Bidirectional multi-symbol phase estimation scheme for optical communications

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Abstract: A bidirectional multi-symbol phase estimation (BD-MSPE) scheme for differentially encoded optical signals, which can realize high-speed processing with superior BER characteristics, is proposed. Conventional MSPE needs decision feedback to correct phases of past symbols, so it is not suitable for parallelization. BD-MSPE, in contrast, uses tentative decision to avoid feedback. Due to the tentative decision, both past and future symbols can be utilized for phase estimation. Moreover, BD-MSPE can be organized in multistage when the decision result of the first stage of MSPE is used as the second tentative decision result for the next stage. Simulation results show the bit-error-rate (BER) curve of the proposed scheme asymptotically approaches that obtained by coherent detection.

Keywords: MSPE, differential coding, incoherent, parallelization

Classification: Fiber-Optic Transmission for Communications

References


1 Introduction

As a result of increasing network traffic, the demand of high speed network is growing rapidly year by year. The power consumption of network equipment has become very high due to the high-speed signal processing performed by that equipment. Incoherent optical communication \([1, 2]\) is one way to reduce the power consumption of network equipment, because it does not need to perform complex signal processing. For example, it does not require a local laser, polarization processing, and carrier recovery. However, it is known that the sensitivity of incoherent detection is inferior to that of coherent detection. To overcome this problem, two techniques have been proposed in \([3]\). Symbol decision based on non-Euclid metric is a technique for fitting detection boundaries of multi-level symbols to the anisotropic distribution of each constellation point of the received signal. Multi-symbol phase estimation (MSPE) \([3, 4]\) is another technique for improving the sensitivity of the receiver. MSPE uses plural past symbols to improve the accuracy of a phase reference for demodulation. The phases of the past symbols are changed by modulation; thus, to correct the phases, MSPE needs feedback to know past decision (demodulation) results. However, a decision-feedback architecture is not suitable for parallel processing which is a common technique for performing signal processing at very high data rate.

In this study, a new scheme, namely, multistage bidirectional MSPE (BD-MSPE), which uses tentative-decision results instead of decision feedback results, is proposed. It uses both past and future symbols to estimate signal phases. The performance of the proposed scheme (BD-MSPE) is confirmed by simulation.

2 Conventional MSPE

A series of phases of received signals is given as \(b_k\). In traditional delay detection, the \(i\)-th signal phase is recovered as a difference between \(b_{i-1}\) and \(b_i\). The traditional delay detection is thus affected by noise in both \(b_{i-1}\) and \(b_i\). Conventional MSPE \([3, 4]\) uses an averaged phase value calculated using plural past symbols as a reference phase instead of \(b_{i-1}\). For example, when the past three symbols, i.e., \(b_{i-3}\), \(b_{i-2}\), and \(b_{i-1}\), are used to calculate the reference phase, these values should be compensated by past data that modulate the received signals. Hereafter the series of phase changes caused by data, which modulates phases of signals, is given as \(A_k\). If \(A_{i-2}\) and \(A_{i-1}\) are known, signal phase \(b_{i-1}\) is also expressed as \(b_{i-2} + A_{i-1}\) and \(b_{i-3} + A_{i-2} + A_{i-1}\). These phase values can thus be used as phase references to demodulate the \(i\)-th symbol. To reduce the effect of noise in the phase references, the average of these three values is used instead of \(b_{i-1}\) alone. The phase changes, \(A_{i-2}\) and \(A_{i-1}\), caused by data can be determined from past demodulation results (possibly including some errors). New phase reference \(b'_{i-1}\), which is the average of three values above, can be expressed as Eq. (1) with weighting factor \(w_k\).

\[
b'_{i-1} = \frac{w_{-1}b_{i-1} + w_{-2}(b_{i-2} + A_{i-1}) + w_{-3}(b_{i-3} + A_{i-2} + A_{i-1})}{\sum_{k=-3}^{-1} w_k}
\]

If received signals are already the results of optical delay detection, phase dif-
ferences $a_k = b_k - b_{k-1}$ should be used instead of $b_k$ in MSPE. In this case, the new phase difference, $a'_i$, which is compensated by MSPE, is given by

$$a'_i = b_i - b'_{i-1} = a_i + \frac{(w_{-3} + w_{-2})e_{i-1} + w_{-3}e_{i-2}}{\sum_{k=-3}^{1} w_k},$$

(2)

where $e_k = a_k - A_k$.

3 Multistage bidirectional MSPE

In conventional MSPE, a decision feedback scheme is used to determine phase change $A_k$ caused by past data. The parallelization of MSPE for high-speed signal processing is thus difficult in practice. To overcome this difficulty, a multistage bidirectional MSPE (BD-MSPE) scheme, which performs tentative decision prior to MSPE, is proposed. Here, the tentative decision is a demodulation process that uses the phase value before phase correction by MSPE. The block diagram of multistage BD-MSPE is shown in Fig. 1. The tentative decision and the phase correction are performed several times alternately. With the proposed scheme, the tentative decision results can include more errors than in the case of the decision feedback in conventional MSPE. The proposed scheme is thus improved in the following two ways. One is a phase correction performed in a bidirectional manner. The other is multistage MSPE processing.

Bidirectional phase correction is described as follows. In conventional MSPE, only $A_k$ corresponding to the past data can be used because decision results for future data are not ready. In the proposed scheme, however, the tentative decision can be performed also for future symbols. Thus, BD-MSPE can correct both the phase before transition $b_{i-1}$ and the phase after transition $b_i$. For example, if $A_{i+1}$ and $A_{i+2}$ (phase changes caused by data corresponding to the future symbols) are known, the phase after transition $b_i$ is also expressed as $b_{i+1} - A_{i+1}$ and $b_{i+2} - A_{i+2} - A_{i+1}$. The new phase value after transition, $b'_i$ can thus be calculated as the average of these three values with weighting factor $w_k$ as follows.

$$b'_i = \frac{w_1 b_i + w_2 (b_{i+1} - A_{i+1}) + w_3 (b_{i+2} - A_{i+2} - A_{i+1})}{\sum_{k=1}^{3} w_k}$$

(3)

Phase difference compensated in bidirectional manner, $a'_i$, is thus expressed as Eq. (4) instead of Eq. (2), which is derived from Eq. (1) and Eq. (3), where $a_k = b_k - b_{k-1}$ and $e_k = a_k - A_k$.

$$a'_i = b'_i - b'_{i-1} = a_i + \frac{(w_{-3} + w_{-2})e_{i-1} + w_{-3}e_{i-2}}{\sum_{k=-3}^{1} w_k} + \frac{(w_2 + w_3)e_{i+1} + w_3e_{i+2}}{\sum_{k=1}^{3} w_k},$$

(4)

In Eq. (4), the second term is the phase correction value based on past symbols, and the third term is the phase correction value based on future symbols. In Fig. 1, the block labeled “Calculate amount of phase correction” performs the calculation on the basis of the second and third terms of Eq. (4).
The multistage configuration is described as follows. As shown in Fig. 1, multistage processing is adopted along with the bidirectional phase correction described above. The first tentative decision, namely (1) in the figure, is performed to output $A_k$ using the received signals (phase and amplitude). Non-Euclid decision scheme proposed in [3] is suitable for the tentative decision. The results of the tentative decision are used for phase correction in the first MSPE. The compensated phase difference, $a_{0k}$ given by Eq. (4), is then output. Next, the second tentative decision, namely (2) in Fig. 1, is performed using $a_{0k}$ and the amplitude of the received signal, and it outputs $A_{0k}'$ (which include less errors than those included in $A_k$ output by the first tentative decision). The second compensated phase difference is then calculated by using $A_{0k}'$. The tentative decision process and the phase correction process are thus repeated alternately. Lastly, the final decision is performed on the basis of the compensated phase difference value ($a_{000k}$) and the amplitude. In this way, the accuracy of the decision improves stage by stage. Note that Fig. 1 does not include any feedback loops; therefore, parallelization is easy.

4 Simulations

To confirm the performance of the proposed multistage BD-MSPE scheme, bit-error rate (BER) characteristics of BD-MSPE were evaluated by simulation. The parameters in each process block were optimized so that the BER was minimized. The BER characteristics under additive white Gaussian noise (AWGN) after parameter optimization are shown in Fig. 2. Differentially encoded (i.e., phase pre-integration described in [1]) 16-quadrature amplitude modulation (16-QAM) was used as the modulation scheme. In this simulation, to simplify phase pre-integration, phases of the constellation points of 16-QAM were quantized into multiples of $\pi/8$ radians. The number of averaged symbols was ten in each MSPE process.

In Fig. 2(a), the BER characteristics of BD-MSPE using several numbers of stages are compared with those of traditional delay detection (w/o MSPE) and coherent detection. It is shown that the BER obtained by proposed BD-MSPE is significantly reduced compared to that obtained by traditional delay detection. Even in the case of a one-stage configuration, required signal-to-noise ratio (SNR) for BER of $10^{-5}$ is reduced by almost 2 dB. Moreover, the BER characteristic improves as the number of stages increases. The degree of BER improvement, however, is almost saturated at two or three stages. The maximum gain in the case
of four-stage configuration is almost 3 dB, and the BER curve for BD-MSPE asymptotically approaches the BER curve for coherent detection at high SNR.

In Fig. 2(b), the BER characteristic obtained by four-stage BD-MSPE is compared with that obtained by conventional MSPE. Although both characteristics are similar, BD-MSPE is slightly superior to the conventional one.

Variation of the shape of constellation was also confirmed by simulation. The constellation of the received signal before (or without) MSPE at SNR of 20 dB is shown in Fig. 3(a). It is clear from the figure that each constellation point spreads anisotropically; that is, the variance in phase is larger than the variance in amplitude as a result of delay detection. The constellation after four-stage BD-MSPE is shown in Fig. 3(b). The variance in phase is significantly reduced, especially at inner signal points. Each constellation point is clearly separated. The reason that the variance in phase becomes less than the variance in amplitude is the effect of the bidirectional phase correction. In other words, not only the noise in phase before transition $b_{i-1}$ but also the noise in phase after transition $b_i$ is reduced by BD-MSPE.

![Fig. 3. Constellations based on simulations (SNR = 20 dB)](image-url)
5 Conclusion

A “multistage bidirectional multi-symbol phase estimation (BD-MSPE)” scheme was proposed. The architecture of the proposed scheme is decision-feedback free. For this reason, proposed BD-MSPE is suitable for parallelized implementation for high-speed signal processing. Multistage BD-MSPE uses tentative decision (which possibly includes more errors than decision feedback) to exclude decision feedback; therefore, it is improved in two ways. One is phase correction in a bidirectional manner. That is, BD-MSPE uses not only past symbols but also future symbols to improve the accuracy of the phase difference. The other is a multistage configuration, which utilizes the processed results of the first MSPE as the tentative decision results for the next stage and repeats the MSPE processes in plural stages. Thanks to the multistage configuration, errors in tentative decisions are reduced stage by stage. The BER characteristics of BD-MSPE have been confirmed by simulation. The simulation results indicate that multistage BD-MSPE improves BER characteristics by SNR of 3 dB at a maximum in comparison with that of traditional delay detection. They also indicate that the BER curve obtained by proposed MSPE scheme approaches asymptotically that obtained by coherent detection at high SNR. As well as being superior in the BER characteristic to conventional MSPE, BD-MSPE can be parallelized easily.

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