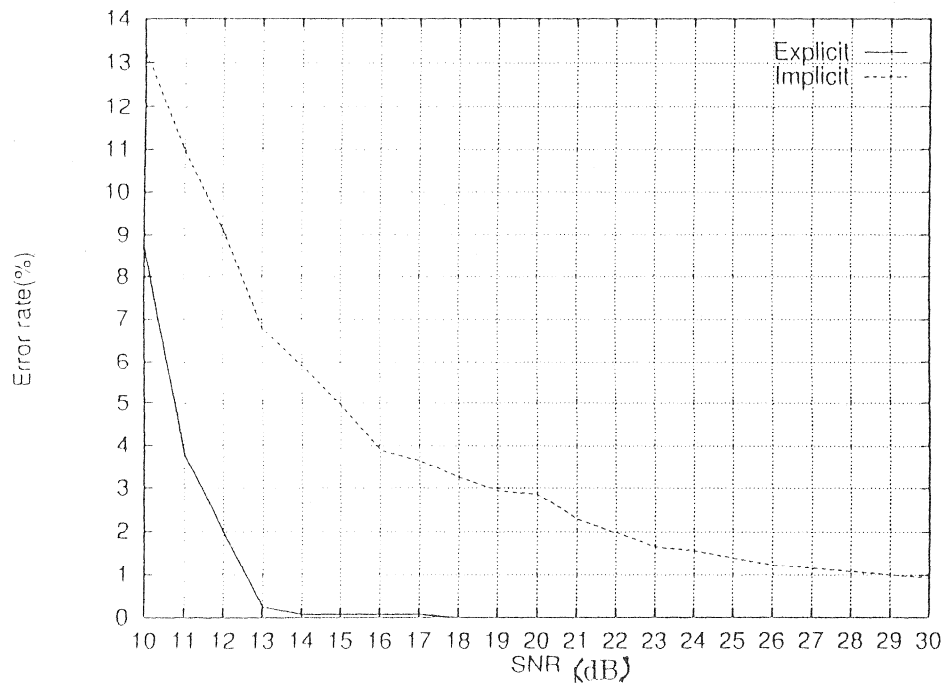
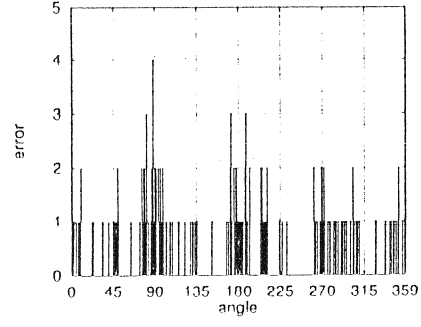
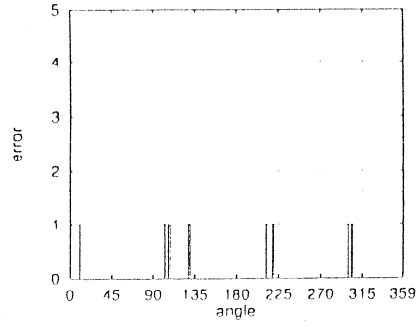
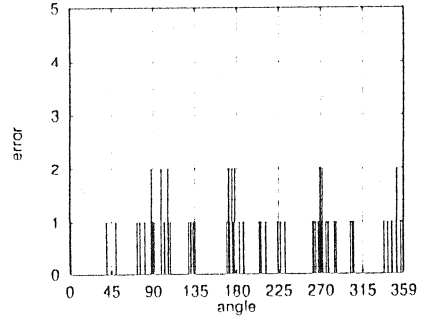
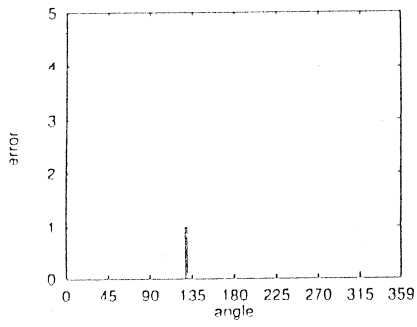


Figure 2 Error rate

SNR=12 dB



SNR=15 dB



SNR=18 dB

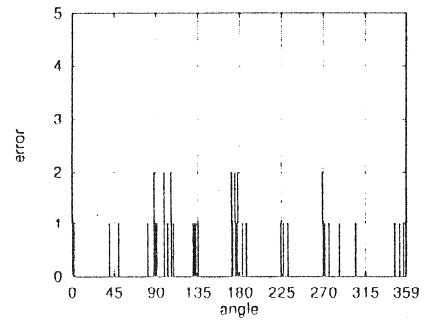
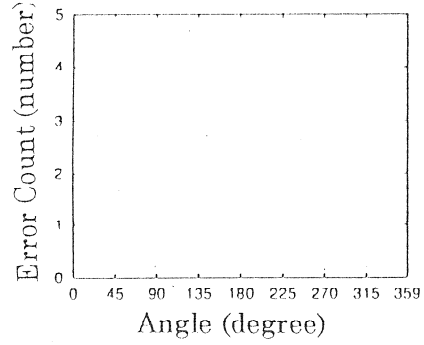


Figure 3 Error count