Real-time 6-Mode 19-Core Fiber Transmission

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Abstract: We demonstrate the real-time few-mode multicore fiber transmission for the first time. The C- and L-band WDM DP-QPSK signals transmitted over an 11-km 6-mode 19-core fiber were demodulated in real-time by an FPGA-based MIMO DSP. © 2023 The Author(s)

1. Introduction

Space division multiplexing using few-mode fibers and multicore fibers is a promising technology to increase the transmission capacity beyond that of single-mode fibers [1]. Few-mode multicore fibers (FM-MCFs) [2-4] are a hybrid approach of few-mode fibers and multicore fibers, which enables a spatial multiplicity over 100 [3,4]. Recently, 10 Pb/s transmissions were reported using 6-mode 19-core [3] and 3-mode 38-core [4] fibers with C- and L-band wavelength division multiplexed (WDM) signals. However, multiple-input multiple-output digital signal processing (MIMO-DSP) to suppress modal crosstalk was performed offline.

Real-time MIMO DSPs are indispensable for the practical deployment of mode-division multiplexed transmission systems. We have reported a real-time 4-mode transmission over coupled 4-core fibers using a field programmable gate array (FPGA) based MIMO DSP for intra-dyne detection by employing digital carrier frequency offset and phase compensators [5]. In recent years, a real-time 7-mode MIMO transmission over coupled 7-core fibers was reported [6], although the receiver was based on delayed self-homo-dyne detection. In the reported real-time few-mode MIMO transmission experiments, the spatial multiplicity has been less than 10. To achieve a spatial multiplicity of 100 or more, real-time FM-MCF MIMO transmissions are essential.

In this work, we implement a real-time 6-mode MIMO DSP and demonstrate a real-time FM-MCF transmission for the first time. The C- and L-band WDM dual polarization (DP-) QPSK signals were transmitted over an 11-km 6-mode 19-core fiber (6M-19CF) with the spatial multiplicity of 114 (= 6 modes × 19 cores) and demodulated in real time. Bit error rates (BERs) below an assumed forward error correction (FEC) threshold were achieved. The feasibility of real-time FM-MCF transmission systems is confirmed.

2. Implemented 6-mode real-time MIMO DSP

Figure 1 shows the configuration of the real-time 6-mode MIMO DSP using FPGA evaluation boards. As the input signals, we assume electrical 2.048-GBd. QPSK signals with pilot tones after intra-dyne detection, which suffers from modal crosstalk occurred in a 6-mode fiber. First, the signals were sampled by 4-channel 4.096 GSa/s analogue-to-digital converters (ADCs) with 12-bit resolution embedded on Xilinx ZCU111 evaluation boards. After front end corrections, the waveforms were sent to the 1st-stage FPGAs (Xilinx VCU128 evaluation boards) by 100-Gb/s optical transceivers. In the 1st-stage FPGA, a pilot-tone-based two-stage frequency offset estimation (FOE) [7] was performed to compensate for the frequency offset with the frequency resolution of 62.5 kHz. After compressing the bit resolution from 12 to 10 bits, we sent the waveforms of all spatial modes to the 2nd-stage FPGA for MIMO equalization. The FPGA board mounted Xilinx Virtex Ultrascale+ VU13P. The number of DSP slices was 12,288. Here, the required receiver bandwidth of the 2nd-stage FPGA is proportional to the number of spatial modes [8]. To handle 6 spatial modes with dual polarizations, we constructed a 1.2-Tb/s optical link using 12 100-Gb/s optical transceivers. The speed was twice that of our previous FPGA board for 4-mode MIMO [5]. After the timing synchronization with a training sequence, the waveforms were equalized by real-value adaptive 24×4 MIMO T/2-spaced finite impulse response (FIR) filters operated with an FPGA clock frequency of 128 MHz. The parallelization degree was 16. The number of FIR taps was 27. The FIR taps were updated by the training-aided least mean square (LMS) algorithm and subsequently switched to the decision-directed mode. A desired spatial mode at a parallel tributary was extracted by selecting the training sequence. The feedback-based carrier phase and frequency recovery were integrated within the MIMO equalization loop [5,9]. After the MIMO equalization, the BER averaged over polarizations was measured. All spatial modes were successively demodulated by switching the training sequence for each spatial mode in the training-aided LMS algorithm.

3. Real-time 6M-19CF transmission

The experimental setup for real-time MIMO 6M-19CF transmission is shown in Fig. 2. The 12.5-GHz-spaced 16-WDM 5-subcarrier multiplexed 2.048-GBd QPSK signals with frequency pilot tones were generated with an even and odd decorrelation method. The wavelengths of the center channels were 1549 and 1592 nm for the C- and L-band WDM signals, respectively. The pilot tones were used for FOE in the real-time MIMO DSP. The subcarrier multiplexing technique was used to reduce the required sampling rate of ADCs at a receiver. The WDM signal was polarization multiplexed with a relative delay of 87 ns and split into two paths to prepare SDM dummy signals. The measurement signal was mode-multiplexed with a relative delay of 200 ns using a 6-mode multiplexer as LP01, LP11a, LP11b, LP21a, LP21b, LP02 and launched into a core under test (CUT) of the 11-km 6M-19CF [3] using a fan-in (FI) device. The 18 SDM dummy signals were generated using single-mode fiber couplers, delay lines for decorrelation, 6-mode multiplexers, and 6-mode fiber couplers. The 18 SDM dummy signals were launched into 18 cores except for the CUT to emulate intercore crosstalk. The optical launched power was 5 dBm in all cores. After the 6M-19CF transmission, the measurement signal in the CUT was extracted using a fan-out (FO) device. The transmission loss, including FIFO devices, was less than 6 dB. The signal was mode demultiplexed by a 6-mode demultiplexer. The details of the SDM devices are shown in [3]. After optical pre-amplification, the center wavelength of 16-WDM channels was extracted by optical bandpass filters. The signals were detected with local oscillators (LOs) with a linewidth of 5 kHz by 6 integrated coherent receivers based on intra-dyne detection. By adjusting the LO frequencies, 1 subcarrier was demultiplexed by electrical low-pass filters. The 2.048-GBd electrical QPSK signals with pilot tones were sent to a real-time MIMO DSP to compensate for the modal crosstalk.

Figure 3(a) shows the cross section of the 6M-19CF [3]. The core #1 has the largest spatial modal dispersion among all cores [3] because the core is located near a core-identification marker which deforms shape of the core. Figures 3(b) and (c) show the BER in each subcarrier in the core #1 using the C-and L-band WDM signals after the

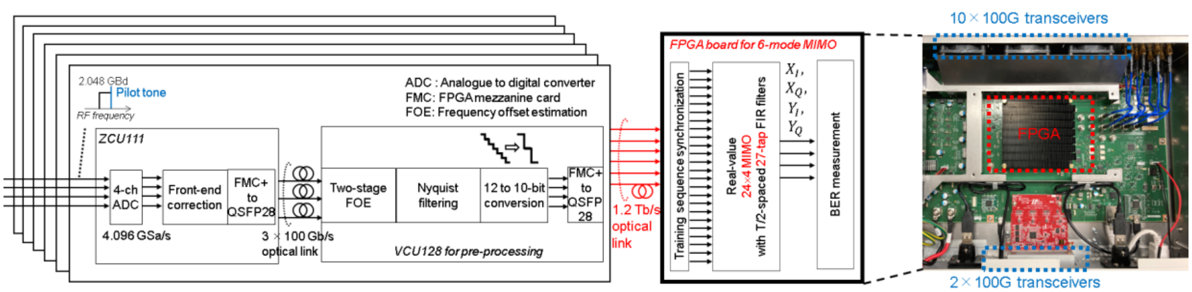

Fig. 1. Configuration of real-time 6-mode MIMO DSP.

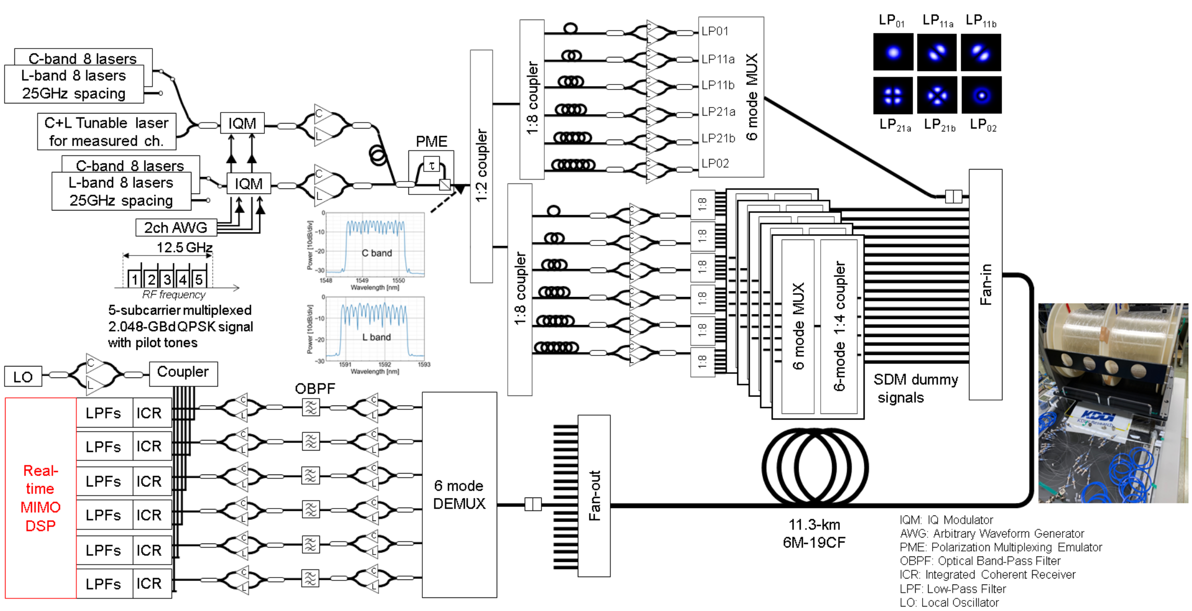

Fig. 2. Experimental setup for real-time MIMO 6M-19CF transmission.

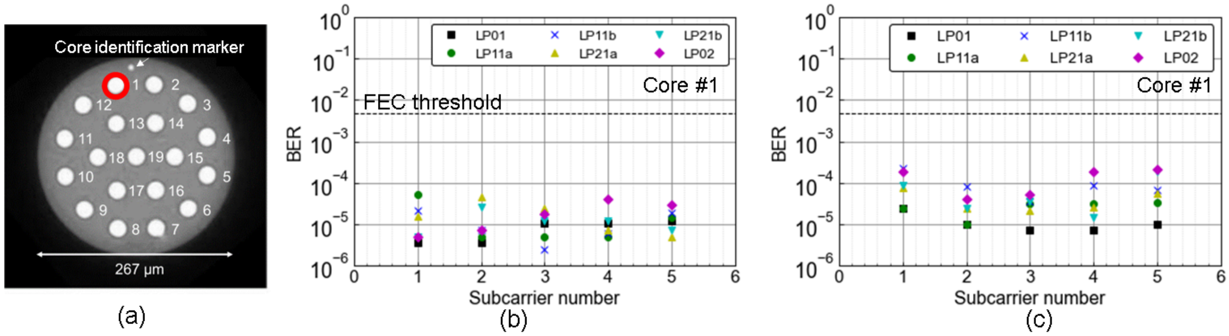

Fig. 3. (a) Cross section of the 6M-19CF [3]. BERs in the core #1 in each subcarrier using (b) C and (c) L band after the real-time 6M-19CF transmission.

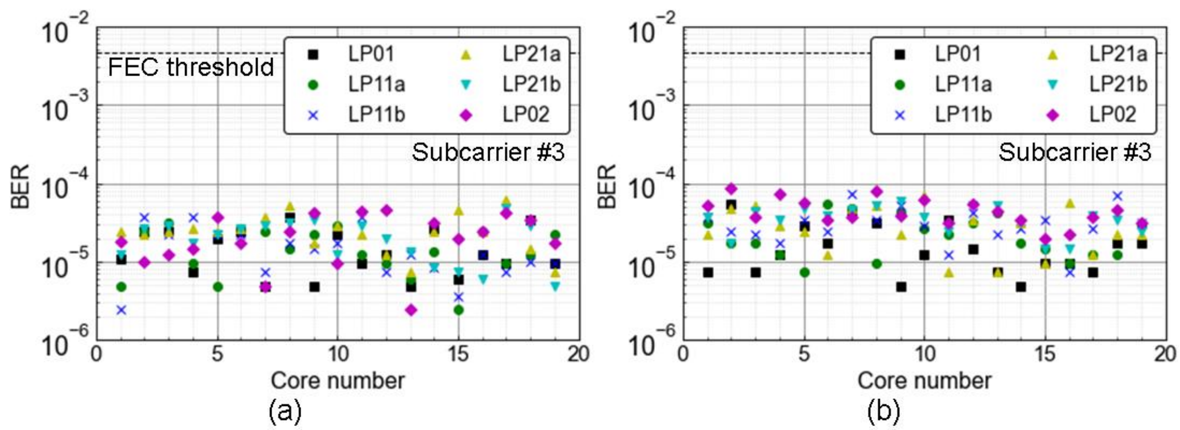

Fig. 4. BERs of the center subcarrier in each core using (a) C and (b) L band after the real-time 6M-19CF transmission.

real-time 6M-19CF transmission, respectively. The variance of the measured BERs was observed. This variance comes from the imperfection of the feedback-based carrier frequency and phase tracking due to the low clock frequency and calculation delay in the FPGA board [5,10]. The measured BERs below 4.7×10^{-3}, which can achieve error-free performance even with a 6.25% overhead hard-decision FEC [11], were obtained in all subcarrier tributaries in both of the C and L bands. Figures 4(a) and (b) show the BER of the center subcarrier (i.e., subcarrier #3) in each core using the C- and L-band WDM signals after the real-time 6M-19CF transmission, respectively. As shown in Fig. 4, the BERs below the FEC threshold were achieved in all cores and spatial modes in both of C and L bands. Thus, the feasibility of real-time few-mode multicore fiber transmission systems with the spatial multiplicity of 114 using C and L band was confirmed.

4. Conclusions

We demonstrated real-time 6-mode MIMO transmission over a 6-mode 19-core fiber in the C and L band. These results show the feasibility of real-time few-mode multicore fiber transmission systems with the spatial multiplicity of 100 or more.

5. Acknowledgements

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6. References

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