# Real-time strongly-coupled 4-core fiber transmission

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**Abstract:** We show a real-time optical coherent MIMO receiver for 4-mode division multiplexed transmission. With the receiver, we demonstrate real-time strongly-coupled 4-core fiber transmission of WDM DP-QPSK signals over 60 km.

## 1. Introduction

Mode-division-multiplexed (MDM) transmission systems with multiple-input multiple-output digital signal processing (MIMO-DSP) which enables to compensate modal coupling is an attractive candidate for future high-capacity transmission systems [1–3]. In particular, coupled-core multi-core fibers (CC-MCF) have been actively discussed for long-haul transmission, because their small spatial modal dispersions reduce the calculational complexity of MIMO-DSP. So far, the MDM transmission experiment over 12,100-km CC-MCF with seven cores was reported, although the MIMO equalization was implemented in an off-line DSP [3].

It is indispensable to verify the real-time transmission performance with utilizing real-time MIMO receivers for the practical MDM transmission systems. The 60-km three-core CC-MCF transmission experiment with real-time MIMO equalization has been already reported [4]. Although constant modulus algorithm (CMA) was implemented for the adaptive equalization in the real-time MIMO, it suffers from the singularity problem[5,6], in which each equalized output converges with the same mode and polarization tributary due to mode and polarization dependent loss. As increasing the number of the multiplexed modes, the problem could become more serious[6]. To avoid the singularity problem, the training-aided MIMO equalization is essential. Recently, we implemented a singularity-problem-free real-time training-aided MIMO receiver based on the least-mean-square (LMS) algorithm, but its MIMO dimension was still limited to two modes [7].

In this paper, we show a real-time four-mode MIMO receiver based on the LMS algorithm, in which the singularity problem is perfectly avoidable. With the receiver, we demonstrate the real-time MDM transmission of three-channel wavelength-division multiplexed (WDM) four-mode-multiplexed dual-polarization quadrature phase shift keying (DP-QPSK) signals over a 60-km four-core CC-MCF (4C-MCF).

## 2. Real-time coherent MIMO receiver

We designed an optical MIMO receiver to demodulate four spatial modes and two polarization components of six-subcarrier-modulated [8] DP-QPSK signals with 12.5-GHz bandwidth. In order to reduce the required sampling rate of analogue-to-digital convertors (ADCs), the signal was demultiplexed to six subcarriers with the signal baudrate of 2.048 Gbaud. Compared with our previous work (18 subcarriers with the 625 Mbaud) [7], the subcarrier number was reduced to be six and the ADC sampling rate increased to 4.096 GS/s. The pilot tones were also used for frequency offset estimation (FOE). The configuration of our coherent MIMO receiver is shown in Fig. 1. The four-mode-multiplexed DP-QPSK signal was demultiplexed into four spatial modes by a fan-out (FO) device based on free space optics (FSO). They were simultaneously received by four polarization-diversity integrated optical coherent receivers (ICRs). A tunable laser with linewidth of 5 kHz was used as a local oscillator (LO). One subcarrier was demultiplexed by tuning the LO frequency. Figure 2 shows the detailed configuration of implemented field-programmable gate array (FPGA) boards. The outputs of ICRs were connected to four 4-

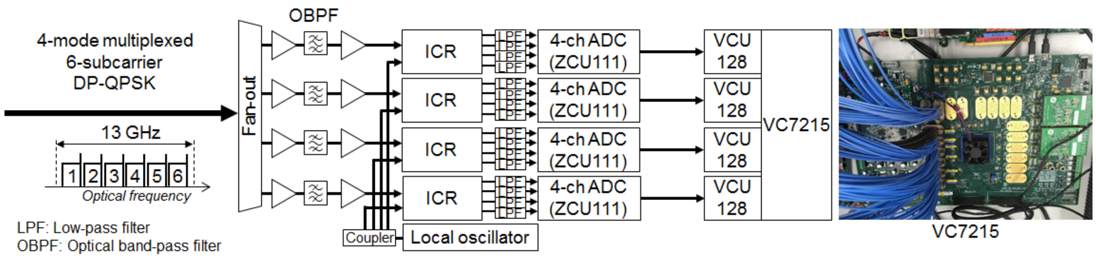


Fig. 1. Configuration of the real-time coherent MIMO receiver.

channel 12-bit ADCs, which were embedded on Zynq UltraScale+ RFSoC ZCU111 evaluation board. The four 197 Gbps (12 bit × 4.096 GS/s × 4 ch) data were sent to four Virtex UltraScale+ FPGA boards (VCU128). To transfer the ultra-high-speed data between FPGA boards, we employed four sets of three 100-Gbps commercialized optical transceivers (100GBASE-SR4), as shown in Fig. 2. In the VCU 128 boards, rectangular filtering and FOE were performed in the frequency domain. After down-sampling from 2 to 1 sample/symbol, the data were sent to another Xilinx Virtex-7 FPGA board (VC7215) for singularity-problem-free LMS-based MIMO adaptive equalization [7]. Their boards were connected by SMA cables via FPGA mezzanine card (FMC) to SMA conversion boards. Compared with our previous experiment [7], the signal baudrate was increased from 625 Mbaud to 2.048 Gbaud. Since the data rate exceeded maximum bandwidth of FMC-SMA conversion boards, we reduced the bit resolution of the data from twelve to eight bits.

## 3. Real-time demonstration of 4-core coupled-core Fiber transmission

With the real-time MIMO receiver prototype, we demonstrated a real-time 4C-MCF transmission experiment of WDM DP-QPSK signals over 60 km. The experimental setup is shown in Fig. 3. The center channel and the adjacent WDM channels were independently modulated by two optical IQ modulators, which were driven with electrical six-subcarrier QPSK baseband signals including pilot tones generated from an arbitrary waveform generator (AWG) with 25 GS/s sampling rate. The signal bandwidth was 12.5 GHz. After polarization multiplexing and wavelength multiplexing with frequency spacing of 13 GHz, we obtained three-channel WDM DP-QPSK signals. The power spectra of the single-channel and WDM signals are shown by dashed line and solid line in the inset of Fig. 3, respectively. The WDM signals were split into four copies with relative delay of around 200 ns, and then they were mode-multiplexed by the FSO-based fan-in (FI) device. Here, we named four input data streams as #1, #2, #3 and #4 according to the value of relative delay at the input of FI as shown in Fig. 3. The four-mode-multiplexed signal was transmitted over the 60-km 4C-MCF at the launched power of –2 dBm/ch/core. The average span loss of 4C-MCF including FI and FO devices was 12 dB and spatial modal dispersion was 7.1 ps/km$^{1/2}$. Then they were de-multiplexed to four WDM DP-QPSK signals by the FSO-based FO device and received with the real-time coherent MIMO receiver prototype.

First, we measured bit error rate (BER) characteristics as a function of optical signal to noise ratio (OSNR) for the single-mode single-channel DP-QPSK signal in the back-to-back configuration. The average measured BERs over $x$ and $y$ polarization tributaries of the all subcarrier (SC) are plotted in Fig. 4. The error floor in around BER

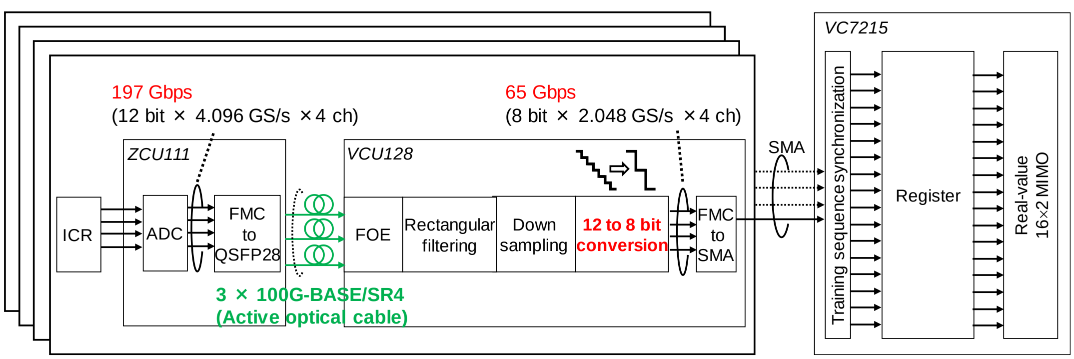


Fig. 2 Detailed configuration of FPGA boards implementation.

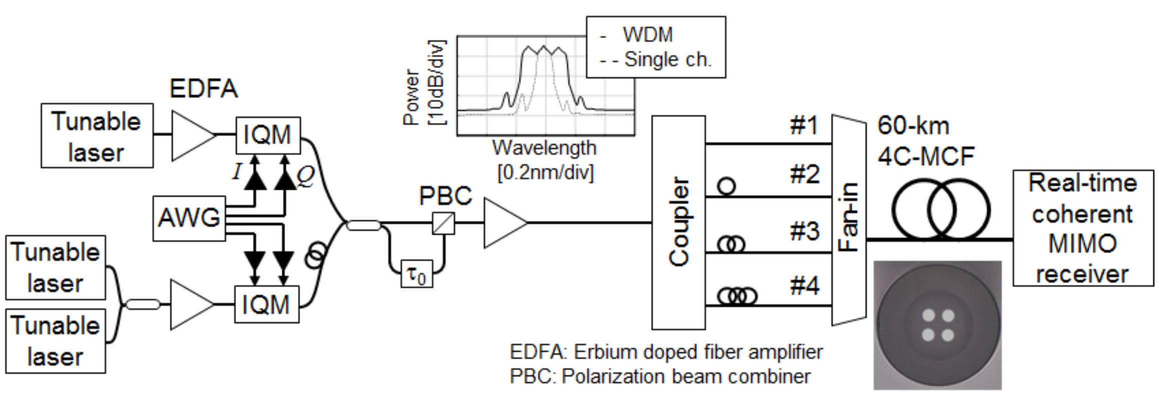


Fig. 3 Experimental setup for the real-time four-MDM transmission over 60-km 4C-MCF.

of $10^{-4}$ at center subcarrier was found. This would be because quantization noise comes from reduction of bit resolution in VCU128 boards as the above mentioned. In addition, although we found the subcarrier dependence of the measured BERs due to the bandwidth limitation of the AWG, the BERs of smaller than $2\times10^{-3}$ for all subcarriers were achieved. Figure 5 shows the measured BERs of all spatial modes with the WDM case for all subcarriers after the 4C-MCF transmission. For comparison, the results of the center subcarrier in the single-charrier case are plotted in the same figure. We found that the BER degradation in the WDM case caused by insufficient output voltages from ICRs compared with single channel case. It would be settled by increasing a gain of transimpedance amplifiers in ICRs and matching input range of ADCs. We observed the BERs of smaller than $2.7\times10^{-2}$ even in the WDM case, which was the BER threshold for 20%-overhead forward error correction (FEC) [9]. In the experiments, the transmission capacity of 160 Gbit/s per the WDM channel was achieved assuming 20%-overhead FEC. These results show the feasibility of the singularity-problem-free real-time four-MDM transmission.

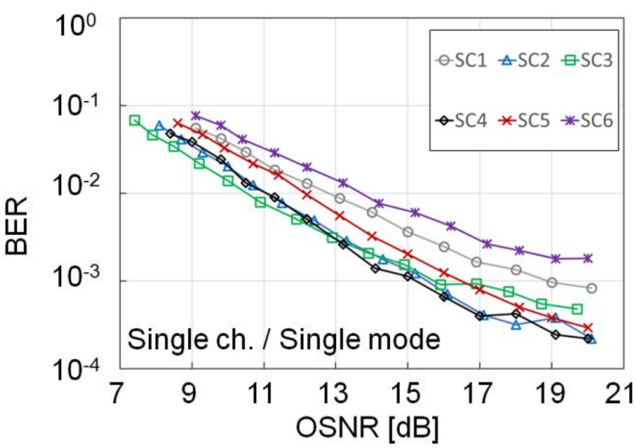


Fig. 4 Measured BERs as a function of OSNR of all subcarriers in back-to-back.

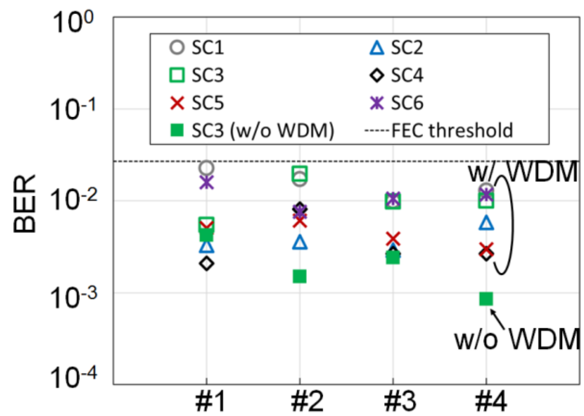


Fig. 5 Measured BERs after 60-km 4C-MCF transmission with WDM (all subcarriers) or without WDM (center subcarrier).

## 4. Conclusion

We demonstrated the singularity-problem-free real-time optical coherent four-MDM transmission of three-channel WDM DP-QPSK signals over the 60-km 4C-CC-MCF for the first time.

## 5. Acknowledgements

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