Experimental demonstration of adaptive frequency-domain equalization for mode-division multiplexed transmission

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Abstract: We experimentally demonstrate adaptive frequency-domain equalization with low algorithmic complexity for a 6×6 coherent MIMO transmission system in a few-mode fiber. Master-slave carrier recovery is also proposed and demonstrated for further reduction of algorithmic complexity.
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1. Introduction

Recently, mode-division multiplexed transmission (MDM) in few-mode fibers (FMF) has gained attraction due to its potential to achieve ultra-high capacity beyond the nonlinear Shannon limit of the single-mode fiber. In an MDM system, differential mode group delay (DMGD) and mode coupling can severely degrade system performance. To mitigate these impairments, multiple-input-multiple-output (MIMO) equalizers are required. To date, most single-carrier MDM transmission experiments have used time-domain equalizers (TDE) adapted using the data-aided least mean square (DA-LMS) algorithm [1,2]. In the moderate mode coupling regime, algorithmic complexity per bit grows linearly with the number of modes and with total link DMGD. To make MIMO decoding complexity feasible, the equalizer must be made more efficient. Recently, we proposed using a frequency-domain equalizer (FDE) for the MIMO equalizer [3]. Due to the computational advantage of the fast Fourier transform (FFT) which scales logarithmically with FFT size, the complexity of an FDE grows much more slowly than a TDE [4]. In this paper, we demonstrate FDE experimentally for 6×6 MIMO transmission over 50km of FMF. The complexity of our FDE is only 11.8% of a conventional TDE while achieving similar BER performance. For long haul MDM transmission, FDE can potentially reduce the algorithmic complexity by 2 orders of magnitude compared to TDE.

In the proposed FDE, frequency offset compensation and carrier phase recovery are performed similarly as for a TDE using the DA-LMS algorithm [2]. We first estimate carrier phase independently for each received signal mode. The resulting phase estimates are strongly correlated due to the underlying phase noise process coming from the same transmitter laser and local oscillator (LO) sources. We exploit this correlation by estimating frequency offset and carrier phase only once for a "master" mode channel; the estimated frequency offset and carrier phase is then shared with other mode channels (slaves). The digital signal processing (DSP) architecture for MIMO equalization with master-slave carrier recovery (MS-CR) is shown in Fig. 1. MS-CR consists of two stages. The first stage uses the equalized symbols in the master mode channel to compute a carrier phase estimate. The second stage uses this estimate and de-rotates all the mode channels. MS-CR reduces the complexity of carrier recovery by the total number of modes. This complexity-reduction technique was first proposed for multi-core fiber (MCF) transmission [5]. We adopt the same concept for FMF transmission with MIMO equalization. Our experiment results verify that MS-CR can reduce algorithmic complexity with negligible performance penalty.

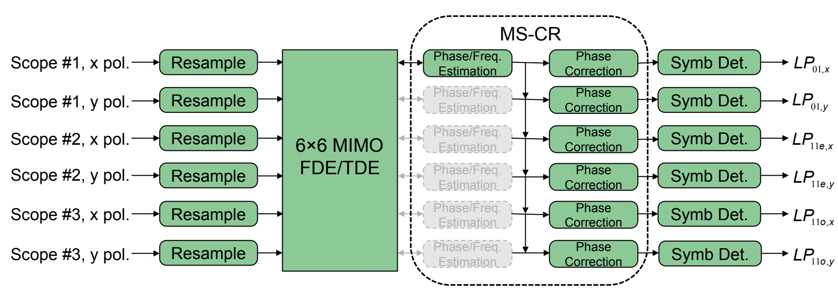

Fig. 1 DSP architecture using master-slave carrier recovery scheme.

2. Experimental Setup

The experimental setup is shown in Fig. 2. At the transmitter, an external cavity laser at 1550.12 nm with a linewidth of 100 kHz is modulated by QPSK symbols at 28 Gbaud using a Mach Zehnder I/Q modulator. The I and

Q symbols are chosen from pseudorandom binary sequences (PRBS) of duration $2^{31}-1$. Polarization-division multiplexing is performed by splitting the signal into two paths, delaying one path by 405 symbols, and re-combining the two de-correlated signals with a polarization beam splitter (PBS). After amplification, the signal is split into three tributaries with relative delays of 0, 1365 and 2272 symbols. The de-correlated signals are modulated onto the three orthogonal spatial modes (LP_{01}, LP_{11e}, and LP_{11o}) of a 50 km span of FMF using a free space mode multiplexer (M-MUX). Details of the M-MUX can be found in [1]. At the output of the FMF, a mode de-multiplexer (M-DEMUX) identical to the M-MUX is used to recover the signal's three spatial mode components on three parallel single-mode fibers. Following amplification by single-mode EDFAs, the recovered mode components are detected in three parallel coherent receivers where the signals are mixed with a common LO in polarization-and-phase diversity hybrids followed by photo-detectors. The baseband electrical signals are then sampled and digitized using three synchronized sampling oscilloscopes with sampling rates of 40 GSa/s and 16 GHz bandwidth. The output symbols are recovered by offline processing.

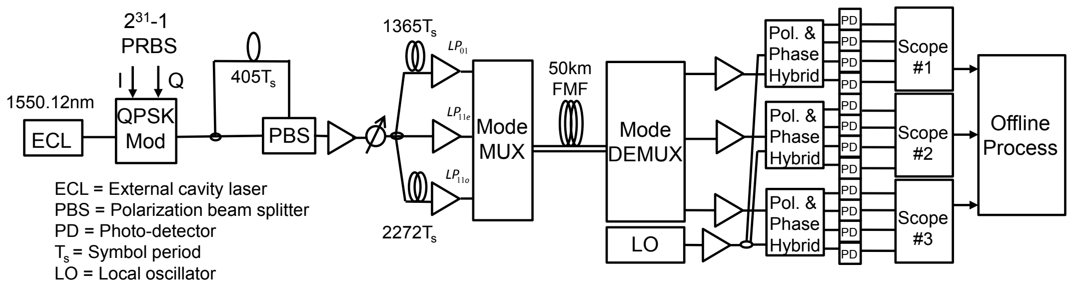

Fig. 2 Experimental setup.

3. Experimental results

To evaluate the proposed FDE, we captured data sets at received optical signal-to-noise ratios (OSNR) ranging from 14.5 dB to 23.5 dB, and processed these offline using the FDE and TDE approaches. The receiver DSP structure is shown in Fig. 1. We digitally re-sampled the captured signals to 2× baud rate and recover the signal constellations in the six spatial/polarization modes using a 6×6 MIMO equalizer. To adapt the FDE or TDE and to estimate frequency offset, a training sequence of 30,000 symbols is used. After initial convergence, we switch to decision-directed (DD) adaptation. A total of 490,000 symbols per spatial/polarization mode are evaluated to estimate bit error ratio (BER). For fair comparison between the TDE and FDE, we use the same equalizer length, initialize their coefficients with the same tap values, and train their coefficients using the same step size. The DMGD of the FMF is 63 ps/km. The total link DMGD of 3.15 ns corresponds to 88 symbols. An equalizer length of 256 per MIMO tributary was chosen, corresponding to a memory length of 128 symbols. This is sufficient to undo the channel's DMGD, but is shorter than the minimum de-correlation delay between the six spatial/polarization modes to avoid spurious convergence. The equalizer length was chosen to be an integer power of two to facilitate efficient FFT implementation. The FDE was implemented using the overlap-and-save method with an overlap of 128 samples (half the FFT size).

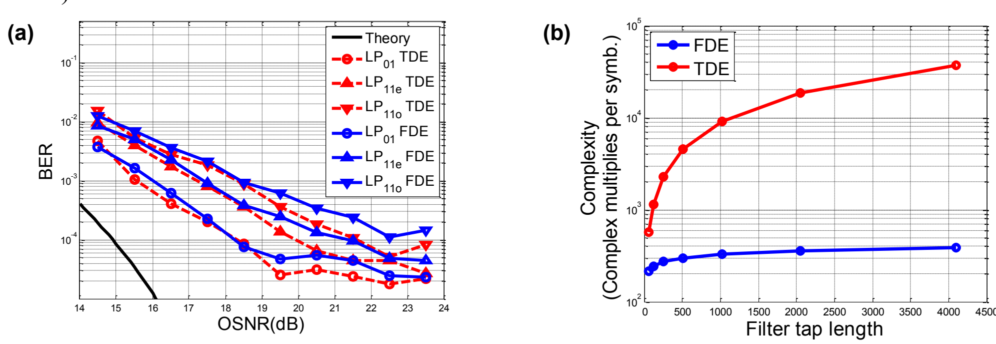

Fig.3 (a) BER vs. OSNR; (b) Complexity as a function of filter tap length.

Fig. 3(a) shows BER vs. OSNR using both the TDE and FDE. The BER shown for each spatial mode is the average of the two orthogonal polarizations. Independent phase estimation is performed on each spatial/polarization mode for both FDE and TDE. We observe similar BER performance for both FDE and TDE. Fig. 3(b) compares the algorithmic complexity of the FDE and TDE in complex multiplications per symbol as a function equalizer length, computed using formulae derived in [3]. At an equalizer length of 256, the FDE approach reduces algorithmic complexity by a factor of 8.5 compared with the TDE. The computational savings become even larger at longer distances and larger DMDG, due to the computational advantage of the FFT at longer filter lengths.

We also investigated the performance of the FDE as a function of the length of the training sequence. Fig. 4(a) shows Q^2 factor vs. training length at an OSNR of 23.5 dB. A minimum of 5,000 training symbols are required to obtain initial convergence. The recovered constellations at a training length of 30,000 are shown in Fig. 4(b).

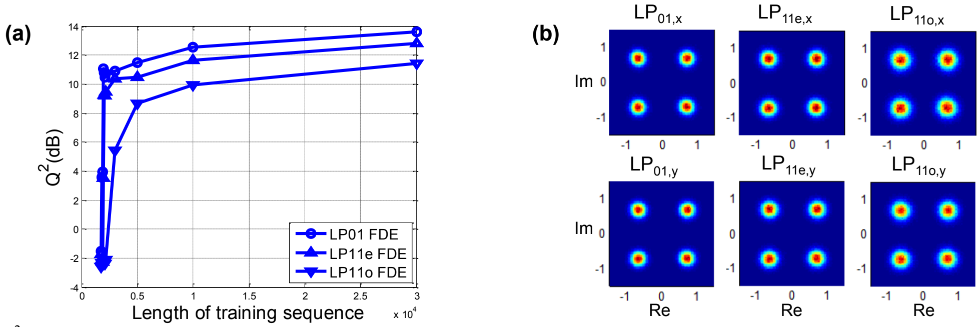

Fig. 4. (a) Q^2 factor vs. training sequence length when using the FDE; (b) recovered signal constellations at a training length of 30,000.

Thus far, we have performed independent frequency offset compensation and carrier phase recovery on each mode. During training, carrier phase is roughly estimated by comparing the phase of the equalizer output with the training symbols; during DD adaptation, the Viterbi-Viterbi algorithm is used. The one-shot phase estimates are then averaged over a window of length 64 to obtain a more accurate estimate of the carrier phase at that symbol. The carrier phases estimated for the six modes are shown in Fig. 5(a), confirming strong correlation as they differ only due to DMGD [6] and noises in the receiver's EDFAs. Therefore, the carrier phase estimated in one mode can be used to de-rotate the equalized symbols in the other modes. Fig. 5(b) compares the BER performances of MS-CR versus conventional CR. For the MS-CR scheme, we select $LP_{01,x}$ as the master channel as we assume the fundamental mode has the lowest BER enabling the most accurate phase estimation. The MS-CR scheme achieved similar BER as conventional CR. Small penalties are observed for LP_{11e} and LP_{11o} due to error between the actual and estimated carrier phases arising from tracking error and receiver noise.

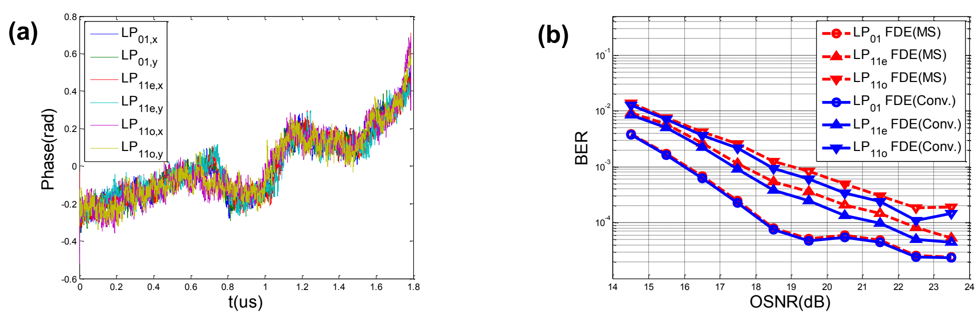

Fig. 5 (a) Phases independently estimated from six spatial channels; (b) BER vs. OSNR compared between MS-CR and conventional CR.

4. Conclusion

We experimentally demonstrated adaptive frequency-domain equalization with low algorithmic complexity for 6×6 coherent MIMO transmission over 50-km of few-mode fiber. For long haul MDM transmission, FDE can potentially reduce the algorithmic complexity by 2 orders of magnitude compared to TDE. We showed that master-slave carrier recovery can be used for further reduction of algorithmic complexity, with negligible performance penalty compared with conventional carrier recovery.

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