Joint Maximum Likelihood Sequence Estimation for Chromatic-Dispersion Compensation in ASK-DPSK Modulation Format

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***Abstract*—We determine the fundamental impairment mechanism in the chromatic-dispersion (CD)-limited hybrid amplitude shift keying (ASK)–differential phase-shift keying (DPSK) modulation format and propose the employment of joint maximum likelihood sequence estimation (J-MLSE) for CD compensation to extend the transmission reach of such format. We find that it is not the intrasubchannel interference of the ASK or DPSK subchannel but the interaction between these two subchannels that limits the transmission distance. Therefore, electronic equalization of the two subchannels separately cannot improve the overall CD tolerance of the ASK-DPSK signal. J-MLSE, however, exploits the correlation information between the detected ASK and DPSK signals and is numerically shown to improve the CD tolerance of the ASK-DPSK signal significantly.**

***Index Terms*—Amplitude modulation, electronic equalization, phase modulation.**

I. Introduction

HYBRID amplitude shift keying (ASK)–differential phase-shift keying (DPSK) modulation format is an attractive spectral efficient multibit per symbol modulation format to enable close channel spacing in dense wavelength-division-multiplexing transmission, to carry optical payload/label in optical networks, and to provide capacity upgrade without component replacement [1]–[5]. However, despite many experimental demonstrations of this format in the applications, few studies have been performed to investigate its chromatic-dispersion (CD) tolerance [1], [2]. In [1], where the phase modulator (PM) is employed for DPSK subchannel modulation, it is shown that the DPSK subchannel of the ASK-DPSK signal has much better CD tolerance than the ASK subchannel. Such a great difference of the CD tolerance between the two subchannels, however, is not manifest in [2], where Mach–Zehnder modulator (MZM) is used for DPSK subchannel modulation in the ASK-DPSK transmitter. Despite their contributions, these papers have not revealed the fundamental mechanism that limits the transmission distance in the CD-limited hybrid ASK-DPSK modulation format.

Electronic dispersion compensation has attracted considerable interest because of its cost-effectiveness and adaptive equalization capability [6], [7]. The implementation of 10-Gb/s conventional maximum likelihood sequence estimation (MLSE) has been reported [7]. A new MLSE structure, joint MLSE (J-MLSE), was also proposed for differential quaternary phase-shift keying [8]. However, there is little prior work for the investigation of the electronic device to extend the transmission reach of ASK-DPSK format. Electronic equalization of multibit per symbol format relaxes the speed limitation of electronic devices for high-speed optical transmission.

In this letter, we determine the fundamental transmission limitation of the ASK-DPSK format. It is found that for the two different implementation schemes of the DPSK subchannel generation (PM or MZM), the transmission distance of the ASK-DPSK signal is limited by the ASK subchannel and the intrinsic limitation mechanism is from the interaction between the two subchannels. Therefore, conventional MLSE which only considers intrasubchannel interference of the two subchannels separately cannot improve the CD tolerance of the ASK-DPSK signal. J-MLSE can make full use of the correlation information between the two subchannels. Simulations show that 10-Gb/s J-MLSE can effectively improve the CD tolerance of 20-Gb/s ASK-DPSK signal.

II. Simulation System Model

Fig. 1 shows the simulation system model. A continuous-wave light is phase modulated by a 10-Gb/s DPSK data train using a PM or an MZM. The following 10-Gb/s intensity modulation with finite extinction ratio (ER) is implemented in another MZM. The DPSK and ASK data trains both consist of 500 000 raised-cosine shaped bits with 40 samples per bit. The generated ASK-DPSK signal is amplified and launched into an optical fiber where CD is introduced. Before detection, the signal is filtered by a 50-GHz Gaussian-shaped optical bandpass filter. The ASK subchannel is directly detected while the DPSK subchannel is demodulated by a delay interferometer and detected by a balanced detector. After optical–electrical conversion, three kinds of decision schemes are employed. In the first scheme, the detected DPSK or ASK signal is electrically amplified, filtered by an electronic filter (EF), sampled, and compared with the optimal threshold. The second scheme applies two separate 10-Gb/s MLSEs to the detected ASK and DPSK signals, respectively. The ASK or the DPSK signal is amplified, filtered, sampled, and analog-to-digital converted with resolution of 5 bits. MLSE operates with two samples per bit. The metric of MLSE, $\mathrm{PM}(b_{i,n})$, i being ASK or DPSK, is

$$\mathrm{PM}(b_{i,n}) = \mathrm{PM}(b_{i,n-1}) - \sum_j \log(p\,(I_i(t_j)|b_{i,n-m}, \ldots, b_{i,n})) \quad (1)$$

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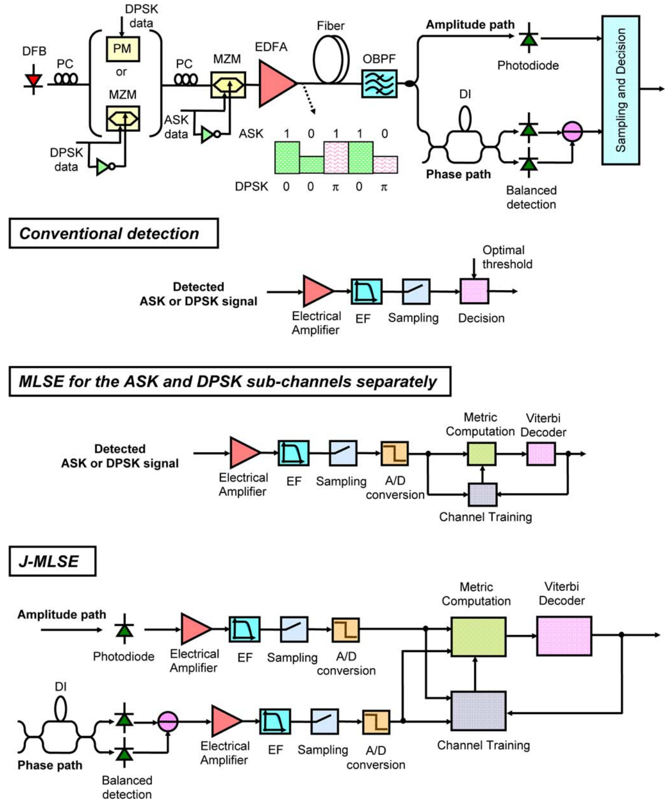

Fig. 1. Simulation system model.

where $j \in \{n\ n+1/2\}$. $b_{i,n}$ and $p(I_i(t_j)|b_{i,n-m},\ldots,b_{i,n})$ are the nth ASK or DPSK logical data and the probability of the sampled ASK or DPSK signal value at time t_j giving the logical data $b_{i,n-m},\ldots,b_{i,n}$, respectively. m is the memory length. The initial metric in the channel training table is obtained using a nonparametric histogram method by a 200 000-bit training sequence. The third scheme, J-MLSE, exploits the detected ASK and DPSK signals simultaneously in both initial channel training and metric computation. The metric of two-sample per bit J-MLSE is

$$\begin{aligned}\mathrm{PM}(b_{\mathrm{ASK},n}, b_{\mathrm{DPSK},n}) &= \mathrm{PM}(b_{\mathrm{ASK},n-1}, b_{\mathrm{DPSK},n-1}) \\ &\quad - \sum_i \sum_j \log\left(p\left(I_i(t_j)|b_{\mathrm{ASK},n-m},\ldots,b_{\mathrm{ASK},n},\right.\right. \\ &\qquad\qquad \left.\left. b_{\mathrm{DPSK},n-m},\ldots,b_{\mathrm{DPSK},n}\right)\right). \quad (2)\end{aligned}$$

Note that the complexities of one J-MLSE and two conventional MLSEs are proportional to $2^{2\times(m+1)}$ and $2 \times 2^{m+1}$, respectively. In this letter, J-MLSE has 64 metrics with the memory length m of 2 while each MLSE in the second scheme has 32 metrics with m of 4 for fair comparison. In the three schemes, EF is a 7-GHz fourth-order Bessel filter. The system is thermal-noise limited. The performance is evaluated in terms of receiver power penalty at bit error rate of 10^{-4}, which can be corrected below 10^{-15} using forward-error correction.

III. Fundamental Transmission Limitation of ASK-DPSK Modulation Format

The dependence of the receiver power penalty of the ASK (circles) and DPSK (triangles) subchannels on the ER of the ASK subchannel is shown in Fig. 2(a). Note that the receiver power penalty is with respect to the back-to-back receiver sensitivity of the ASK subchannel at ER of 4.9 dB, and this reference is used throughout this letter. From the figure, it is shown that at this ER, the receiver sensitivities of the ASK subchannel and the DPSK subchannel are almost the same [1]. Fig. 2(b) depicts the CD tolerance of the ASK (circles) and DPSK (triangles) subchannels of 10-Gsym/s ASK-DPSK signal at ER of 4.9 dB when the DPSK subchannel is generated by MZM. The CD tolerance of 20-Gb/s pure ASK signal with infinite ER (squares) is also given in Fig. 2(b) for comparison. From the figure, it is shown that despite its 1.6-dB back-to-back penalty, ASK-DPSK modulation format outperforms pure ASK format for cumulative CD larger than 400 ps/nm. To determine the intrinsic transmission limitation mechanism and find out the extrinsic parameters on which the CD tolerance of the ASK-DPSK format depends, Fig. 3 shows the receiver power penalty versus CD for (a) ER of 1.25 dB and DPSK subchannel generation by PM; (b) ER of 6 dB and DPSK subchannel generation by PM; (c) ER of 1.25 dB and DPSK subchannel generation by MZM; and (d) ER of 6 dB and DPSK subchannel generation by MZM. Circles and triangles represent the ASK and DPSK subchannels of the ASK-DPSK signal, respectively. Squares represent the pure ASK signal in the absence of the DPSK subchannel at the ER of 1.25 dB for Fig. 3(a) and (c) and 6 dB for Fig. 3(b) and (d). From the figure, two conclusions can be drawn. First, compared to that of the pure ASK signal in the absence of the DPSK subchannel, the CD tolerance of the ASK subchannel in the ASK-DPSK signal is significantly reduced. Such phenomenon is even more severe for small ER value and is also related to the choice of PM or MZM for phase modulation. When the DPSK subchannel is generated by PM, the imperfect phase modulation in data transition region induces chirp, which limits the CD tolerance of the ASK subchannel below several hundreds picoseconds per nanometers. In contrast, for the DPSK generation by MZM, phase in the data transition region jumps instantaneously and the transmission reach is extended. Second, the DPSK subchannel of the ASK-DPSK signal has much better CD tolerance than the ASK subchannel. Therefore, it is the ASK subchannel that limits the overall transmission distance of the ASK-DPSK signal and the intrinsic limitation mechanism is from the interaction between the ASK and DPSK subchannels.

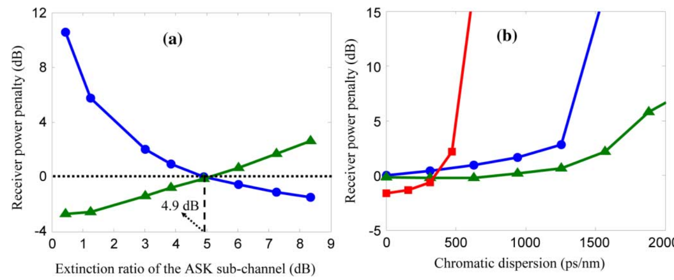

Fig. 2. (a) Receiver power penalty of the ASK (circles) and DPSK (triangles) subchannels of the ASK-DPSK signal versus the ER of the ASK subchannel. The receiver power penalty is with respect to the back-to-back receiver sensitivity of the ASK subchannel at ER of 4.9 dB. (b) Receiver power penalty of the ASK (circles) and DPSK (triangles) subchannels of 10-Gsym/s ASK-DPSK signal versus CD for ER of 4.9 dB when the DPSK subchannel is generated by MZM. Squares represent the CD tolerance of 20-Gb/s pure ASK signal with infinite ER.

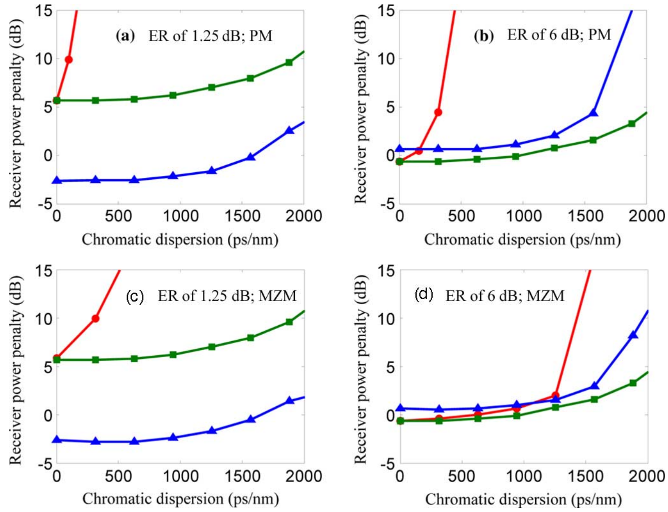

Fig. 3. Receiver power penalty versus CD for (a) ER of 1.25 dB and DPSK subchannel generation by PM; (b) ER of 6 dB and DPSK subchannel generation by PM; (c) ER of 1.25 dB and DPSK subchannel generation by MZM; and (d) ER of 6 dB and DPSK subchannel generation by MZM. Circles and triangles represent the ASK and DPSK subchannels of the ASK-DPSK signal, respectively. Squares represent the pure ASK signal in the absence of the DPSK subchannel at the ER of 1.25 dB for (a) and (c) and 6 dB for (b) and (d).

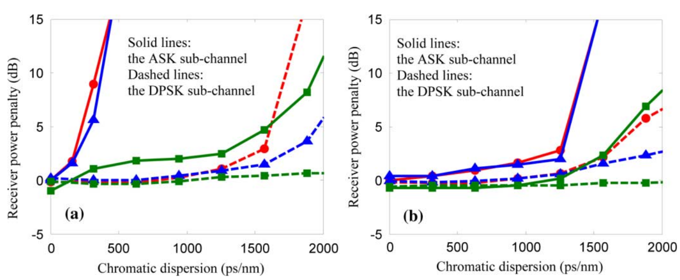

Fig. 4. Receiver power penalty versus CD by using conventional detection (circles), MLSE for the ASK and DPSK subchannels separately (triangles), and J-MLSE (squares) at ER of 4.9 dB when the DPSK subchannel is generated by (a) PM, and (b) MZM. The solid lines and the dashed lines represent the ASK subchannel and the DPSK subchannel of the ASK-DPSK signal, respectively.

IV. J-MLSE of ASK-DPSK Modulation Format

To show the effectiveness of J-MLSE for CD compensation in ASK-DPSK format, Fig. 4 depicts the receiver power penalties versus CD by using conventional detection (circles), MLSE for the ASK and DPSK subchannels separately (triangles), and J-MLSE (squares). In the figure, ER is 4.9 dB and the DPSK subchannel is generated by (a) PM and (b) MZM. The solid lines and the dashed lines represent the ASK subchannel and the DPSK subchannel, respectively. From Fig. 4, for both (a) and (b), individual MLSE for the two subchannels cannot improve the CD tolerance of the ASK subchannel, and thus the overall CD tolerance of the ASK-DPSK signal. It is because the transmission distance is not limited by the intrasubchannel interference. By employing J-MLSE, however, the performances of the ASK subchannel, including not only the CD tolerance but also the back-to-back receiver sensitivity, are effectively improved. The reason is twofold. First, because different ASK data lead to different amplitude levels in the detected DPSK signal [1], the knowledge of the detected DPSK signal definitely helps the decision of the ASK data. Second, because the transmission limitation is from the interaction between the ASK and DPSK subchannels, a J-MLSE that considers both ASK and DPSK data is effective for CD compensation. Therefore, from the figure, it is shown that at ER of 4.9 dB, negative receiver power penalty of the ASK subchannel is achieved for cumulative CD less than 160 ps/nm in Fig. 4(a) and 1200 ps/nm in Fig. 4(b) by using J-MLSE. The CD tolerance of the ASK subchannel at 1-dB receiver power penalty is enhanced by J-MLSE from 120 to 300 ps/nm in Fig. 4(a) and from 640 to 1400 ps/nm in Fig. 4(b). Because the main transmission limit of the ASK-DPSK signal is from the ASK subchannel, as a result, the overall transmission reach of such format is enhanced by J-MLSE.

V. Conclusion

We determine the fundamental impairment mechanism in the CD-limited hybrid ASK-DPSK modulation format and propose the employment of J-MLSE to enhance the transmission reach of such format. It is found that the transmission distance of the ASK-DPSK signal is limited by the ASK subchannel and the intrinsic limitation mechanism is the interaction between the ASK and DPSK subchannels. J-MLSE makes full use of the correlation information between the two subchannels and is numerically shown to improve not only the back-to-back receiver sensitivity but also the CD tolerance of the ASK-DPSK signal significantly.

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