Impact of MAP Detection on the Mutual Information of a 1.2 Tb/s Three-Carrier DP 16-QAM Superchannel

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Abstract: For a 1.206 Tb/s three-carrier DP 16-QAM superchannel, the mutual information is evaluated without and with fixed look-up table based maximum-a-posteriori detection at the receiver to mitigate pattern-dependent distortion in the transmitted signal.
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1. Introduction

A superchannel based on dual-polarization m-ary quadrature-amplitude modulation (DP m-QAM) is an effective way of achieving 1 Tb/s with high spectral efficiency and an optical signal-to-noise ratio (OSNR) requirement that can be matched to the enables long-haul transmission. For example, superchannels with a bit rate of 1 Tb/s have been demonstrated using DP 8-QAM and 9 subcarriers with baud rates of 23 Gbaud [1], DP 16-QAM and 4 subcarriers with baud rates of 40 Gbaud [2], and DP 16-QAM and 2 subcarriers with baud rates of 80 Gbaud [3]. For high baud rate experiments that use multi-level modulator drive signals, steps are taken to minimize the distortion of the transmitted signal and to mitigate the distortion that does exist.

Recently, the transmission performance of a 1.206 Tb/s three-carrier superchannel was assessed using a modified version of maximum-a-posteriori (MAP) detection at the receiver that was implemented using a look-up table (LUT) [4]. The MAP detector was used to mitigate the effects of pattern-dependent distortion in the transmitted signal due to the high symbol rate (50.25 Gbaud). As such, the LUT entries for the MAP detector are determined for a received training signal in a back-to-back system and are fixed; the resultant LUT is used for all other system configurations with varying optical signal-to-noise ratio (OSNR) and fiber length. The performance was assessed in terms of the bit error ratio (BER).

In this paper, the performance of a 1.206 Tb/s three-carrier DP 16-QAM superchannel signal is evaluated in terms of the mutual information (MI) without and with modified MAP detection based on a fixed LUT at the receiver. By using the MAP detector an increase in the MI of about 0.45 bits/symbol is achieved for a back-to-back system and for transmission over standard single-mode fiber (SMF) with erbium doped fiber amplifiers (EDFAs).

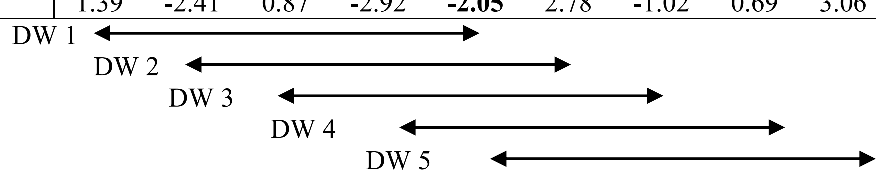
2. Modified fixed look-up table based MAP detection

Due to the limitations of high-speed linear amplifiers and optical modulators, recovered 50.25 Gbaud four-level in-phase and quadrature signals exhibit pattern-dependent distortion or non-linear ISI with memory [4]. For each polarization signal, LUT-based MAP detection is used to separately mitigate the pattern-dependent distortion of the in-phase and quadrature four-level signals.

Conventional MAP detection performs symbol detection based on determining the Euclidean distances between the received sample values for $2n + 1$ consecutive symbols and LUT entries. The decision about the center symbol is obtained from the address for the single LUT entry with the minimum Euclidean distance. For a 5-symbol LUT, conventional MAP detection uses detection window (DW) #3 in Table 1 to make a decision about the sample value -2.05. There are, however, $2n + 1$ observations of each symbol as the detection window slides by.

Table 1: Modified LUT-MAP detection algorithm

Transmitted sequence	1	-3	1	-3	**-1**	3	-1	1	3
Received sample values	1.39	-2.41	0.87	-2.92	**-2.05**	2.78	-1.02	0.69	3.06



Here a modified version of MAP detection is used in which all $2n + 1$ observations of a symbol are considered (Table 2). The decision is based on the DW with the minimum Euclidean distance between the sample value for the symbol of interest (-2.05) and the corresponding LUT entry (in this example -1.33 for DW 1). In this example, conventional MAP detection yields an incorrect decision while the modified MAP detection yields a correct decision.

Table 2: Content of averaged 5-symbol LUT and their addresses (decisions)

DW	Selected 5-symbol LUT entry					Address for 5-symbol LUT entry				
1	0.65	-2.96	0.6	-3.07	**-1.33**	1	-3	1	-3	**-1**
2	-2.98	0.60	-3.18	**-1.29**	2.71	-3	1	-3	**-1**	3
3	0.75	-3.20	**-2.88**	2.76	-1.06	1	-3	**-3**	3	-1
4	-3.16	**-2.86**	2.77	-0.90	0.84	-3	**-3**	3	-1	1
5	**-1.12**	2.79	-1.03	0.96	2.67	**-1**	3	-1	1	3

3. Mutual information

The mutual information *I(X;Y)* between the input and output signals of a system (denoted *X* and *Y*, respectively) represents the amount of information about *X* that is contained in the observation *Y* when *X* is transmitted. For a modulation order *M*, the MI is

$$I(X;Y) = \sum_{m=1}^{M} \sum_{y} p_X(x_m) p_{(Y|X)}(y|x_m) \log_2 \left[p_{(Y|X)}(y|x_m) / p_Y(y) \right] \quad (1)$$

where $p_{Y|X}(y|x_m)$ is the conditional probability density function (PDF) of y given the m^{th} input realization of X, $p_Y(y)$ is the PDF of the output *Y*, and $p_X(x)$ is the PDF of the input *X*, which is taken as uniformly distributed $p_X(x_m) = 1/M$.

The MI can be estimated using histograms as PDF estimators in the case that the optimal histogram bin widths are obtained from blind algorithms [6-8]. Choosing the correct value for the bin width is a key requirement for estimating the MI precisely. For a large number of bins (small bin width) the MI tends to be overestimated, and for a small number of bins the histogram does not approximate the true PDF well [5]. Scott [6] derived a method for the optimal bin width by minimizing the integrated mean squared error of the histogram [6]. Shimazaki proposed a method based on the spike count static [7]. Knuth introduced a straightforward blind method by assigning a multinomial likelihood and a non-informative prior of the given data [8].

4. Experimental setup

Four copies of a 50.25 Gb/s 2^{15}-1 pseudorandom bit sequence were attenuated and combined to generate two four-level drive signals that were split and applied to two IQ modulators (25 GHz 3-dB bandwidth) with delays for de-correlation of the symbol patterns. One modulator was used for channels 1 and 3, and one modulator was used for channel 2. Three external cavity lasers with linewidths of 100 kHz were used to generate the optical carriers with a channel spacing of 75 GHz. After polarization multiplexing emulation, the even and odd channel signals were amplified, applied to two programmable optical filters with prescribed raised-cosine responses (roll-off factor of 0.6), and then combined.

For the transmission results, a recirculating loop was comprised of four 75 km spans of standard SMF with a dispersion coefficient of 17 ps/km/nm at 1550 nm and an attenuation of 0.19 dB/km. An EDFA and optical band-pass filter (OBPF, 13 nm bandwidth) were used in each span. The received signal was amplified and filtered before detection by a polarization- and phase-diverse coherent receiver with 32 GHz bandwidth. The local oscillator laser had a nominal linewidth of 100 kHz. The four signals from the balanced photodetectors were digitized by 80 GSa/s analog-to-digital converters using two synchronized real-time sampling oscilloscopes (33 GHz bandwidth). The off-line receiver signal processing was the same as in [4]. The BER (direct bit error counting using rectilinear decision boundaries) and MI were evaluated without and with modified LUT-MAP detection.

5. Experimental results

Fig. 1 shows the dependence of the MI and BER on OSNR for the 1.2 Tb/s three-carrier DP 16-QAM superchannel in a back-to-back system without modified LUT-MAP detection. MI results for three different methods of choosing an optimal histogram bin width are compared [6-8]. The MI results illustrate that all three algorithms yield similar results with the approach of Knuth [8] providing slightly larger values. In the results below, the Knuth algorithm is used because it is easily extended to two polarizations.

The dependence of the MI and BER on OSNR is illustrated in Fig. 2 without and with the 7-symbol modified LUT-MAP detector. With the LUT-MAP detector, the required OSNR is 26.6 dB for BER=10^{-3}. The MI is increased by 0.45 bits/symbol (MI is calculated for each polarization and then averaged over both polarizations).

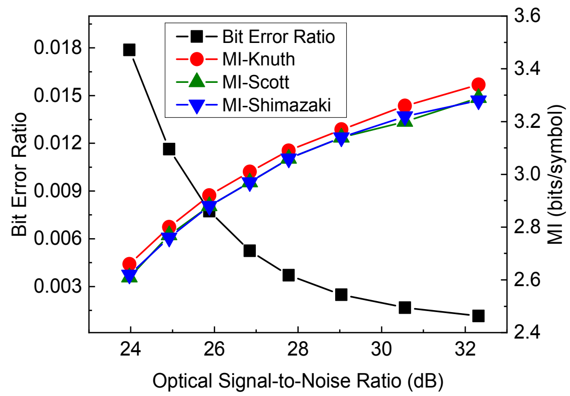


Fig. 1. MI and BER versus OSNR for a back-to-back system without modified LUT-MAP detection.

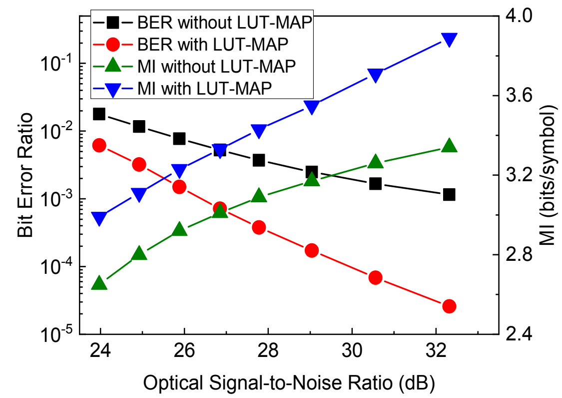


Fig. 2. MI and BER versus OSNR for a back-to-back system without and with 7-symbol modified LUT-MAP detection.

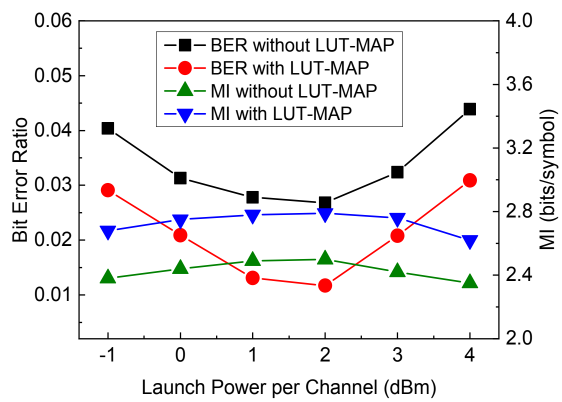


Fig. 3. MI and BER versus launch power for 1.206 Tb/s superchannel and 1500 km fiber without and with 7-symbol modified LUT-MAP detection.

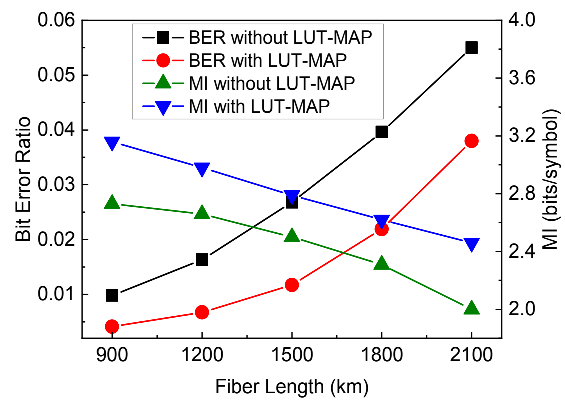


Fig. 4. MI and BER versus fiber length for 1.206 Tb/s superchannel without and with 7-symbol modified LUT-MAP detection.

Fig. 3 illustrates the dependence of the MI and BER on launch power for 1500 km of SMF without and with 7-symbol modified LUT-MAP detection. At the optimum launch power of 2 dBm, the MI is 2.5 and 3.0 bits/symbol without and with MAP detection, respectively. Fig. 4 indicates the dependence of the MI and BER on the fiber length for a launch power of 2 dBm without and with 7-symbol modified LUT-MAP detection. With MAP detection, an increase in the BER from 0.004 to 0.02 corresponds to a decrease in the MI from 3.2 to 2.8 bits/symbol.

6. Conclusion

The performance of 1.206 Tb/s three-carrier DP 16-QAM superchannel has been demonstrated by evaluating MI and BER after using a modified fixed LUT-MAP detector for transmitter-based pattern-dependent distortion. The 7-symbol modified LUT-MAP detector provides an increase in the MI of about 0.45-0.50 bits/symbol per polarization.

References

[1] R. Cigliutti, E. Torrengo, G. Bosco, N. Caponio, A. Carena, V. Curri, P. Poggiolini, Y. Yamamoto, T. Sasaki and F. Forghieri, "Transmission of 9 × 138 Gb/s prefiltered PM-8QAM signals over 4000 km of pure silica-core fiber," J. Lightw. Technol. **29**, 2310–2318 (2011).

[2] J. Renaudier, O. Bertran-Pardo, H. Mardoyan, P. Tran, G. Charlet, S. Bigo, A. Konczykowska, J. Dupuy, F. Jorge, M. Riet and J. Godin, "Spectrally efficient long-haul transmission of 22-Tb/s using 40-Gbaud PDM-16QAM with coherent detection," Conf. Opt. Fiber Commun., 2012, OW4C.2.

[3] G. Raybon, S. Randel, A. Adamiecki, P. J. Winzer, L. Salamanca, R. Urbanke, S. Chandrasekhar, A. Konczykowska, F. Jorge, J. Dupuy, L. L. Buhl, S. Draving, M. Grove and K. Rush, "1-Tb/s dual-carrier 80-Gbaud PDM-16QAM WDM transmission at 5.2 b/s/Hz over 3200 km," IEEE Photon. Conf., 2012, PD1.2.

[4] A. Rezania, Y. Gao and J. C. Cartledge, "1 Tbit/s three-carrier dual polarization 16-QAM superchannel transmission over 1500 km using modified fixed look-up table based MAP detection," Eur. Conf. Opt. Commun., 2014, P.5.25.

[5] T. Fehenberger and N. Hanik, "Mutual information as a figure of merit for optical fiber systems," arXiv:1405.2029v1, 2014.

[6] D. W. Scott, "On optimal and data-based histograms," *Biometrika* **66**, 605-610 (1979).

[7] H. Shimazaki and Shinomoto, "A method for selecting the bin size of a time histogram," *Neural Computation* **19**, 1503-1527 (2007).

[8] K. Knuth, "Optimal data-based binning for histograms," arXiv:physics/06055197v2, 2013.