Optics Communications 359 (2016) 304–310

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Flexible multi-dimensional modulation method for elastic optical networks

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ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form
27 September 2015
Accepted 28 September 2015

Keywords:
Coherent optical communication
Modulation

ABSTRACT

We demonstrate a flexible multi-dimensional modulation method for elastic optical networks. We compare the flexible multi-dimensional modulation formats PM-kSC-mQAM with traditional modulation formats PM-mQAM using numerical simulations in back-to-back and wavelength division multiplexed (WDM) transmission (50 GHz-spaced) scenarios at the same symbol rate of 32 Gbaud. The simulation results show that PM-kSC-QPSK and PM-kSC-16QAM can achieve obvious back-to-back sensitivity gain with respect to PM-QPSK and PM-16QAM at the expense of spectral efficiency reduction. And the WDM transmission simulation results show that PM-2SC-QPSK can achieve 57.5% increase in transmission reach compared to PM-QPSK, and 48.5% increase for PM-2SC-16QAM over PM-16QAM. Furthermore, we also experimentally investigate the back to back performance of PM-2SC-QPSK, PM-4SC-QPSK, PM-2SC-16QAM and PM-3SC-16QAM, and the experimental results agree well with the numerical simulations.

1. Introduction

Currently, elastic optical networks [1] and software defined networks [2] have been touted as solutions for enhanced spectral efficiency and optimized network resource utilization. These architectures require transceivers with tunable modulation format and symbol rate to support tradeoffs among optical reach, bit rate, and spectral efficiency [3]. There exist several approaches to realize flexibility in both reach and bit rate. In principle, reach can simply be traded against spectral efficiency and bit rate by employing polarization division multiplexed m-ary quadrature amplitude modulation (PM-mQAM) with varying size m of the modulation alphabet [4]. However, because available modulation formats such as PM-QPSK and PM-16QAM, are with big difference in terms of spectral efficiency and achievable transmission distance, the resulting options in terms of deployment are insufficient for the flexible systems.

The granularity of this trade-off can be further refined by time domain interleaving of symbols belonging to different sizes m of the modulation alphabet. The resulting modulation formats are referred to as time-domain hybrid QAM [5]. Additionally, rate adaptive forward error correction (FEC) codes can be employed for an extra degree of freedom [6]. In such schemes, the FEC code rate and the size of the modulation alphabet are adjusted to optimally support the desired net bit rate over a requested reach. However, some studies suggest that rate adaptive FEC requires significant additional hardware effort, thus increasing transceiver cost [5]. Another option to achieve a finer granularity is the application of alternative modulation formats in four-dimensional (4D) signal space, which have recently received a lot of attention due to their interesting features. For instance, polarization-switched QPSK (PS-QPSK) was identified as the most power-efficient modulation format [7] in four dimensions and can be derived from PM-QPSK by using Ungerboeck's set-partitioning scheme [8] in four dimensions, where the minimum Euclidean distance between the constellation points is increased by $\sqrt{2} \approx 1.76$ dB after one partition [9,10]. Similarly, another popular four dimensional format 128-SP-QAM can be derived from PM-16QAM by set partitioning, i.e., a subset of $M = 128$ points out of 256 are chosen from the PM-16QAM constellation by increasing the minimum Euclidean distance [11].

In this paper, we present the flexible multi-dimensional modulation method, PM-kSC-mQAM, and then compare with traditional modulation formats PM-mQAM using numerical simulations in both back-to-back and wavelength division multiplexed (WDM) transmission (50 GHz-spaced) scenarios at the same symbol rate of 32 Gbaud. We also experimentally investigate the back to back performance of PM-2SC-QPSK, PM-4SC-QPSK, PM-

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http://dx.doi.org/10.1016/j.optcom.2015.09.098
0030-4018/

2SC-16QAM and PM-3SC-16QAM at the same symbol rate of 32 Gbaud, and the experimental results of sensitivity gain agree well with the numerical results. In conclusion, this multi-dimensional modulation method can be used to make transmission systems flexible with a fine granularity in the trade-off between data throughput and transmission reach.

2. Principle of flexible multi-dimensional modulation method

We use the single parity check code to correlate k consecutive symbols on single polarization, and to realize a multi-dimensional modulation, shown in Fig. 1. We choose square mQAM (m=4, 16, 64, …) as 2-dimensional modulation format, and the bit-symbol mapping rule of mQAM follows Gray mapping. The signal space is expanded to 2 k-dimensional since these k mQAM symbols are related (each mQAM symbol is 2-dimensional). We denote these multi-dimensional modulation formats as kSC-mQAM (SC represents for Symbol Check, and k is the number of related symbols).

The SPC code is an extremely low complexity FEC code. The encoding is done by adding one parity bit to n_{ib} number of information bits, b_1, b_2, …, b_n. The parity bit is encoded as an modulo-2 addition on the n_{ib} information bits such that

$$b_{SPC}=b_1 \oplus b_2 \oplus \cdots \oplus b_{n-1} \oplus b_{n_{ib}} \quad (1)$$

where the symbol $\oplus$ denotes the modulo-2 addition, which is an XOR-operation. In this paper we use square mQAM as the 2D symbol to be related which gives a total number of information bits

$$n_{ib}=\log_2 m \times k - 1 \quad (2)$$

Where k is the number of symbols over which the SPC is applied, the $\log_2 m$ comes from the fact that mQAM carries $\log_2 m$ bits per symbol and the -1 results from the parity check bit.

To decode the SPC, we propose a joint decision algorithm for k consecutive received symbols in each group. As shown in Fig. 2, firstly (i) decode the input k symbols to get n bits ($n = k \log_2 m$ for mQAM), then (ii) make the parity check for these n bits, if the parity is matching, output the front $n-1$ bits as the final decision results; else find the most likely error symbol from the input k symbols (we consider the received symbol which is farthest to the decided constellation as the most likely error symbol), and change the decision of the error symbol to the second closest constellation, then the parity check must succeed since the mapping rule follows Gray mapping (only one bit difference for adjacent constellation).

To compare the kSC-mQAM formats to other modulation formats, we use the spectral efficiency (SE) [12] which defined as

$$SE=\frac{\log_2 M}{N/2}, \quad (3)$$

where N is the number of dimensions and N=2k for coherent kSC-mQAM. As a reference, we note that QPSK has an SE of 2 bit/symbol/polarization. It should be noted that this is a general definition of SE and that in experimental investigations it is more common to give SE in units of bit/s/Hz.

For the kSC-QPSK formats $M = 2^{2k-1}$, it can be shown that the SE for the kSC-QPSK formats can be expressed as

$$SE_{kSC-QPSK}=2 - \frac{1}{k}=SE_{QPSK}\left(1 - \frac{1}{2k}\right), \quad (4)$$

For the kSC-16QAM formats $M = 2^{4k-1}$, it can be shown that the SE for the kSC-16QAM formats can be expressed as

$$SE_{kSC-16QAM}=4 - \frac{1}{k}=SE_{16QAM}\left(1 - \frac{1}{4k}\right). \quad (5)$$

We apply the polarization multiplexing on the kSC-mQAM to get the multi-dimensional modulation formats PM-kSC-mQAM, these formats are compatible with PM-mQAM, since the two orthogonal polarizations are kept independent, and this makes the implementation of PM-kSC-mQAM simpler.

3. Numerical simulations

We have carried out numerical simulations of the performance of PM-kSC-QPSK and PM-kSC-16QAM and compared with traditional PM-QPSK and PM-16QAM, respectively. Both in the back-to-back case and in the transmission simulations, the linewidth of the laser and the frequency offset from the local oscillator (LO) are included.

3.1. Transmitter

The transmitter setup is shown in Fig. 3. We use sequences of 2^{16} bits with random data as the data signals and that are different for each WDM channel. The data signals for each polarization are independently encoded by identical SPC coder. In the case of PM-kSC-QPSK, the SPC coder adds a check bit for each group of 2 $k-1$ input bits. And in the case of PM-kSC-16QAM, the SPC coder adds a check bit for each group of 4 $k-1$ input bits. The symbol mapper transforms the binary signals into multi-level signals (I and Q) for corresponding formats, and the mapping rule follows Gray mapping. The driving signals to the modulator are bandwidth-limited

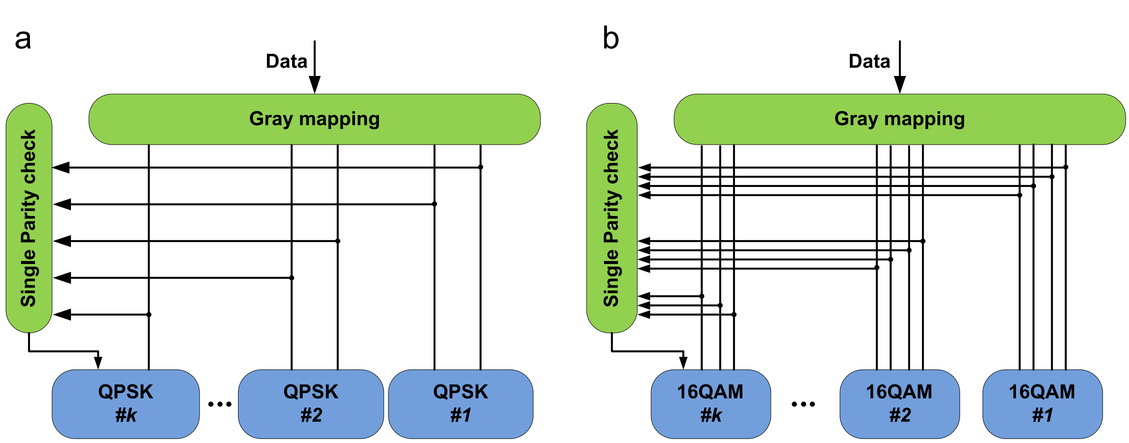

Fig. 1. Illustration of the principle of multi-symbol parity check, (a) kSC-4QAM (kSC-QPSK); (b) kSC-16QAM.