Spectrally-Efficient High-Speed Optical Transmission Technologies

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Abstract

We review and discuss several enabling technologies for recent breakthrough in high-speed and high spectral efficiency optical transmission, focusing on single-carrier based multi-level, multi-dimensional modulation formats and digital signal process based intradyne coherent detection techniques.

Introduction

With the rapid growth of capacity demand on carrier's transport networks, spectrally-efficient modulation and detection technology have become increasingly important due to their potential to reduce cost per transmitted bit by sharing fiber and optical components over more capacity. Among various modulation and detection techniques, single carrier based multi-level, multi-dimensional coding combined with digital signal processing (DSP) based coherent detection has attracted significant attentions in the research community [1-14], enabling record spectral efficiency (SE) and fiber capacity being experimentally demonstrated [10-14].

In this paper we discuss generation and detection of several multi-level and multi-dimensional modulation formats recently demonstrated for high-SE 100-Gb/s transmission. These include 16-ary PDM-QPSK, 64-ary PDM-8PSK, and 64-ary PDM-8QAM. We review the used modulator technologies and DSP algorithms for constellation recovery as well as performance improvement. Several high-SE and large-capacity DWDM transmission experiments have also been summarized in this paper.

Multi-level, Multi-dimensional modulation

With digital coherent detection, 16-ary PDM-QPSK is the optimal 16-ary modulation format because the sixteen symbol values are equally encoded in the four dimensions (with binary modulation at each dimension). At the same bit rate, the noise sensitivity of 16-ary PDM-QPSK is (in theory) identical to binary PSK. PDM-QPSK can be generated by using a $\pi/2$-biased dual-parallel $(0,\pi)$ Mach-Zehnder modulator (MZM). It can also be generated by a common $(0,\pi)$ MZM followed by a $(0, \pi/2)$ phase modulator (PM).

64-ary PDM-8PSK is not the optimal 64-ary modulation format in terms of noise tolerance. It is attractive because, 1) 8-PSK can be easily generated by adding a $(0, \pi/4)$ PM after a QPSK modulator, and 2) 8PSK may have better fiber nonlinear tolerance than other 64-ary modulation formats due to its constant amplitude.

In theory PDM-8QAM can tolerate 1.5 dB more noise than PDM-8PSK [15] because it encodes the signal in all four dimensions of an optical carrier, and is probably the optimal 64-ary modulation format. Generation of an 8-QAM optical signal is not as straight forward as 8PSK because both the phase and the amplitude have to be modulated in a coordinated way. Recently we have proposed and demonstrated a novel synthesizing method for high-speed 8QAM generation by using a $\pi/4$-biased dual-parallel MZM followed by a $(0, \pi/2)$ PM [9]. In Fig. 1 we illustrate the operational principle.

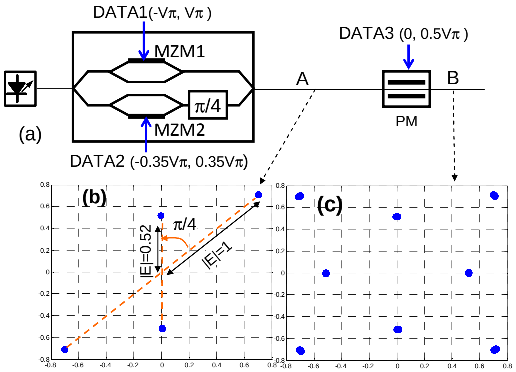

Fig. 1. Illustration of the proposed 8QAM modulator.

Digital Coherent Detection

In Fig. 2 we show an illustration of a digital coherent receiver using single-ended photo detection with the typical DSP functional blocks included. For the DSP part, the two 'fixed' (or slowly adaptable) equalizers (EQ1 in Fig. 2) are used for digital compensation of large amounts of CD for an optical transmission system without using optical dispersion compensation. The four adaptive digital equalizers (EQ2 in Fig. 2) are used for polarization recovery and de-multiplexing, polarization-mode-dispersion (PMD) compensation as well as residual CD compensation. Other linear distortions such as optical filtering effects can also be compensated by this adaptive equalization. Carrier recovery consists of carrier frequency and phase estimation. For different modulation formats, the algorithms used for adaptive equalization and carrier recovery may be different. For example, as a blind equalization algorithm, the classic constant modulus algorithm (CMA) has shown to be highly effective for PDM-QPSK and PDM-8PSK, but is less effective for PDM-8QAM [9].

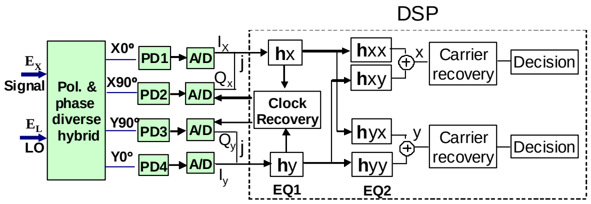

Fig. 2. Illustration of a typical digital coherent receiver using single-ended photo detection, PD: photodetector, EQ: equalizer.

To achieve blind polarization de-multiplexing of PDM-8QAM, recently we proposed a new cascaded multi-modulus algorithm (CMMA). The principle of the proposed new algorithm in terms of the error signal calculation method is illustrated in Fig. 3. As can be found in [9], CMMA can achieve much better signal-to-noise performance than the classic CMA for PDM-8QAM, which does not present constant amplitude.

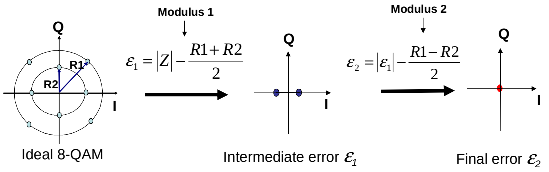

Fig. 3. Illustration of the proposed algorithm for PDM-8QAM signals.

A digital coherent receiver using single-ended photodetection may have a significant cost advantage (compared to balanced detection) but comes with a problem that the direct square-law detection of the modulated signal will cause distortion to the original signal. Such distortion becomes more severe for high-level modulated optical signals [8]. To address this problem, we recently proposed and experimentally verified a novel DSP algorithm which can largely remove this distortion from the original signal [11]. This method has enabled us to demonstrate record SE and fiber capacity using a simpler single-ended coherent receiver front with high-level modulation formats PDM-8PSK [10] and PDM-8QAM [13].

High-SE, large-capacity DWDM Experiments

By using RZ-shaped 16-ary PDM-QPSK modulation format and single-ended digital coherent detection (offline process), we have experimentally demonstrated 25GHz-spaced, hybrid 112 and 44-Gb/s DWDM transmission over 1600km of standard single mode fiber (SSMF) using EDFA-only optical amplification at a SE of 2.8-bit/s/Hz [6]. Further more, by using RZ-shaped 64-ary PDM-8PSK, we successfully demonstrated the first 114Gb/s DWDM transmission over 25GHz DWDM grid, achieving a SE of 4.2-bit/s/Hz, a record spectral efficiency demonstrated at that time [10, 12].

Just recently, we have successfully generated and detected the first 114-Gb/s PDM-8QAM optical signal [9]. By using this more noise tolerant modulation format (with RZ pulse shaping) and the above described CMMA blind polarization de-multiplexing algorithm and distortion mitigation algorithm, we have demonstrated a record of 32-Tb/s (320×114Gb/s) capacity over 580 km of SMF-28 ultra-low loss fiber [13]. For this experiment, we used both C and L-band but we did not use Raman amplification or optical dispersion compensation. In Fig. 4 (a, b) we show the measured optical spectra of the 320-channel signal before and after transmission, respectively. The total launch power is +20 dBm, corresponding to -5 dBm per channel. The measured BERs (an average of both X- and Y-polarization) for all the 320 channels are shown in Fig. 5, where the inset shows the received constellation diagrams at 1539.97 nm, which is among the worst performing channels.

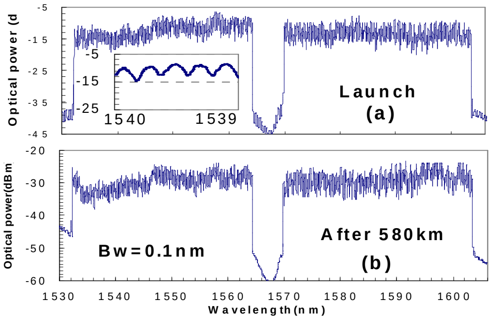

Fig. 4. Monitored optical spectra at 0.1 nm resolution

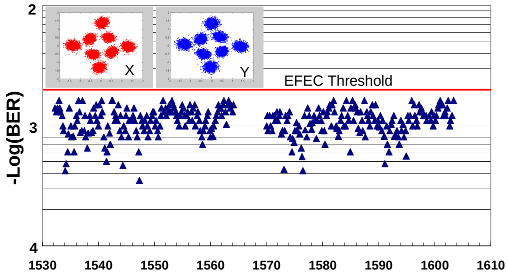

Fig. 5. Measured BER after 580km km transmission. The inset shows the received constellation diagram at 1539.97nmnm.

Conclusions

We show that advanced multi-level and multi-dimensional modulation formats plus DSP-based coherent equalization algorithms can significantly improve the spectral utilization and therefore fiber capacity for our future optical communication system.

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