Real-time MIMO Adaptive Equalization with Carrier-phase Recovery for Mode-division Multiplexed Optical Coherent System

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Abstract: We review our designed and implemented real-time MIMO adaptive equalization with carrier-phase recovery and frequency offset, which has been introduced to real-time mode-division multiplexed transmission experiments.

1. Introduction

Mode-division multiplexed (MDM) technique in few-mode fibers is a candidate to overcome limitation of transmission capacity in standard single-mode fibers (SSMFs) [1]. In the MDM systems, mode coupling during MDM transmission is not avoidable, causing linear crosstalk between the MDM channels. To compensate the mode crosstalk, multiple-input multiple-output (MIMO) equalization with adaptive control is indispensable. Recently, a 55×MDM transmission experiment has been reported using 110×110 MIMO equalization [2]. By a joint of the MDM technique with multicore fibers (MCFs), 10-Pbit/s-class transmission capacity has been achieved [3,4].

In the most MDM transmission experiments reported so far, large-size MIMO equalization has been performed offline. Increasing not only the number of modes but also the tap length of MIMO equalization, the adaptive control of MIMO equalization becomes more difficult to achieve stable operation. We come up with a question if real-time implementation of MIMO adaptive equalization for MDM systems would be achievable. Before development of application specific integrated circuit (ASIC), it is cost effective to confirm the feasibility of the real-time digital signal processing (DSP) implementation using field programmable gate array (FPGA) circuits.

The real-time DSP is also required to evaluate statistical characteristics in the MDM systems [5]. The bit error rate (BER) performance is strongly determined from mode dependent loss (MDL), which is temporally and statistically fluctuated. To investigate the statistical BER characteristics, transmission experiments using offline DSP are not enough. The real-time DSP is effective to characterize the statistical BER performance.

We have reported some demonstrations of the real-time MDM transmission using real-time DSP implemented on FPGA. In this paper, we discuss the real-time MIMO adaptive equalization with carrier-phase recovery (CPR) and frequency offset compensation (FOC) required for the MDM transmission systems. We review real-time DSP in conventional single-mode coherent receivers for dual-polarization (DP) high-order quadrature amplitude modulation (QAM) optical signals. Improving the concept for MDM application, we design and implement real-time DSP based on FPGA possible to decode four-mode-multiplexed DP-16QAM optical signals.

2. Real-time MIMO adaptive equalization with carrier phase recovery

We start real-time DSP for the single-mode DP-QAM optical signals [6,7]. Figure 1(a) shows the configuration of MIMO equalization with CPR and FOC, where we neglect the other DSP parts. For high-order QAM optical signals, the MIMO adaptive control becomes unstable owing to its small tolerance against phase noise and frequency offset. To achieve the highly-reliable decoding operation, we usually introduce the coarse CPR and FOC based on pilot symbols before MIMO equalization [8,9]. Known pilot symbols are transmitted with information symbols, and they are used for CPR and FOC in the receiver, resulting in the stable operation of the adaptive control in the following MIMO. After the MIMO equalization, fine CPR is usually performed [6,7].

In the optical transmission systems, the bitrate of the optical signal is usually larger than ten times the clock rate of the real-time DSP, requiring deserialization in the real-time implementation. Even with the deserialization, the feedforward control is possible to process sequentially by dividing the serial sample sequences into multiple serial blocks. On the other hand, the symbol-by-symbol MIMO equalization is not possible because the adaptive control is based on the feedback configuration. Therefore, the parallel configuration is required for the MIMO adaptive equalization. In Fig. 1(a), we show configuration of feedforward-based CPR and FOC, and MIMO adaptive equalization based on parallel configuration. We need deserialization with the degree $P_{SC} = 2f_{SC}/f_{clock}$, where f_{SC} is the signal baudrate and f_{clock} is the DSP clock rate.

For the MDM systems, the critical issue is remarkably-huge differential mode delay (DMD) in few-mode fibers. Even with coupled-core MCFs, the DMD becomes larger than hundreds of polarization mode dispersion (PMD) in SSMFs. To compensate for the large DMD, long taps in MIMO equalization are required. Subcarrier modulation

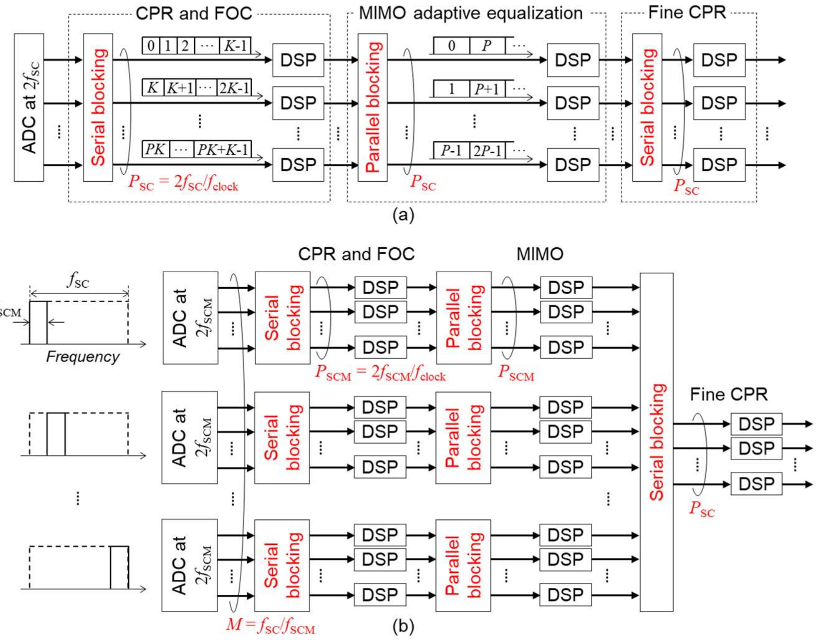

Fig. 1. Deserialization of real-time MIMO with CPR and FOC for (a) single-carrier and (b) subcarrier-modulation cases.

(SCM) technique can reduce the MIMO tap size in proportion to the subcarrier number [10], and it seems effective to reduce the resources of real-time implementation. Figure 1(b) shows the configuration of real-time DSP for the SCM case. Compared with the single-carrier (SC) case shown in Fig. 1(a), the SCM case requires the parallelization for SCM with the degree of $M = f_{SC}/f_{SCM}$, where f_{SCM} is the subcarrier baudrate. For each subcarrier, the deserialization degree is given by $P_{SCM} = 2f_{SCM}/f_{clock}$. Although the SCM case can reduce the tap size in each branch of the parallel MIMO, it increases the deserialization degree by M. The resources of the MIMO implementation are the same in the SC and SCM cases.

Note that the small tap size is very effective for stable operation in the adaptive control of the MIMO taps. With DMD over 10 ps/km$^{1/2}$, the required tap size becomes more than 100 after 1,000-km transmission of 50-Gbaud optical signals. The adaptive control for such long taps is too difficult to operate stably. For the SCM case, the tap size can be maintained to be less than 50 for each subcarrier at several-Giga baud, and it is comparable to the tap size in conventional single-mode coherent receivers.

3. Our designed and implemented real-time DSP based on FPGA

For the CPR and FOC before the MIMO equalization, temporal pilot symbols are widely introduced for the receiver DSP to decode single-mode high-order QAM optical signals [8,9]. Before the MIMO equalization, we require to compensate polarization rotation on temporal pilot symbols. Although the maximum ratio combining would be effective for the small PMD in SSMFs, it is not applicable to compensate for mode coupling with large DMD in the MDM systems.

We have proposed a pilot-tone method for high-resolution FOC before MIMO equalization [11]. The pilot tone outside the signal bandwidth is transmitted, and the frequency of the pilot tone is detected in the receiver, compensating for the frequency offset. The maximum ratio combining is effective for the pilot tone even with large DMD. To achieve the stable operation of the following MIMO adaptive equalization, we require the frequency resolution of more than 10^5. Although a block size of more than 10^5 in fast Fourier transform (FFT) is required, it is not practical for real-time implementation. Our proposed method is based on dual-stage FFT (Fig. 2). In the first stage, the frequency offset is coarsely compensated using FFT with moderate block size. The second FOC is achieved by down-sampling and FFT with small block size. Even with the small-size FFT, the frequency resolution can be improved by down-sampling. The sub-100-kHz frequency resolution is achievable for 2-Gbaud subcarriers, and it is sufficient for stable operation in the following MIMO adaptive equalization. The measured spectra of the pilot tone in the first and second stages are shown in Fig. 3. Although the frequency resolution is limited in the first stage, sub-100-kHz resolution in the second stage can be achieved.

The operation stability in MIMO adaptive equalization strongly depends on phase noise and frequency offset. Although the radius-directed algorithm is effective for stable operation because of its phase insensitivity, the singular

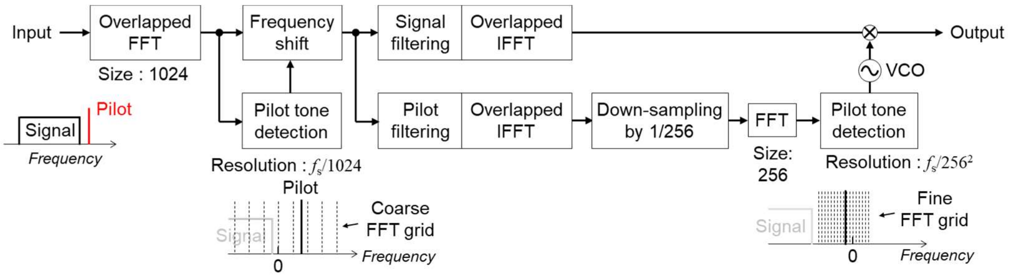

Fig. 2. Dual-stage FOC based on the pilot tone.

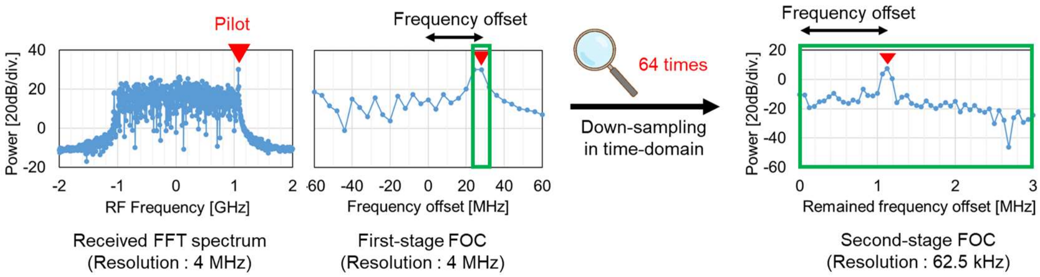

Fig. 3. Measured spectra of the pilot tone using the our FOC implemented on FPGA [11].

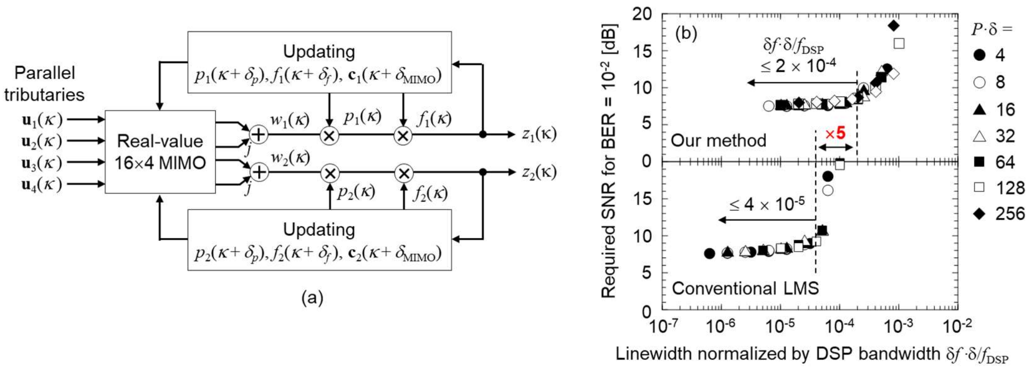

Fig. 4. (a) Configuration of joint adaptive control of MIMO and CPR/FOC. (b) Dependence of calculated required SNR on laser linewidth normalized by DSP bandwidth.

problem becomes seriously critical to increase the number of the modes [12]. To avoid the singular problem, training-aided least mean square (LMS) algorithm is effective, but it is too phase-sensitive to track large phase noise in optical coherent reception. For the stable operation, the joint adaptive control of MIMO and CPR has been proposed [13]. The configuration is shown in Fig. 4(a). The one-tap-based CPR and FOC follow the MIMO equalization, and the tap coefficients are adaptively and simultaneously controlled. The calculated signal-to-noise ratio (SNR) required for the BER of 10^{-2} is shown in Fig. 4(b). The horizontal axis indicates the laser linewidth normalized by the DSP bandwidth, which is defined by the parallel degree and delay. By the joint adaptive control of MIMO and CPR/FOC, the phase tracking performance is improved by around five times compared with the conventional LMS algorithm.

4. Summary

We reviewed real-time MIMO adaptive equalization with CPR and FOC designed for the MDM transmission systems. Using our implemented real-time DSP with MIMO adaptive equalization and high-resolution FOC, we have demonstrated four-mode-multiplexed QPSK transmission experiment over 7,000-km coupled-core MCFs [14] and four-mode multiplexed 16QAM decoding after 60-km transmission [11].

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