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Maximum Likelihood Sequence Estimation for Impairment Compensation in Advanced Modulation Formats

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Abstract
We review and propose novel designs of maximum likelihood sequence estimation (MLSE) for effective impairment compensation in advanced modulation formats. The performance and computation complexity of these MLSE structures are investigated and summarized.

1 Introduction

As the capacity of the transmission systems increases, many signal degradation effects, such as chromatic dispersion (CD) and polarization mode dispersion (PMD), become prominent and seriously degrade the performance of the optical communication systems. Maximum likelihood sequence estimation (MLSE) has recently attracted considerable interest for impairment compensation because of its significant cost saving and adaptive compensation capability required in future dynamic optical networks [1-11]. Advanced optical modulation format such as differential phase shift keying (DPSK) is an alternative method to extend the capacity and the transmission reach of the communication systems. However, few studies have been performed to extend the transmission reach by combining advanced modulation formats and MLSE [12-14]. The optimal design of MLSE structures for different advanced modulation format is different. In this paper, we will review our recent work on the design of novel MLSE structures with high impairment compensation performance and low cost for different advanced modulation formats, including DPSK, amplitude shift keying/DPSK (ASK/DPSK) orthogonal modulation, differential quaternary phase shift keying (DQPSK), and 4-ASK. After evaluating the performance and analyzing the complexity of the proposed schemes, we can then determine the most cost-effective solution for the given requirements of a transmission system.

2 Novel MLSE Structures for Advanced Modulation Formats

(a) Multi-chip DPSK MLSE for CD and PMD Compensation

DPSK is one of the most desirable formats for high-speed optical transmission due to its 3-dB optical signal to noise ratio (OSNR) sensitivity improvement and higher tolerance to fiber nonlinear effects compared to OOK format. However, although conventional MLSE is effective to extend the transmission reach of the OOK format, it provides limited performance improvement for the DPSK format [9-11].

In this paper, we review our recently proposed 3-chip DPSK MLSE for CD and PMD compensation in DPSK format. The proposed method exploits the phase difference between not only the adjacent optical bits but also the bits with one bit slot apart for sequence estimation of the DPSK data [12]. The results show that 3-chip DPSK MLSE significantly outperforms conventional 2-chip DPSK MLSE in CD and PMD compensation. It is shown that 3-chip DPSK MLSE can enhance the CD tolerance of 10-Gbit/s DPSK signal to 2.5 times of that by using 2-chip DPSK MLSE and can bound the penalty for 100-ps differential group delay (DGD) by 1.4 dB. We will further investigate 4-, 5-, and 6-chip DPSK MLSEs. We will show that these structures can provide further performance improvement but at the expense of the implementation complexity increase. We suggest that in practice, 3- or 4-chip DPSK MLSE is optimal in terms of performance and complexity.

(b) Joint MLSE (J-MLSE) and Decision-Feedback J-MLSE (DF-J-MLSE) for CD Compensation in ASK/DPSK Orthogonal Modulation Format

ASK/DPSK orthogonal modulation format is an attractive multi-bit per symbol modulation format to enable close channel spacing in DWDM transmission and to carry optical payload / label in optical networks concurrently [15-17]. However, despite many experimental demonstrations of this format in the applications, few studies on the design of electronic equalization devices for such format have been performed.

In [13], we determined the fundamental impairment mechanism in CD-limited ASK/DPSK orthogonal modulation. Based on the fundamental finding, we showed that conventional MLSEs which only consider intra sub-channel interference of the ASK and DPSK sub-channels separately fail to improve the overall CD tolerance of the ASK/DPSK signal. J-MLSE was proposed to exploit the correlation information between the detected ASK and DPSK signals and was shown to improve the CD tolerance of the ASK/DPSK signal significantly.

However, a J-MLSE has higher implementation complexity which is proportional to $2^{2\times(m+1)}$, whereas a conventional MLSE's complexity is proportional to 2^{m+1}, where m is the MLSE's or J-MLSE's memory length. Recently we are investigating a novel DF-J-MLSE that reduces the implementation complexity to the same as that of a conventional MLSE while preserving the overall CD tolerance the same as that of a J-MLSE.

(c) 3-Chip DQPSK MLSE for CD and PMD Compensation

DQPSK is an attractive multi-bit per symbol modulation format for high-speed optical transmission due to its spectral efficiency and higher tolerance to CD and PMD compared to the DPSK format [18]. To enhance the transmission reach of the DQPSK signal, the design of electronic equalizer was proposed [14]. It was shown that separate equalization of the two tributaries of the DQPSK signal provides limited CD tolerance improvement while J-MLSE can effectively improve the CD tolerance of the DQPSK signal. In this paper, we will show some preliminary results of our recent work on a novel 3-chip DQPSK J-MLSE. The method searches the most probable path through the trellis for data sequence estimation by exploiting the phase difference between not only the adjacent optical bits but also the bits with one bit slot apart. The scheme significantly outperforms conventional MLSE and J-MLSE in CD and PMD compensation while maintaining the implementation complexity comparable to that of a J-MLSE. We show that the 3-chip DQPSK J-MLSE provides twofold CD tolerance enhancement compared to a J-MLSE and exhibits negative penalty for 100-ps DGD at 10 Gsym/s.

(d) 4-ASK MLSE for CD Compensation in CD-Varying Optical Systems

4-ASK format is another cost-effective multi-bit per symbol modulation format and requires only one optical modulator and receiver for signal generation and detection [19-20]. It can also be coded and decoded all optically [20]. However, due to the increased number of levels, such format is sensitive to CD-induced ISI. In [21], we showed that the optimal level spacing of the 4-ASK signal changes with the CD values and improper level spacing design leads to significant CD tolerance reduction. As a result, level spacing optimization is difficult in CD-varying 4-ASK optical systems, in which the CD frequently changes due to the time-varying effects of the installed fibers and different routing paths. In [21], we proposed 4-ASK MLSE for signal detection. It was shown that the proposed method can effectively alleviate the sensitivity of CD tolerance to level spacing, therefore, relaxing the difficulty of level spacing optimization. By using 4-ASK MLSE, the CD tolerance of the 4-ASK signal is significantly enhanced by at least a factor of two.

3 Discussions and Summary

In summary, we have reviewed our recently proposed MLSE structures for different advanced modulation formats. The proposed schemes significantly outperform the existing schemes without much complexity increase, as shown by Table 1. Table 2 compares the performance of different advanced modulation formats under the proposed schemes. As a result, the most cost-effective solution given the requirement of a transmission system can be determined. For instance, for a 100-km range optical network, ASK/DPSK orthogonal modulation is the best modulation format because of its CD tolerance

around 1500 ps/nm and low complexity, as shown in Table 2.

Table 1: Performance improvement of our recently proposed schemes with respect to the existing schemes

		DPSK	ASK/DPSK	DQPSK	4-ASK
The existing electronic equalization schemes		Conventional MLSE	No report (hard decision)	J-MLSE	No report (soft detection)
The proposed electronic equalization schemes		3-chip DPSK MLSE	DF-J-MLSE	3-chip DQPSK J-MLSE	4-ASK MLSE
The proposed schemes vs the existing schemes	B-B sensitivity	1.6-dB reduction	0- ~ 0.7-dB reduction	2.4-dB reduction	0- ~ 2-dB reduction
	CD tolerance	2.5 times	> 2 times	2 times	> 2 times
	Power penalty at DGD=T	1.4 dB vs 4.2 dB	NA	-2 dB vs 4.6 dB	NA
	Receiver complexity	2 times	The same	2 times	The same
	MLSE complexity	comparable	NA	comparable	NA

Note: CD tolerance is evaluated at 3-dB power penalty. T is the time period for one bit slot

Table 2: Performance comparison of different advanced modulation formats under our recently proposed schemes

		DPSK	ASK/DPSK	DQPSK	4-ASK
The proposed electronic equalization schemes		3-chip DPSK MLSE	DF-J-MLSE	3-chip DQPSK J-MLSE	4-ASK MLSE
Comparison between different formats under the proposed schemes	B-B E_s/N_0 sensitivity	13 dB	16.8 dB	13 dB	21.7 dB
	Spectral efficiency	Poor	Good	Good	Good
	CD tolerance at E_s/N_0=20 dB	1600 ps/nm	1500 ps/nm	3600 ps/nm	0 ps/nm
	E_s/N_0 at DGD=T	10 dB	NA	10.2 dB	NA
	Receiver complexity	Two 20-Gbit/s receivers	Two 10-Gbit/s receivers	Four 10-Gbit/s receivers	One 10-Gbit/s receiver
	MLSE complexity	20 Gbit/s and $\propto 2^{m+1}$	10 Gbit/s and $\propto 2^{m+1}$	10 Gbit/s and $\propto 4^{m+1}$	10 Gbit/s and $\propto 4^{m+1}$

Note: All formats are 20-Gbit/s. E_s is the average received signal power in 100 ps. N_0 is the noise spectral power density. The performance is evaluated at BER of 10^{-4}.

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