Multiple Differential Detection with Channel Prediction Employing Soft-Output Per-Survivor Processing

Kazuki Shimomura* and Hiroshi Kubo†
* Graduate School of Science and Engineering, Electrical, Electronic and Computer Systems Course,
Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu-shi, Siga, 525-8577, Japan
E-mail: ri0038hs@ed.ritsumei.ac.jp
† Department of Electronic and Computer Engineering, Faculty of Science and Engineering,
Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu-shi, Siga, 525-8577, Japan
E-mail: kubohiro@fc.ritsumei.ac.jp

***Abstract*—In order to improve tracking performance on fast time-varying channels, this paper proposes a soft-output Viterbi algorithm (SOVA) for multiple differential detection (MDD) employing channel prediction and forward error correction. Although QPSK are generally demodulated based on LLR (log-likelihood ratio) for its soft-decisions, it is difficult for joint detection (JD), which does not explicitly estimate channel state information, to derive LLR. This paper proposes soft-output PSP (per-survivor processing), which derives metrics difference between the two paths in the Viterbi algorithm (VA) of PSP, where PSP is JD based on the VA. The proposed scheme can improve tracking performance for time-varying channels without an increase of computational complexity. Finally, computer simulation results confirm that the proposed scheme can track four times larger maximum Doppler frequency normalized by symbol rate in fading than the conventional schemes.**

***Index Terms*—Soft-Output, Viterbi Algorithm, Multiple Differential Detection, Higher Order Channel Prediction, Fast Time-Varying Fading**

I. Introduction

For mobile communication technologies, there exist important issues to cope with time and frequency selective channels, i.e., doubly-selective channels. For mobile communications, it is well known that wide-zone point to multi point (P-MP) communications [1] and underwater acoustic communications (UWAC) [2], [3] suffer from severe doubly-selective channels. Multi-carrier (MC) modulation schemes employing forward error correction (FEC) are good approaches for such severe doubly-selective channels [4].

MC modulation schemes can control a trade-off between time selectivity and frequency one with respect to symbol period for modulation and demodulation. Although a large symbol period can mitigate frequency selectivity, it results in severe time selectivity, i.e., a large maximum Doppler frequency normalized by symbol rate. In order to achieve a good trade-off between time selectivity and frequency one, the authors have been making a research on differential space-time coding (DSTC) [6]-[8].

For the sake of channel prediction employing per-survivor processing (PSP) [9]-[11], DSTC can improve this trade-off on severe doubly-selective channels, where PSP is joint detection (JD) based on the Viterbi algorithm (VA), which can estimate channel and data simultaneously.

FECs, e.g., convolutional codes, turbo codes and LDPC codes can improve bit error rate (BER) performance in mobile communications. However, these FECs need soft-decisions for further performance improvement. Usually, these FECs use log-likelihood ratio (LLR) in order to improve BER performance. However, it is difficult for demodulators based on the VA, e.g., PSP, to output the LLR. The soft-output VA (SOVA) scheme can solve the problem [12], [13]. For the SOVA, although it is easy to derive soft-decisions of binary data, it needs large computational complexity to derive soft-decisions of multi-level data. Generally, it is easy to derive the LLR in the presence of channel state information (CSI). As some PSPs of JD calculate the branch metrics without CSI, it is difficult for PSP to derive the LLR.

In order to solve the above mentioned issue, this paper proposes a soft-output PSP (SO-PSP) for M-ary phase shift keying (MPSK). The proposed SO-PSP can be applied not only to BPSK but also to MPSK employing multiple differential detection (MDD) with PSP and channel prediction, because it can derive a soft-decision from vector information. Finally, computer simulation results confirm the proposed SO-PSP has better BER performance on fast time-varying fading channels where the maximum Doppler frequency normalized by symbol rate, $f_D T$, is more than 10%.

In the remainder of this paper, $\min[a_1, a_2]$ denotes a_1 or a_2, whichever is smaller, $\min^{(2)}$ denotes the second smallest value, Re$[a]$ and Im$[a]$ denote the real part and the imaginary part of a, respectively, a^* denotes the complex conjugate of a, a_k denotes signals a at symbol time k, and $a_1 \sim a_2$ denotes the metric of a_1 and a_2 are equivalent.

II. Communication Systems

Fig. 1 shows a communication system model with convolutional code and an interleaver. This paper denotes that k' is discrete time before interleaving, and k is after interleaving.

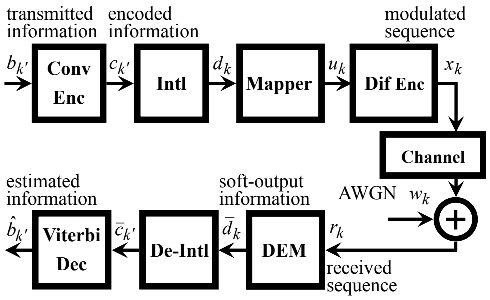

Fig. 1. Communication system model.

The convolutional encoder generates a coded information sequence $c_{k'}$ (m bits data of $c_{k'} = c_{k'}^{(0)}, c_{k'}^{(1)}, \cdots, c_{k'}^{(m-1)}$) from the transmitted information sequence $b_{k'}$ (1 bit data of $b_{k'} \in \{0, 1\}$), i.e., the coding rate R is $1/m$ and the alphabet size M is 2^m. The encoded information sequence $c_{k'}$ is re-arranged to an encoded information sequence $d_k (d_k \in \{0, 1, \cdots, 2^m-1\})$ through the interleaver. The encoded information sequence d_k is converted to the following information sequence signal u_k:

$$u_k = e^{j2\pi(d_k+0.5)/2^m}, \tag{1}$$

where u_k is assumed M-ary PSK signals. The transmitted modulation signals x_k are given by:

$$x_k = u_k x_{k-1}, \tag{2}$$

where $x_0 = 1$. The transmitted modulation signals x_k are corrupted by additive white Gaussian noise (AWGN) w_k, resulting in the following received signals r_k:

$$r_k = h_k x_k + w_k, \tag{3}$$

where h_k is the channel impulse responses (CIRs) of in the absence of intersymbol interference (ISI). The demodulator calculates PSK information sequence with the soft-decision information $\bar{d}_k$ from the received sequence r_k. A de-interleaver restores $\bar{d}_k$ to the temporal order. Finally, a Viterbi decoder based on the VA for convolutional code estimates the information sequence $\bar{b}_{k'}$ from PSK information sequence with the soft-decision $\bar{c}_{k'}$. In the remainder of this paper, let us define that the number of information bits per symbol time m is 2 bits.

III. PSP-MDD Based on The Channel Prediction

This section discusses PSP-MDD (multiple differential detection) with channel prediction described in [15]. According to the data detection based on the VA, a path metric H and a branch metrics Γ_k are described as follows:

$$\Gamma_k = \left| r_k - \tilde{r}_k \right|^2 \tag{4}$$

$$\tilde{r}_k = \tilde{h}_k \tilde{x}_k \tag{5}$$

$$H_k = \sum_k \Gamma_k, \tag{6}$$

where $\tilde{r}_k$ is a replica of the received signal r_k, $\tilde{h}_k$ is a estimated CIR and $\tilde{x}_k$ is a candidate of the transmitted modulation signals x_k on the VA. The estimated CIR $\tilde{h}_k$ is defined using the inverse modulation value $r_k \tilde{x}_k^*$ as follows:

$$\tilde{h}_k = \sum_{i=1}^{S} v_i r_{k-i} \tilde{x}_{k-i}^* \tag{7}$$

$$\sum_{i=1}^{S} v_i = 1, \tag{8}$$

where S denotes an observation span and v_i denotes a weighting coefficient. Substituting (7) into (4) and (5), the following relation is given by:

$$\Gamma_k = \left| r_k - \sum_{i=1}^{S} v_i r_{k-i} \tilde{x}_{k-i}^* \tilde{x}_k \right|^2. \tag{9}$$

Let us assume that:

$$x_k = \tilde{x}_k. \tag{10}$$

Then, the branch metric of (9) could be replaced as follows:

$$\Gamma_k = \left| w_k - \sum_{i=1}^{S} v_i w_{k-i} \right|^2. \tag{11}$$

Since colored noise is included in the branch metric Γ_k on the PSP, a noise component in metric is not independent at each time k.

In order to improve tracking performance, the MDD with channel prediction has been proposed in [15]:

$$v_i = (-1)^{i-1} \binom{S}{i}. \tag{12}$$

IV. The Proposed Soft-Output PSP Scheme for QPSK

A. Conventional SOVA for BPSK

There are two famous types of SOVA for BPSK, Battail's SOVA [12] and Hagenauer's SOVA [13]. There are the following two points in common between these two SOVAs:

- save the difference between the maximum-likelihood (ML) path metric and the discarded path metric corresponding to the inversion bit as a soft-decision value;
- update the past soft-decision value at the present processing time k.

However, there are differences in the updating process of the soft-decision value as follows:

- in Hagenauer's SOVA, update only if the opposite information symbols exist in path comparison;
- in Battail's SOVA, update all information symbols;

This paper focuses on Battail's SOVA. Let us assume that the memory length of the VA is V, and the constraint length of the convolutional code is $K (V = K-1)$. Moreover, this paper defines the state S_k and the branch S_k/S_{k-1} of the trellis as follows:

$$S_k = \tilde{b}_k \tilde{b}_{k-1} \cdots \tilde{b}_{k-V+1} \tag{13}$$

$$S_k/S_{k-1} = \tilde{b}_k \tilde{b}_{k-1} \cdots \tilde{b}_{k-V}, \tag{14}$$

where $S_k/S_k^{(1)}$ denotes the surviving path connected to the state S_k and the branch S_k/S_{k-1}, and $\{S_{k-1}\} \rightarrow S_k$ are possible candidates of the previous state S_{k-1} connected to the state S_k. Battail's SOVA is executed as follows:

1) start from the state S_0 ($\tilde{b}_k = 0,\ k \leq 0$); calculate the branch metric $\Gamma_k[S_k/S_{k-1}]$ and path metric $H_k[S_k/S_{k-1}]$ as follows:

$$\Gamma_k[S_k/S_{k-1}] = \left|r_k - \tilde{r}_k[S_k/S_{k-1}]\right|^2 \quad (15)$$

$$H_k[S_k/S_{k-1}] = H_{k-1}[S_{k-1}/S_{k-2}^{(1)}] + \Gamma_k[S_k/S_{k-1}], \quad (16)$$

where $\tilde{r}_k$ is a replica of the PSK information sequence u_k corresponding to the branch; in addition, there is no surviving path before time 0;

2) select surviving path in all states, and discarded the remaining path:

$$H_k[S_k/S_{k-1}^{(1)}] = \min_{\{S_{k-1}\}\rightarrow S_k} H_k[S_k/S_{k-1}]; \quad (17)$$

3) calculate the soft-decision value; select the second smallest path metrics $H_k[S_k/S_{k-1}^{(2)}]$ in all states, and calculate the difference from the surviving path metric $H_k[S_k/S_{k-1}^{(1)}]$; this is the soft-decision value $\delta_k[S_k]$:

$$H_k[S_k/S_{k-1}^{(2)}] = \min_{\{S_{k-1}\}\rightarrow S_k}{}^{(2)} H_k[S_k/S_{k-1}] \quad (18)$$

$$\delta_k[S_k] = H_k[S_k/S_{k-1}^{(2)}] - H_k[S_k/S_{k-1}^{(1)}]; \quad (19)$$

Exception: since the branch candidate is single in the state S_k from time 1 to time $(V-1)$, the soft-decision value is set as follows:

$$\delta_k[S_k] = \infty; \quad (20)$$

4) update the soft-decision value; compare the information between the path $H_k[S_k/S_{k-1}^{(1)}]$ and $H_k[S_k/S_{k-1}^{(2)}]$, and update the past soft-decision value; the comparison is made until the path $H_k[S_k/S_{k-1}^{(1)}]$ and $H_k[S_k/S_{k-1}^{(2)}]$ to merge on the trellis diagram; let us define that ϕ is a time until these to merge, $i = k-\phi, \cdots, k-1$ is a past time to perform update processing, also $\tilde{b}_i^{(1)}$ and $\tilde{b}_i^{(2)}$ are the estimated information by using $H_k[S_k/S_{k-1}^{(1)}]$ and $H_k[S_k/S_{k-1}^{(2)}]$ at time i, respectively; moreover, $\hat{H}_j[S_j/S_{j-1}^{(1)}]$ and $\hat{H}_{j'}[S_{j'}/S_{j'-1}^{(2)}]$ ($i < j,\ j' < k$) are the smallest path metric with the information different from $\tilde{b}_i^{(1)}$ and $\tilde{b}_i^{(2)}$, which merge $H_k[S_k/S_{k-1}^{(1)}]$ and $H_k[S_k/S_{k-1}^{(2)}]$, respectively; and then, $\Delta H^{(1)}$, $\Delta H^{(2)}$ are the difference between $\hat{H}_j[S_j/S_{j-1}^{(1)}]$, $\hat{H}_{j'}[S_{j'}/S_{j'-1}^{(2)}]$ and $H_k[S_k/S_{k-1}^{(1)}]$, $H_k[S_k/S_{k-1}^{(2)}]$, respectively; switch the update equation of the soft-decision value according to whether $\tilde{b}_i^{(1)}$ and $\tilde{b}_i^{(2)}$ are equal;

- $\tilde{b}_i^{(1)} \neq \tilde{b}_i^{(2)}$

$$\delta_i[S_i] = \min\left[\Delta H^{(1)}, \delta_k[S_k]\right] \quad (21)$$

- $\tilde{b}_i^{(1)} = \tilde{b}_i^{(2)}$

$$\delta_i[S_i] = \min\left[\Delta H^{(1)}, \delta_k[S_k] + \Delta H^{(2)}\right]; \quad (22)$$

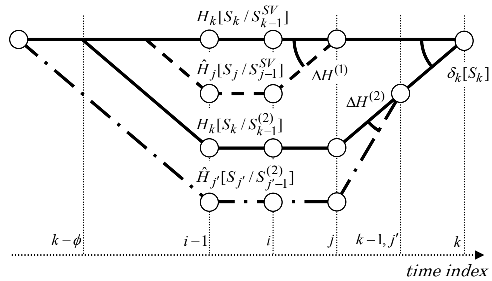

Fig. 2. Update of likelihood ratio with Battail's SOVA at time k.

5) transmit a known signal of length V in order to converge to a desired state;
6) traceback from converged state; a traceback operation mean to trace the surviving path in the past time direction; the decoded sequence with this operation is ML, being determined as a hard-decision information $\tilde{u}_k$;
7) combine the calculated soft-decision value $\delta_k[S_k]$ with the hard-decision information $\tilde{u}_k$. $\delta_k[S_k]$ is determined from the state selected by the traceback.

$$\bar{d}_k = \delta_k[S_k] \times \tilde{u}_k. \quad (23)$$

(End of algorithm)

In addition, the general VA can be realized by omitting the steps 3), 4), and 7).

B. The Proposed SOVA for QPSK

For the conventional SOVA for QPSK, in order to derive soft-decision of the LLR, it is necessary to know about the CSI. However, some PSPs of JD calculate the branch metrics without CSI. Therefore, there exists the issue that these types of demodulators cannot calculate the LLR. Moreover, since the existing equations for the soft-decisions information is derived from the viewpoint of orthogonal constellation by BPSK [16], the issue arises that the equations cannot be applied to multi-level modulation sequences or asymmetric mapping. The proposed SOVA scheme for MPSK is a post-processing, which calculates a soft-decision information after the ML sequence is selected. Calculations of the soft-decision information use the adjacent path for arbitrary states at each time. In order to employ the proposed SOVA scheme for MPSK, the steps 3), 4) and 7) are omitted, and the following procedures A) and B) are added after the step 6). Since the state is uniquely determined during the traceback, the variable indicating the state is omitted. In addition, this paper assumes the QPSK transmitted for simplifying the explanation.

A) calculate soft-decision scalar values for each bit; at the time k during the traceback operation, $H_k^{\min}$ denotes the smallest path to be merged into the arbitrary state, and the estimated information $\tilde{u}_{k-V+1}$ ($\tilde{u}_{k-V+1} \in \{0,1,2,3\}$) correspond to the surviving path on $H_k^{\min}$; select plural signal points that the positional relationship with the estimated information $\tilde{u}_{k-V+1}$ as the starting point is vertical and horizontal from a threshold line the based on phase detection on mapping; in the case of QPSK, there are two threshold lines, and there are the two signal points of information satisfying the condition; $\tilde{u}^{(1)}_{k-V+1}$ and $\tilde{u}^{(2)}_{k-V+1}$ ($\tilde{u}^{(1)}_{k-V+1}, \tilde{u}^{(2)}_{k-V+1} \in \{0,1,2,3\}, \tilde{u}^{(1)}_{k-V+1} \neq \tilde{u}^{(2)}_{k-V+1} \neq \tilde{u}_{k-V+1}$) denote estimated information which differs only in the first bit or the second bit from $\tilde{u}_{k-V+1}$; in addition, $H^{(1)}_k$ and $H^{(2)}_k$ denote path metric with $\tilde{u}^{(1)}_{k-V+1}$ and $\tilde{u}^{(2)}_{k-V+1}$, respectively; the difference between these and $H^{\min}_k$ is defined as the soft-decision scalar values for each direction as follows:

$$\begin{cases} \Delta H^{(1)}_k = H^{(1)}_k - H^{\min}_k \\ \Delta H^{(2)}_k = H^{(2)}_k - H^{\min}_k, \end{cases} \tag{24}$$

since the nature of the VA, the output delay time is proportional to the memory length V, and affects the calculated soft-decision scalar values; take care that the calculated data at time k would be the data at time $(k - V + 1)$;

B) combine the hard-decision information and the soft-decision scalar values; let us combine these information into one symbol; first, calculate the vector from the difference between signal points $\tilde{u}_{k-V+1}$ and $\tilde{u}^{(1)}_{k-V+1}$, as well as $\tilde{u}_{k-V+1}$ and $\tilde{u}^{(2)}_{k-V+1}$; next, multiply the vector by the soft-decision scalar values, and the product is a soft-decision information for each direction; the difference of the first bit or the second bit are assigned to the soft-decision information in the imaginary part or real part direction, respectively; the soft-decision information is given by:

$$\begin{cases} a^{(1)}_{k-V+1} = \tilde{u}_{k-V+1} - u^{(1)}_{k-V+1} \\ a^{(2)}_{k-V+1} = \tilde{u}_{k-V+1} - u^{(2)}_{k-V+1} \end{cases} \tag{25}$$

$$\bar{d}_{k-V+1} = a^{(1)}_{k-V+1} \times \Delta H^{(1)}_k + a^{(2)}_{k-V+1} \times \Delta H^{(2)}_k. \tag{26}$$

(End of algorithm)

Being compared with the SOVA for QPSK using LLR, the proposed scheme can work on the JD, and it can omit the known signal in the transmitted sequence. In addition, since a viewpoint of the calculation formula for the soft-decision information is replaced with the vector, it can employ to MPSK, QAM and also asymmetric mapping. Moreover, it can perform the posterior soft-decision processing by storing all the branch metrics and path metrics. On the other hand, there are disadvantages, e.g., performance degradation occurs due to omitting update process of the soft-decision information, and expand the memory usage. In the former case, the performance can be improved by adding update process, or by using multiple path used for calculation of the soft-decision information as shown in [16].

V. Computer Simulation

This section compares the BER performances of VA-DD (differential detection) and VA-MDD with and without soft-output by computer simulations. This paper defines that E_b is energy per bit in the air.

A. Simulation Parameters

The simulation parameters are as follows:

Transmitter:

- the number of transmitted information bits per symbol, m, is 2;
- the number of transmit antenna, N_T, is 1;
- the modulation scheme is differential encoding (DE);
- the constraint length of the convolutional code, K, is 7;
- the dummy contains 8 symbols, the data slot contains 960 symbols, the postamble contains 16 symbols for traceback;
- the modulation is DE of QPSK.

Receiver:

- the received signal is sampled at the Nyquist timing;
- the number of receive antennas, N_R, is 1;
- the demodulation scheme for DE is DD and MDD;
- the demodulation scheme for MDD employs channel prediction;
- the observation range of the received signal, S, is 4;
- PSP employs only MLSE;
- the memory length of VA for the convolutional code, V, is 6, and for MDD, N, is 3.

Channels:

- channels are assumed independent Rayleigh fading channels without ISI, where the maximum Doppler frequency normalized by symbol rate is fDT;
- The normalized maximum Doppler frequency, f_DT, of 0% corresponds to slowly time-varying fading channels, where channel variation due to Rayleigh fading is negligible during unit data slot.

B. The Proposed SO-PSP Performance

Figs. 3, 4 and 5 show BER performance as a function of average E_b/N_0 on fading channels of $f_DT = 0\%, 2\%$ and 16%, respectively. From Figs. 3, 4 and 5, we can obtain the following results:

- BER performance degradation in the required SNR due to the PSP with channel prediction is about 5 dB on fading channel with f_DT less than 2%;
- BER performance improvement in the required SNR due to the SO-PSP is about 2 dB on fading channel with f_DT more than 0%;
- HOVA-MDD and SOVA-MDD do not suffer from performance degradation due to fast time-varying fading with $f_DT = 16\%$, while the HOVA-DD and SOVA-DD suffer from serious performance degradation;
- the proposed SO-PSP scheme can be used together with the channel prediction.

Fig. 6 shows BER performance as a function of f_DT on fast Rayleigh fading channels. From Fig. 6, we can obtain the following results:

- the best tracking performance is SOVA-DD on fading channel with f_DT less than 8%, while SOVA-MDD is the best when f_DT is 8% or more;

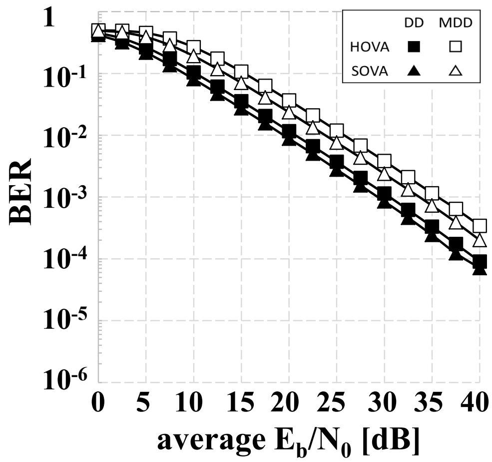

Fig. 3. BER performance on $f_D T = 0\%$.

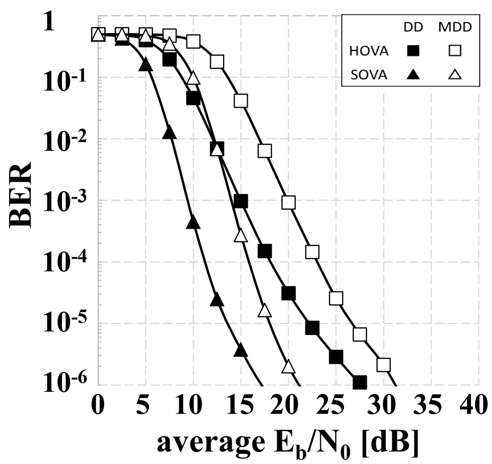

Fig. 4. BER performance on $f_D T = 2\%$.

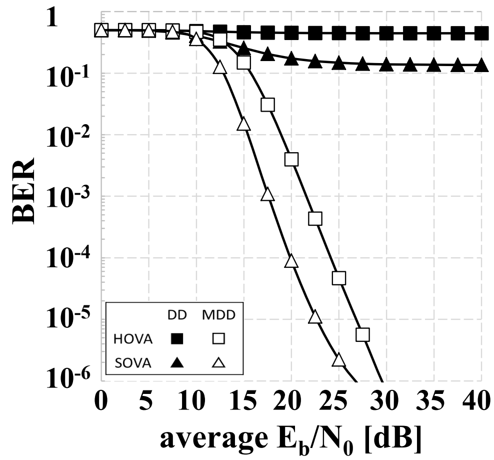

Fig. 5. BER performance on $f_D T = 16\%$.

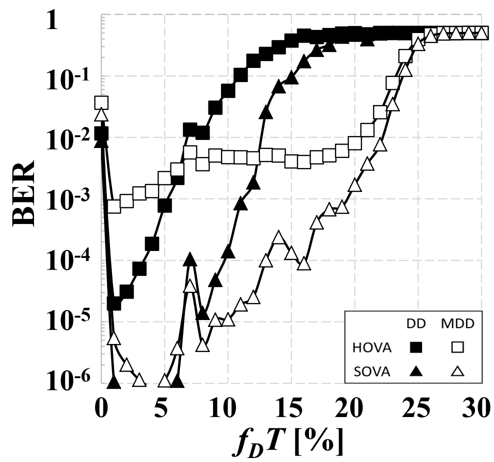

Fig. 6. tracking performance on average $E_b/N_0 = 20$dB.

- the proposed SOVA-MDD can track fast time-varying fading, $f_D T = 19\%$, about 2 time as fast as the SOVA-DD at BER of 10^{-3};
- in the case of a main factor of the signal point fluctuation is AWGN, the tracking performance deteriorates.

Thus, the demodulation scheme with the proposed soft-decisions contributes to improvement of the BER performance, and improvement of BER performance and tracking performance can be achieved by combining it with the channel prediction.

VI. Conclusion

This paper has proposed the SO-PSP of JD in the absence of CSI. Especially, the proposed scheme with channel prediction is suitable for communications employing FEC for fast time-varying fading, where the conventional scheme has difficulty to derive the LLR in this environment. This is because the proposed schemes derive the soft-decisions by means of comparison the corresponding metrics with respect to the hard-decision information. Finally, computer simulation results have confirmed for MMD of DQPSK employing PSP and channel prediction that the proposed SO-PSP has better performance than the PSP with hard-decisions. In addition, the proposed scheme can track the maximum Doppler frequency normalized by symbol rate of 20% in the case of targeting to the BER performance of 10^{-3}. The proposed SO-PSP for QPSK has room for improving receiver sensitivity by using unused path. Therefore, the authors have been investigating effective ways as a future topic.

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