Advanced Digital Incoherent Multilevel Signaling Techniques

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Abstract: We review recently proposed advanced digital signal processings for ultra-high speed incoherent (direct-detection) multilevel signaling, realizing the use of arbitrary signal constellation, digital compensation of chromatic dispersion and high OSNR senstivity.

1. Introduction

The digital coherent signaling (Ex. [1][2][3]) has been considered as one of the promising candidate for the next-generation high-speed long-distance optical fiber transport links at 40, 100 Gbit/s, or beyond. Another approach is the use of "incoherent detection (direct-detection)" of (differential) phase and amplitude components of optical field by using delay-differential detectors and an intensity detector. The advantage of using incoherent detection lies in its potential simplicity; It doesn't require high-power local lasers nor its frequency tracking mechanism. Also the direct detection is immune to the polarization state of the received signal, therefore, it doesn't need to have polarization multiplexing nor diversity reception. Therefore, smaller, lower cost and less power-consuming multilevel transceivers can be realized. Also it has higher tolerance to signal phase noise, that is, to laser linewidth and fiber non-linear effects.

The configuration of incoherent multilevel receiver can be simplified with the introduction of orthogonally-coupled differential receiver with digital signal processing [4], since it enables the high-resolution detection of signal differential phase ($\Delta\phi(t)=\phi(t)-\phi(t-T)$, T: delay time, ϕ: absolute phase of received symbol). We demonstrate 8DPSK (Differential Phase Shift-Keying) [5] and 32APSK (Amplitude- and Phase-Shift Keying)[4] signaling experiments, where 32APSK is the combined modulation of 8DPSK and QASK(Quaternary Amplitude-Shift Keying). However, previous incoherent multilevel signaling had several drawbacks, originating from the use of delay differential detection: Signal constellation designs are limited to such as n-DPSK and n-APSK with non-ideal signal point distance. Also it has limited receiver-side digital CD compensation capability [6][7]. Each results in poor OSNR sensitivity and limited fiber transmission distance without optical CD compensators, respectively.

In this paper, we introduce some advanced digital signal processing techniques to overcome these problems and realizing highly-sensitive incoherent multilevel signaling enabling the use arbitrary signal constellation like 16QAM with the digital equalization of fiber CD.

2. Direct-detection multilevel transceiver

Figure 1 and 2 show the basic configuration of the experimental incoherent multilevel transmitter and receiver with advanced digital signal processing. The transmitter is an arbitrary optical field modulator, in which an LN-IQ modulator is driven by two high-speed D/A converters generating real and imaginary parts of transmitted fields. The receiver consists of a pair of orthogonally-coupled delay-differential receivers (phase difference 0 and π, output: dI(t) and dQ(t)) [6][13] and an intensity receiver (output: P(t)), all followed by high-speed A/D converters running at the symbol rate of 10 Gsymbol/s. In our experiment, they are emulated by a real time digital oscilloscope and stored sample sequence is used for further off-line digital signal processing. Since the two output signals dI(t) and dQ(t) are the cosine and sine functions of the differential phase $\Delta\phi(t)$, $\Delta\phi(t)$ can be calculated by taking the arctangent of (dI, dQ). Also signal power P(t) is converted to field amplitude r(t) by taking square root of it. Both $\Delta\phi(t)$ and r(t) are used for the detection of received symbols.

2. Principle of signal processing

To overcome the problems of the limited digital CD compensation capability and signal constellation, two transmitter-side signal processing, "CD pre-distortion" and "phase pre-integration" are introduced: The former is the technique to cancel the linear transmission impairment like fiber CD by applying its inverse transmission function on the transmitting field in advance. So far, a 5120-km SMF transmission with 10-Gbit/s binary signal (DPSK) has been reported using it [8].

The latter, "phase pre-integration"[9] is a newly introduced technique enabling the use of almost arbitrary signal constellation in incoherent multilevel signaling, by canceling the receiver-side phase-differential operation. Denoting an original multilevel symbol (I(t),Q(t)) generated at a symbol generator in Fig. 1(a) as $r(t)\exp(j\theta(t))$, the phase pre-integration, that is, "symbol-by-symbol numerical accumulation of symbol phase yields the output $r(n)\exp(j\Sigma\theta(t))$. It becomes co-centric constellation with increased signal points as the inset of Fig.1 of 16QAM case. When such a phase pre-integrated signal is received by the incoherent multilevel receiver in Fig. 2, the output differential phase becomes $\Delta\phi(t)=\Sigma\theta(t)-\Sigma\theta(t-T)=\theta(t)$, that is, the original signal phase, since the phase pre-integration acts as differential pre-coding and cancels out the effect of delay-differential detection. By combining $\theta(t)$ and separately detected field amplitude r(t), original multilevel symbols can be reconstructed.

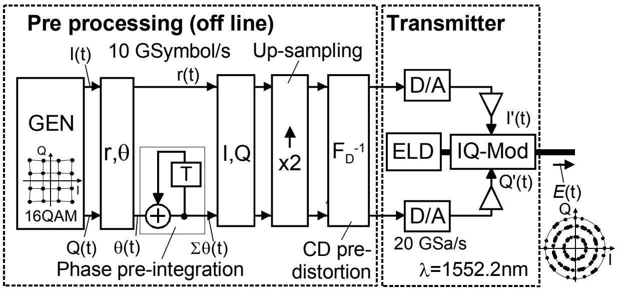

Fig. 1. Schematic configuration of experimental incoherent optical multilevel transmitter with digital signal processing. (GEN: Symbol generator, ELD: External cavity laser diode, IQ-Mod: LN-IQ modulator, (r,q): polar coordinate conversion, (I,Q): Cartesian field conversion) The right-most inset shows the output signal constellation without CD pre-distortion.

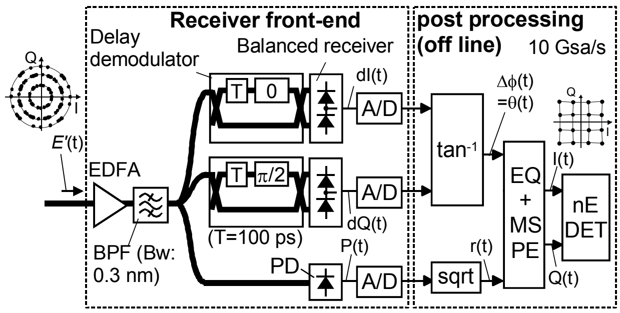

Fig. 2. Schematic configuration of experimental incoherent optical multilevel receiver consisting of orthogonally-coupled differential detectors and intensity detector. (EQ+MSPE: digital adaptive equalizer with MSPE, nE-DET: Symbol detector with non-Euclidean metric)

The other cause of the OSNR sensitivity impairment in the incoherent multilevel signaling is the existence of excess phase noise (or differential detection penalty[10]). To cope with it, we have introduced two signal processing, the symbol detection with non-Euclidean metric and the MSPE as in Fig. 2. The use of non-Euclidean metric is intended to have the best bit error ratio (BER) under non-isotropic noise distribution (excessive phase noise) by widening the decision boundaries into angular direction. We adopted non-Euclidean distance $d_{nE}(x,y)= d_{Euclid}(x,y)+a(|x|-|y|)^2$ with a constant $a>0$, in which radial weight makes the boundaries wider in angular direction.

The multi-symbol phase estimation (MSPE) is the other technique to alleviate the differential detection penalty, by using previous received symbols as additional phase references to average the phase noise out. Optical [11] and electrical [12][13] implementations have been proposed and demonstrated.

4. Experimental results

The feasibility of the proposed techniques is experimentally verified: Figure 3(a) shows the experimentally received and reconstructed signal point distribution of 30-Gbit/s 8QAM signals (back-to-back), in which original eight level signal constellation is clearly observed thanks to the phase pre-integration technique. The decision boundaries with conventional Euclidean (a=0) and non-Euclidean (a=2) metric are also shown in Fig.3(a) and (b), and the latter fits the signal point distribution better and result in the OSNR sensitivity (@BER=10^{-3}) improvement of 1.4 dB. Received and reconstructed 16-QAM signal points with the non-Euclidean decision boundary are also shown in Fig. 3(c), and clearly separated original four by four pattern is obtained. The OSNR sensitivities of 20-Gbit/s DQPSK, 30-Gbit/s 8QAM, 35.8-Gbit/s 12QAM and 40-Gbit/s 16QAM signaling are measured to be 9.5 dB, 13.5 dB, 16.0 and 18.1 dB (NRZ, BER=10^{-3}), respectively, which are within 1 to 2 dB away from those of coherent experiments when converted to the same rate [14].

We have also performed 8QAM, 12QAM, 16QAM transmission experiments [9][15] over 400-km, 240-km and 160-km single-mode fiber (SMF) without using optical CD compensators. As far as we know, these are the sole experimental demonstrations of more than four-level signaling using CD pre-equalization at the highest bit rate (up to 40 Gbit/s).

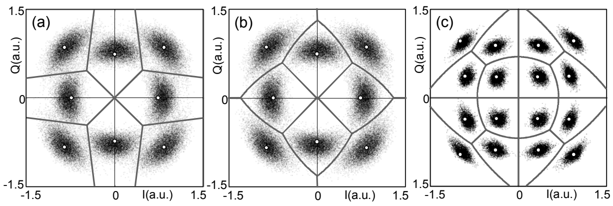

Fig. 3 Experimentally received signal point distribution (dots) and decision boundaries (gray lines) of various incoherent multilevel signaling (back-to-back). (a) 8QAM with Euclidean metric (a=0), (b) 8QAM with non-Euclidean metric (a=2), (c) 16QAM with non-Euclidean metric (a=2).

4. Summary

In this paper, we review recently introduced advanced signal processing for incoherent multilevel signaling, which makes it as the attractive choice for next-generation high-performance optical fiber links.

5. References

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