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Compensation of front-end IQ-mismatch in coherent optical receiver

Sun Hyok Chang *, Hwan Seok Chung, Kwangjoon Kim

Optical Internet Research Department, Electronics and Telecommunications Research Institute, 161 Gajeong-dong, Yuseong-gu, Daejeon 305-700, Republic of Korea

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ABSTRACT

Impacts of in-phase/quadrature-mismatch (IQ-mismatch) in polarization division multiplexed-16 level quadrature amplitude modulation (PDM-16QAM) coherent optical receiver are investigated and the IQ-mismatch compensation by digital signal processing is examined. All the results are compared with those of PDM-quadrature phase shift keying (QPSK) receiver.

1. Introduction

Recently, coherent optical transmission technology has received significant attention from the optical communication community, as a future-proof technology in the field of high speed long-haul optical transmission. Digital signal processing in coherent optical receiver is a very powerful tool to mitigate optical impairments of chromatic dispersion and polarization mode dispersion (PMD) in transmission fiber [1–4]. Among various modulation formats, polarization division multiplexed quadrature phase shifted keying (PDM-QPSK) is regarded as the most favorable solution to realize 112-Gb/s long-haul DWDM transmission on a 50 GHz channel grid. Meanwhile, higher multi-level modulation formats have been studied to achieve higher spectral efficiency (SE). PDM-16 level quadrature amplitude modulation (PDM-16QAM) is a promising candidate in that it doubles SE compared to PDM-QPSK [5,6].

In a coherent optical receiver, phase-diversity is provided by introducing a 90° optical hybrid in front of photo-detectors. The role of the optical hybrid is providing in-phase (I) and quadrature (Q) signals which have phase difference of 90°. The imperfection of the optical hybrid may cause IQ-amplitude mismatch and/or IQ-phase mismatch. The IQ-amplitude mismatch can be compensated by adjusting the gain of variable gain amplifier (VGA) in front of analog-to-digital converter (ADC). However, the IQ-phase mismatch is hard to detect and could be compensated by digital signal processing.

We have recently investigated the impacts of the IQ-mismatch and demonstrated the compensation method in coherent optical receivers [7,8]. In this paper, we will study the impacts of the IQ-mismatch and the effects of the compensation method in coherent optical PDM-16QAM receiver, and the results will be compared with those of PDM-QPSK modulation.

2. Analysis set-up

In order to evaluate the impacts of the IQ-mismatch in coherent optical receiver, the modulation scheme shown in Fig. 1 was adopted. A 56-Gb/s 16QAM signal was generated by superimposing two QPSK signals, which were produced by upper two IQ-modulators with 6-dB attenuation in front of one of the IQ-modulators. An IQ-modulator is made of two parallel Mach–Zehnder interferometers. Each IQ-modulator was driven by 14-Gb/s pseudo-random binary sequence (PRBS) signal separately and each driving signals had a relative multiple-bit decorrelation delay. In order to generate 112-Gb/s PDM-16QAM signal, the polarization of 16QAM signal produced by lower two IQ-modulators was converted and then combined with the other 16QAM signal at polarization beam combiner (PBC). In Fig. 1b, two 56-Gb/s QPSK signals were generated by each IQ-modulator and they were polarization-multiplexed to form 112-Gb/s PDM-QPSK signal. In this case, each IQ-modulator was driven by 28-Gb/s PRBS signal.

Before entering the receiver, the polarization of the signal was rotated to make an arbitrary polarization orientation. Polarization-diversity coherent receiver is shown in Fig. 2. The input signal is mixed with a local oscillator (LO) laser in polarization-diversity optical hybrid. Each polarization component of the signal is mixed with corresponding polarization component of LO. For the simulation, VPI TransmissionMaker was used with sample rate of 448 GSample/s. The samples were down-sampled to two samples per one symbol, i.e., 28 GSample/s for PDM-16QAM and 56 GSample/s for PDM-QPSK, at the ADCs shown in Fig. 2. After obtaining

* Corresponding author. Fax: +82 42 860 5213.
E-mail address: shchang@etri.re.kr (S.H. Chang).

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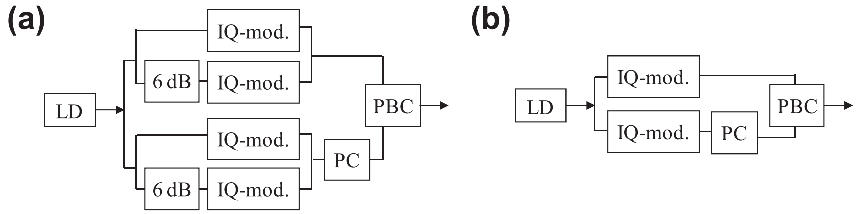

Fig. 1. Block diagrams of optical transmitters for (a) PDM-16QAM and (b) PDM-QPSK. LD: laser diode, 6 dB: 6 dB attenuation, PC: polarization converter, PBC: polarization beam combiner.

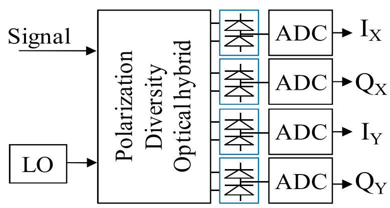

Fig. 2. Block diagram of coherent receiver. LO: local oscillator laser, ADC: analog-to-digital converter.

the four sample sequences, digital signal processing was done off-line by Matlab. Measured block size corresponded to ~65,000 symbols for PDM-16QAM and ~130,000 symbols for PDM-QPSK (~0.5 million bits for both cases). The number of samples was limited by the performance of the simulator.

3. Digital signal processing

Fig. 3 shows the block diagram of the digital signal processing used in the coherent optical receiver. The four signal streams of I_X, Q_X, I_Y, and Q_Y are digitally sampled sequences. In the Res. blocks shown in Fig. 3, the sample streams are resampled to simulate the effects of the ADC bit resolution. In-phase and quadrature parts (I and Q) of the sample sequences are combined to be complex numbers. In the block of IQ-mismatch compensation, Gram–Schmidt orthogonalization procedure (GSOP) was applied [7,8]. The GSOP transforms a set of non-orthogonal samples into a set of orthonormal samples by calculating correlation parameter between I and Q signals. The effects of the IQ-mismatch compensation will be shown in the next section.

In the DSP block of dispersion compensation, a finite impulse response (FIR) filter compensated the dispersion of transmission fiber. The FIR filter coefficients were easily calculated because the response function of the chromatic dispersion in the transmission fiber could be analytically obtained [9]. Subsequently, adaptive filters of H_{XX}, H_{XY}, H_{YX}, and H_{YY} were used to realize polarization separation and residual equalization of the signals. Each filter was implemented as a FIR filter with five taps. The number of taps

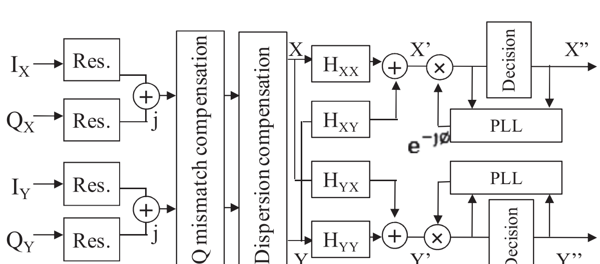

Fig. 3. Block diagram of the digital signal processing used within the coherent optical receiver. Res.: bit resolution of ADC, PLL: phase-locked loop.

can be increased to improve the differential group delay (DGD) tolerance of the receiver.

These filters were initially adapted with the well-proven constant modulus algorithm (CMA), which minimized the errors $\varepsilon_X = R^2 - |X'|^2$ and $\varepsilon_Y = R^2 - |Y'|^2$. $R = 3.633$ for 16QAM and $R = 1.414$ for QPSK were used in the calculation. Once the CMA converged, the received signals were roughly decomposed into its two polarizations. In order to mitigate the phase noise, carrier phase was estimated by the decision-directed phase-locked loop (PLL) as shown in Fig. 3. A loop filter was designed to be a proportional and integral structure, and implemented as a running average over the phase difference between pre-decision and post-decision signal samples [10]. X' and Y' were multiplied by the output of the PLL so as to stabilize the constellation at the designated position. The decisions X'' and Y'' were based on the standard rectilinear grid of QAM decision boundaries.

After an initial carrier phase was estimated, the adaptive filters were moved into a decision-directed mode. Phase-independent error signals, $\varepsilon_{X,DD} = |X''|^2 - |X'|^2$ and $\varepsilon_{Y,DD} = |Y''|^2 - |Y'|^2$ were used with the similar filter coefficients update algorithm as the CMA [2,9]. The filter adaptation was accompanied with the decision-directed PLL. The decisions were decoded to bit sequences, and bit error rate (BER) was measured.

4. Analysis results

Amplified spontaneous emission (ASE) noise was added to adjust the optical signal to noise ratio (OSNR) of the received signal. Before entering the receiver, the signal was optically filtered by a 2nd-order Gaussian filter. In order to evaluate the impacts of IQ-mismatch, the phase difference between I and Q signals in the optical hybrid was varied. We assumed the same IQ-phase mismatch for both polarizations in the polarization-diversity optical hybrid.

Fig. 4 shows the BER measurements with various OSNR. Each symbol represents the result when the IQ-phase mismatch was varied from 0° to 20°. Fig. 4a shows the results in PDM-16QAM, where detrimental impacts by the IQ-mismatch are evident. The effects of IQ- PDM-QPSK are shown in Fig. 4b. In each case, the linewidth of laser was 10 kHz and the ADC resolution was ideal.

The GSOP explained in Section 3 dramatically remedied the degradation by the IQ-mismatch. Fig. 5 shows the constellations of the received signals when the IQ-phase mismatch of optical hybrid was 15°. The deformation of the constellation of PDM-16QAM and PDM-QPSK left virtually no trace after the compensation by GSOP.

Fig. 6 shows the OSNR penalty at the BER of 10^{-3}. Modulation format was PDM-16QAM in Fig. 6a and PDM-QPSK in Fig. 6b. With ideal resolution of ADC, the OSNR penalty was increased up to 4.3 dB by the IQ-phase mismatch of 15°. The OSNR penalty was decreased to nearly zero by applying the GSOP. Because ADC has a limited resolution in real situation, ADC bit resolution was varied in the simulation. The results with ADC resolution of six bits are also shown in Fig. 6a. The OSNR penalty was decreased from 8.6 dB to 3.1 dB by the GSOP at the IQ-mismatch of 15°, though