Fixed-state Log-MAP detection for intensity-modulation and direct-detection optical systems over dispersion-uncompensated links

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Abstract: In this paper, an optimized detection using log-maximum a posteriori estimation with a fixed number of surviving states (fixed-state Log-MAP) is proposed for a C-band 64-Gbit/s intensity-modulation and direct-detection (IM/DD) on-off keying (OOK) system over a 100-km dispersion-uncompensated link. For dispersion-uncompensated links, maximum likelihood sequence estimation (MLSE) is usually employed to deal with the severe inter-symbol interference (ISI) caused by chromatic dispersion. However, MLSE has an exponential increase in computational complexity and state storage with an increase in memory length, which overloads the computing resources and internal storage space of the hardware. Compared to MLSE, the fixed-state Log-MAP decreases the computational complexity and state storage from an exponential order of memory length to a linear order of surviving states. The memory length of fixed-state Log-MAP is no longer limited by computing resources and storage resources of the hardware, which has the potential to compensate larger ISI. The experimental results show that the optimal receiver sensitivity using fixed-state Log-MAP detection has a 2-dB improvement compared to that using MLSE. In conclusion, the fixed-state Log-MAP detection shows potential for practical IM/DD optical systems over dispersion-uncompensated links.

1. Introduction

With the rapid development of bandwidth-thirsty services such as 4K/8K high-definition video, interactive games and social media applications, the traffic of data center interconnects is increasing dramatically [1–3]. The data center interconnects, which enable data exchange among multiple data centers, are normally from a few kilometers to a few hundred kilometers. Metro data center interconnects transmission links are up to 80-120 km [4]. Owing to low-cost, low-power-consumption and small-footprint characteristics, optical interconnects tend to adopt the intensity-modulation and direct-detection (IM/DD) scheme with a simple structure [5, 6]. However, chromatic dispersion (CD) of fiber causes severe power fading on signal spectrum in C-band IM/DD optical systems. With an increase in the capacity-distance product, the intense distortion becomes increasingly more severe, which rapidly degrades the system performance [7]. Owing to the limitation of capacity-distance product caused by CD distortion in C-band IM/DD systems, the coherent system is a recommended scheme [8]. However, trying to solve the CD problem in C-band IM/DD systems is another solution. Recently, many studies have been conducted to deal with the CD distortion. O-band transmission is an obvious solution, which essentially circumvents CD distortion caused by optical fiber [9]. However, the optical transmission in O band has a high fiber loss and lacks mature optics such as erbium-doped fiber amplifier (EDFA) [10]. As a consequence, many studies have focused on eliminating the
CD-induced power fading in C band.

Optical dispersion compensation using dispersion compensation fiber (DCF) is the simplest way, but DCF introduces a high fiber loss and implementation cost [11]. Other CD-compensation schemes, including CD pre-compensation, single sideband or vestigial sideband modulation (SSB/VSB), and Kramers-Kronig receiver, can effectively compensate the CD distortion. However, a complex transceiver structure and extra expensive devices are required [12–15]. These schemes increase the implementation cost and footprint, leading to a limitation of their applications for optical interconnects. Other solutions used to alleviate CD impairment are to adopt advanced digital signal processing (DSP) techniques without changing the traditional structure of IM/DD systems. Tomlinson-Harashima precoding (THP) is an effective pre-coding scheme to equalize channel distortions at the transmitter, but THP fundamentally has a precoding loss and requires channel feedback to obtain appropriate coefficients for pre-equalization [16–19]. Therefore, the electrical equalization only at receiver side is being extensively studied to adaptively equalize the channel distortions [19–22]. In [22], a record 64-Gb/s on-off keying (OOK) system over a 100-km dispersion-uncompensated link is reached. At the receiver side, a polynomial nonlinear equalizer (PNLE) combined with decision feedback equalization (DFE) is employed to compensate the channel distortions including CD-induced spectral nulls, and a post-filter then whitens the colored noise. The following maximum likelihood sequence estimation (MLSE) is used to eliminate the inter-symbol interference (ISI) caused by post-filter and realize an optimal detection. However, the spectral nulls caused by severe CD distortion lead to ISI with a long memory length. To accurately whiten the in-band noise, the post-filter needs a sufficiently long tap $L$, resulting in a long memory length $L - 1$ for the following MLSE. MLSE has an exponentially increasing computational complexity and state storage with an increase in memory length. The computing resources and internal storage space of the hardware are overloaded due to the long memory length of MLSE. The maximum memory length achieved by MLSE is $L - 1 = 15$. Therefore, using a post-filter followed by MLSE, the tap number of post-filter is limited, resulting in residually enhanced noise, which makes performance degradation.

In this paper, to solve the severe CD problem, a fixed-state log-maximum a posteriori estimation (fixed-state Log-MAP) detection is proposed to replace MLSE for IM/DD optical systems over dispersion-uncompensated links. The number of surviving states $M$ is introduced. The computational complexity and state storage of fixed-state Log-MAP are independent of memory length and are linearly related to surviving states $M$. The fixed-state Log-MAP availability overcomes the constraint of memory length, which has the potential to compensate larger ISI. We demonstrate a C-band 64-Gbit/s IM/DD OOK system over a 100-km dispersion-uncompensated link. The receiver sensitivity has 2-dB improvement when the memory length of fixed-state Log-MAP is set to 47 compared to that when the memory length of MLSE is set to a maximum value of 15. Moreover, when an $L$-tap post-filter is employed, the complexity order decreases from $O(2^L)$ of MLSE to $O(2^M)$ of fixed-state Log-MAP, and the state storage decreases from $2^{L-1}$ states to $M$ states. The fixed-state Log-MAP detection with a low computational complexity and fewer state storage shows its superiority in achieving a better performance.

2. Principle of proposed detection algorithm

The CD-channel distortion of a C-band IM/DD system can be expressed as

$$
\text{Re}\{H(f)\} = \cos(2\pi^2\beta_2^2L_0 f^2) \tag{1}
$$

where $\beta_2$ denotes the group velocity coefficient, $L_0$ is the fiber length, and $f$ is the signal frequency. Eq. (1) shows that our desired signal is subjected to severe distortion with a cosine function of the quadratic frequency after optical fiber channel transmission. The CD-induced power fading results in spectral nulls. As shown in Fig. 1, taking a 64-Gb/s Nyquist OOK signal as an example, there are 0/7/14 spectral nulls after a 2/50/100-km standard single-mode
fiber (SSMF) transmission, respectively. The spectral nulls increase with an increase in the transmission distance, and the transmitted signal suffers from an increasingly severe ISI.

Adaptive channel-matched detection (ACMD) is an effective solution to compensate channel distortions over dispersion-uncompensated links [22]. ACMD includes PNLE & DFE, autoregression (AR)-based post-filter and MLSE. PNLE & DFE is used to equalize channel distortions at the cost of enhancing the in-band noise at the corresponding frequency. The enhanced in-band noise has a similar spectral profile with the frequency response of PNLE & DFE. Ideally, an $L$-tap AR-based post-filter is employed to accurately suppress the enhanced noise. Meanwhile, the known ISI is inevitably introduced by post-filter. A $2^{L-1}$-state MLSE is then adopted to eliminate the known ISI. However, the ISI has a long memory length for severe-CD systems. The bottleneck of MLSE is an exponential increase in computational complexity and state storage with an increase in memory length, which overloads computing resources and storage resources. Therefore, a fixed-state Log-MAP detection independent of the memory length is proposed, which replaces MLSE to eliminate the long-memory-length ISI.

The output of fixed-state Log-MAP detection is the log-likelihood ratio (LLR). The basic derivation refers to the traditional Log-MAP [23]. Different from traditional Log-MAP, the number of surviving states $M$ is introduced ($M \leq 2^{L-1}$). For a two-level pulse-amplitude modulation (PAM-2) signal, the output can be expressed as

$$LLR(u_k) = \ln \frac{P(u_k = +1|z)}{P(u_k = -1|z)},$$

(2)

where $u_k$ is a PAM-2 symbol with the elements of $\{-1, 1\}$. $P(u_k|z)$ is the probability of transmitted symbol $u$ at time $k$ under the condition of received sequence $z$. $P(u_k|z)$ is derived as

$$P(u_k|z) = \exp \left[ \ln(\alpha_{k-1}(s')) + \ln(\gamma_k(s', s)) + \ln(\beta_k(s)) \right],$$

(3)

where $s'$ and $s$ represent the state at time $k - 1$ and $k$, respectively. $\gamma_k(s', s)$, $\alpha_{k-1}(s')$, and $\beta_k(s)$ mean branch transition probability, forward probability, and backward probability, respectively.

$$\ln(\gamma_k(s', s)) = -\frac{1}{2\sigma^2} \left| z_k - \sum_{i=0}^{L-1} h_i c_k \right|^2,$$

(4)

where $c_k$ is the constellation, $h_i$ is the channel information provided by AR-based post-filter ($0 \leq i \leq L - 1$). $L$ is tap number of the AR-based post-filter, which introduces $(L - 1)$-memory-length ISI. $\alpha_{k-1}(s')$ and $\beta_k(s)$ are calculated recursively as follows:

$$\ln(\alpha_k(s)) = \ln \sum_{s'} \exp \left( \ln(\alpha_{k-1}(s')) + \ln(\gamma_k(s', s)) \right),$$

(5)
\[ \ln(\beta_{k-1}(s')) = \ln \sum_s \exp \left( \ln(\beta_k(s)) + \ln(\gamma_k(s', s)) \right). \] 

During the calculation of forward probability \( \alpha \), we reserve \( M \) maximum probability detections from all \( 2^{L-1} \) states and discard the others. Take \( M = 2 \) as an example, the trellis diagram is as shown in Fig. 2. For the calculation of \( \alpha \), we reserve 2 states with the maximum forward probability, and each reserved state generates 2 branches, including \( u_k = +1 \) and \( u_k = -1 \). Therefore, we merely calculate 2 state * 2 branches/state = 4 branches. The calculation of backward probability \( \beta \) is conducted according to the path reserved by forward probability without any additional path extensions. As a consequence, the computational complexity and state storage can be reduced.

### Table 1. Comparison of the computational complexity and state storage between MLSE and fixed-state Log-MAP.

| Type of algorithm       | State storage | Complexity order | Remarks             |
|-------------------------|---------------|------------------|---------------------|
| MLSE                    | \( 2^{L-1} \) states | \( O(2^L) \)     | Exponential order of \( L \) |
| Fixed-state Log-MAP     | \( M \) states | \( O(2M) \)      | Linear order of \( M \) |

A comparison of the computational complexity and state storage between MLSE and fixed-state Log-MAP is shown in Table 1. For MLSE, \( 2^{L-1} \) states require to be stored. The computational complexity is in order of \( O(2 \times 2^{L-1}) \), which suffers from an exponential increment as the memory length increases. Generally, the maximum memory of MATLAB is \( 2^{15} \) states; in other words, the maximum memory length (i.e., \( L - 1 \)) of MLSE is 15. Otherwise, the state storage runs out of memory resulting in an error. The computing resources and storage space of hardware are also overloaded. For fixed-state Log-MAP detection, we reserve \( M \) surviving states and calculate the probability of \( 2M \) detections. The \( M \)-state storage and \( O(2M) \)-order computational complexity are linearly related to surviving states and are independent of memory length. Therefore, the fixed-state Log-MAP detection overcomes the limitations of memory length, making the elimination of a long-memory-length ISI possible.

### 3. Experimental setup

Fig. 3 shows the experimental setup of a C-band 64-Gbit/s IM/DD optical OOK system over a 100-km dispersion-uncompensated link. At the transmitter, the pseudo-random binary sequences (PRBS) are mapped into PAM-2 symbols with the elements of \{−1, 1\}. A digital PAM-2 frame consists of 5000 training sequences and 77240 payload symbols. The PAM-2 signal is added a DC component to generate a unipolar OOK signal. The OOK signal is then up-sampled.
Fig. 3. Experimental setup of a C-band 64-Gbit/s IM/DD optical OOK system over a 100-km dispersion-uncompensated link.

and shaped by a digital root-raised cosine (RRC) filter with a roll-off factor of 0.25. The resampling is then employed for matching the sampling rate of digital-to-analog converter (DAC). The data is uploaded into the 90-GSa/s DAC with an 8-bit resolution and 3-dB bandwidth of 16 GHz. Afterwards, the electrical OOK signal is amplified by an electrical amplifier (EA, Centellax OA4SMM4) followed by a 3-dB attenuator (ATT). The external cavity laser (ECL) with 1550.116-nm center wavelength is used to generate the optical carrier. The electrical OOK signal is modulated on the optical carrier using a 40-Gbps Mach-Zehnder modulator (MZM) at the single-drive mode (Fujitsu FTM7937EZ) with +2-V bias voltage, which is to ensure the modulation within the linear regions. The generated optical OOK signal is fed into a 100-km SSMF, and the launch power is set to 7 dBm (i.e., the maximum launch power of the device). The link loss is approximately 20 dB.

At the receiver, a variable optical attenuator (VOA) is applied to adjust the received optical power (ROP). The optical signal is then amplified by an EDFA, which ensures that the input power of the photoelectric detector is sufficient. The output power of EDFA is fixed at -4 dBm. The optical signal is converted into an electrical signal by a 31-GHz PIN with a trans-impedance amplifier (PIN-TIA) (Finisar MPRV1331A). The electrical signal is then sampled by a 80-GSa/s real-time oscilloscope (RTO) with 36-GHz bandwidth (Tektronix MSO72004C). However, the bandwidth ranges from 32 GHz to 36 GHz, and the filtering effect is severe. Finally, the off-line DSP is conducted on the sampling electrical signal, including resampling, RRC matched filter, time synchronization, PNLE & DFE, AR-based post-filter, fixed-state Log-MAP detection, and bit error ratio (BER) counting.

4. Experimental results and analysis

We conducted a 64-Gbit/s optical OOK experiment over a 100-km dispersion-uncompensated link to verify the feasibility of the fixed-state Log-MAP detection. The hard-decision forward error correction (HD-FEC) with 7% overhead is employed, and the net rate is approximately 56.18 Gbit/s (64 Gbit/s × 77240/82240/(1 + 7%) = 56.18 Gbit/s). Through a trade-off between system performance and computational complexity, the tap number of 3-order PNLE and DFE are set to (291, 81, 41) and (71, 61), respectively. Afterwards, an $L$-tap AR-based post-filter is used to accurately whiten the in-band noise to obtain optimum signal-to-noise ratio. The following fixed-state Log-MAP detection with $(L - 1)$-memory length eliminates the ISI caused by post-filter to achieve an optimal detection.
Fig. 4 shows the BER against memory length and surviving states of fixed-state Log-MAP detection for a 64-Gbit/s IM/DD optical OOK system over a 100-km SSMF transmission. The number of surviving states is $M$. The ROP is set to -14 dBm. Fig. 4 illustrates that the larger $M$ yields a better BER performance since it guarantees a higher probability to reserve the global maximum posterior probability detection. The performance saturates when $M$ is 16. Besides, with an increase in the memory length, the BER performance improves gradually. When the memory length of fixed-state Log-MAP is set to $L = 47$, the BER performance saturates and achieves the optimum. Therefore, the number of taps of post-filter is set to $L = 48$, and the number of surviving states $M$ of fixed-state Log-MAP is fixed at 16.

Fig. 5 (a) shows a comparison of computational complexity and state storage between MLSE and fixed-state Log-MAP ($M = 16$). The square and triangle denote MLSE and fixed-state Log-MAP at $M = 16$, respectively. The pentacle represents the finally used memory length. The solid line represents the realizable memory length, and the dashed line represents the theoretical but unrealizable memory length. The left vertical axis is the order of complexity (blue line). MLSE has an exponential increase in computational complexity in order of $O(2^L)$. The amount of state storage (red line) is $2^{L-1}$, referring to right vertical axis. Once the memory length $(L - 1)$ of MLSE is greater than 15, the computing resources and internal storage space of the hardware are overloaded. The overloaded region is within the range of the dashed line. Consequently, when MLSE is employed after post-filter, the maximum tap number of post-filter is $L = 16$. However, for severe CD-distortion links, the memory length of ISI is much longer than 15 owing to the multiple CD-induced nulls. For fixed-state Log-MAP detection ($M = 16$), the computational complexity and state storage are invariable. Thanks to the fixed-state Log-MAP independent of memory length, MLSE can be replaced to solve the issue of the memory length limitation.

Fig. 5 (b) depicts the BER performance using MLSE and fixed-state Log-MAP versus ROP for a 64-Gbit/s IM/DD OOK system over a 100-km SSMF transmission. When the memory length of MLSE is set to the maximum value of 15 (i.e. $L = 16$), the achieved ROP is -14.2 dBm at 7% HD-FEC limit. For post-filter followed by MLSE, this is achieved best performance. When a 16-tap post-filter is used, the performance of fixed-state Log-MAP at $M = 16$ is consistent with the achieved optimal performance of MLSE. For a 100-km dispersion-uncompensated link, the memory length of ISI is greater than 15. Theoretically, MLSE should have same performance as fixed-state Log-MAP. However, the state storage and computational complexity of MLSE will be out of computer memory, when the memory length is greater than 15. Therefore, the
Fig. 5. (a). The comparison of computational complexity and state storage between MLSE and fixed-state Log-MAP ($M = 16$) (the solid line represents realizable ranges, and the dashed line represents the theoretical but unrealizable ranges). (b). BER performance using MLSE and fixed-state Log-MAP versus ROP for a 64-Gbit/s IM/DD optical OOK system over a 100-km SSMF transmission.

post-filter followed by MLSE is unable to do anything about it owing to the huge computing and storage burden. The fixed-state Log-MAP overcomes these limitations of MLSE making the elimination of a long-memory-length ISI possible. When a 48-tap post-filter is employed before fixed-state Log-MAP with $M = 8$ and $M = 16$, the receiver sensitivity achieves a 1.3-dB and 2-dB improvement at 7% HD-FEC limit, respectively.

5. Summary

In this paper, we proposed a fixed-state Log-MAP detection for IM/DD optical systems over dispersion-uncompensated links. Compared to MLSE, fixed-state Log-MAP has a linear computation complexity and fixed state storage, which are independent of the memory length. The fixed-state Log-MAP availably overcomes the constraint of memory length caused by an exponential computation complexity and state storage of MLSE. Therefore, post-filter can use a sufficient number of taps to adequately whiten the enhanced in-band noise. We experimentally demonstrate a C-band 64-Gbit/s IM/DD OOK system over a 100-km dispersion-uncompensated link. Compared to MLSE with the maximum memory length of 15, the receiver sensitivity achieves a 1.3-dB and 2-dB improvement using fixed-state Log-MAP at $M = 8$ and $M = 16$ with memory length of 47, respectively. Moreover, the computational complexity of fixed-state Log-MAP is in order of $O(2M)$, which is much lower than the $O(2^L)$ of MLSE. The state storage also decreases from $2^{L-1}$ states of MLSE to $M$ states of fixed-state Log-MAP. In conclusion, the fixed-state Log-MAP detection shows superiority in both computational complexity and state storage, and supports a post-filter with a sufficient number of taps to achieve better performance. We believe this work is of significant value for future data center networks.

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Disclosures

The authors declare no conflicts of interest.

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