Single-Wavelength Net 1 Tb/s Transmission in SMF and 6.4 Tb/s in Weakly-Coupled 7-Core MCF Using a Phase- and Polarization-Diverse Direct Detection Receiver in Jones space

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***Abstract*—We demonstrate a record single-wavelength net 1.04-Tb/s transmission over 40-km SMF using 56.5-GHz Jones-space direct-detection receiver with the highest electrical spectral efficiency of 18.4 b/s/Hz. Using the 42-km weakly-coupled 7-core multi-core fiber, we achieve a net 6.49-Tb/s signal transmission for large-scale and high-capacity data center interconnects.**

Keywords—Jones space, direct detection, electrical spectral efficiency, multi-core fiber

I. Introduction

The exponential growth of data center traffic drives the demand for high-speed and spectrally-efficient optical transceivers for data center interconnects (DCI). The coherent detection (CoHD) scheme receives extensive interest due to high spectral efficiency and high capacity enabled by field recovery employing both phase- and polarization-diversity. When combined with advanced digital signal processing (DSP) techniques, CoHD allows digital compensation of the fiber impairments at a reduced cost compared to measures operating in the optical domain. However, the requirement of a costly narrow-linewidth local oscillator (LO) for CoHD imposes additional power consumption and hardware that impedes the use of CoHD at shorter communication reaches.

Eliminating the LO while unlocking the capability of field recovery traditionally found in CoHD is part of the key effort in developing advanced direct detection (DD) schemes having enhanced transmission performance. In addition, it is mostly desirable to exploit four modulation dimensions (MD) of an optical carrier in order to push the electrical spectral efficiency (ESE) towards the theoretical coherent limit. Herein ESE is defined as the net bitrate per unit electrical bandwidth of the receiver. Recently, DD schemes with various modulation dimensions have been demonstrated, including 1-dimension (1-D, i.e. only amplitude) [1-3], 2-D [4-8], 3-D [9-11], and 4-D (amplitude, phase, and polarizations) [12-13]. Note that the ESE is improved by utilizing more modulation dimensions leveraging advanced receiver structures.

However, 4-D DD schemes with the capability of field recovery remain unexplored, which constrains the attainable reach and capacity as a consequence of unmanaged fiber impairments. One critical issue is polarization fading which forms a fundamental barrier to accessing the polarization diversity as needed to realize 4-D DD systems with a co-traveling carrier. The random polarization rotation in the fiber could lead to the complete loss of the carrier power on one polarization, thus impeding the realization of a polarization diverse direct-direction system.

Most recently, we propose a 4-D Jones-space DD receiver that can recover the optical field with both phase- and polarization-diversity in Jones space. Our proposed scheme overcomes the polarization fading issue owing to a 3×3 optical coupler-based receiver structure [14]. In addition to a quadrupled ESE relative to the traditional intensity modulation and direct detection scheme, the Jones-space DD receiver can digitally compensate for the fiber impairment for extended transmission reach when compared with the previous 4-D schemes [12-13].

In this paper, we demonstrate the proposed 4-D Jones-space DD receiver [14] with phase-diverse units based on Mach-Zehnder interferometers (MZIs) [7] and achieve single-wavelength transmission of net 1.04-Tb/s over 40-km single-mode-fiber (SMF) with a record net ESE of 18.4 b/s/Hz. A single-wavelength net data rate of 920 Gb/s is achieved using only linear equalization with a record net ESE of 16.3 b/s/Hz. In addition to the phase- and polarization diversity, parallel spatial channels including fiber cores and modes are well-suited for high-capacity transmission [15-18]. We achieve a net data rate beyond 6.4 Tb/s in a 42-km weakly-coupled 7-core fiber using a low-complexity sparse Volterra nonlinear equalizer. Fig. 1 summarizes the net ESEs and data rate of state-of-the-art DD systems beyond 100 Gb/s. The demonstrated Jones-space 4-D DD receiver offers a spectrally-efficient and cost-effective candidate for large-scale and low power-consumption data-center interconnects.

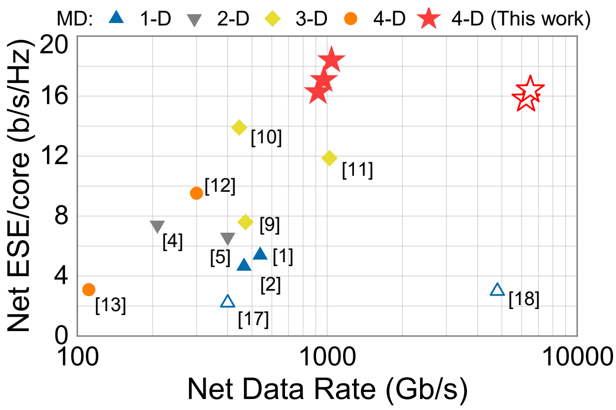

Fig. 1. Net ESE per core and net data rate comparison in direct detection systems beyond 100 Gb/s. MD: modulation dimensions; Solid symbols: results using single-mode fiber; Hollow symbols: results using multi-core fiber.

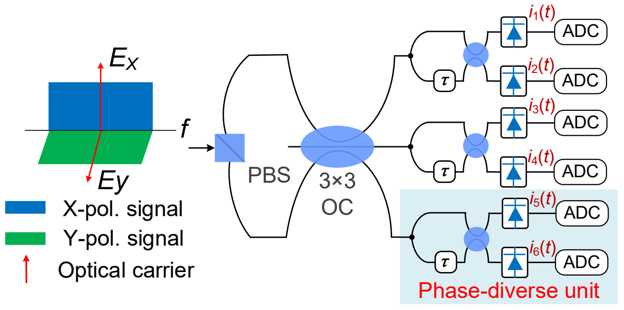

Fig. 2. Receiver structure of Jones-space direct detection with a phase-diverse unit implemented by an MZI. PBS: polarization beam splitter; OC: optical coupler; τ: optical delay, 8 ps in this experiment; ADC: analog-to-digital converter.

II. PRICIPLE OF JONES SPACE OPTICAL FIELD RECOVERY

In [6, 14], the principle of Jones space field recovery has been illustrated and experimentally verified by use of Kramers-Kronig receiver-based phase-diverse units each having a single-ended photodiode. Moreover, the phase-diverse unit inside the receiver structure could be realized based on the asymmetric self-coherent detection scheme composed of an MZI and two single-ended photodiodes [7] as shown in Fig. 2. The 3×3 optical coupler is employed to eliminate the polarization fading phenomenon while the phase-diverse units recover both in-phase and quadrature information. The electrical field of the signal can be reconstructed in the receiver DSP by linearly combining the photocurrents $i_1(t)$ to $i_6(t)$. With iterative signal-to-signal beating interference (SSBI) elimination or nonlinear equalization [7], the information encoded on the amplitude and phase of the optical field can be demodulated in a direct detection receiver without a need for an LO.

III. EXPERIMENTAL SETUP AND DSP PROCEDURES

A. *Experimental Setup based on MZIs*

In this section, we experimentally demonstrate the proposed Jones space direct detection receiver with MZIs. Figure 3(a)-(b) illustrate the experimental setup and DSP algorithms implemented at the transceiver, respectively. Four independent 53-GBd probabilistically-shaped (PS)-64QAM symbols are generated using a constant composition distribution matcher at a length of 212000 for negligible entropy loss. Next, the symbols are unsampled and shaped by a root-raised-cosine (RRC) filter with a roll-off factor of 0.01. The four independent signals are up-converted to an intermediate frequency of ±29.765 GHz with a guard band from -3 GHz to 3 GHz, as shown in Fig. 3(c).

The electrical signals generated by an arbitrary waveform generator (AWG, Keysight 8199A) operating at 128 GSa/s drive a dual-polarization IQ modulator biased at the null point that modulates the light from the external cavity laser (ECL). The 10% tributary from ECL serves as the optical carrier with an uncontrolled polarization state. The carrier-to-signal power ratio is optimized to 16.5 dB using a variable optical attenuator (VOA). After transmission in SMF or MCF, the PDM signals are amplified to 22 dBm using an erbium-doped fiber amplifier (EDFA) and detected by the proposed 4-D Jones-space DD receiver with an insertion loss of 6 dB.

The transmitted and received optical spectra are shown in Fig. 3(e). For the designed receiver structure, the 3×3 optical coupler ensures that the optical field can be recovered at any polarization state [14] and the MZI with a delay (τ) of 8 ps is used to retain both in-phase and quadrature information of signal [7]. Here, the transfer function of the MZI-based phase diverse unit, i.e. $\mathcal{FFT}\{\delta(t)+j\delta(t-\tau)\}=1+je^{-j2\pi f\tau}$ in the frequency

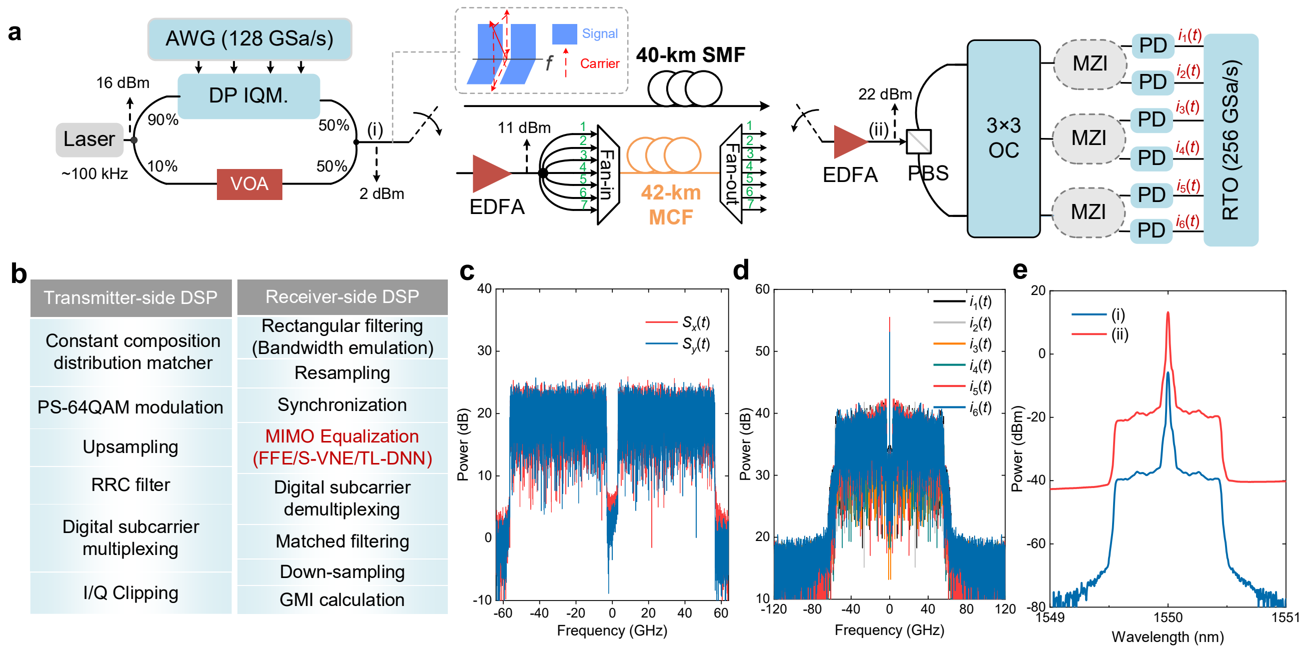

Fig. 3. (a) Experimental setup. AWG: arbitrary waveform generator; DP IQM.: dual-polarization IQ modulator; VOA: variable optical attenuator; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber; MCF: multi-core fiber; PBS: polarization beam splitter; OC: 3×3 optical coupler; MZI: Mach-Zehnder interferometer; PD: photodiode; RTO: real-time oscilloscope. (b) DSP stacks at the transmitter- and receiver- side. RRC: root-raised-cosine; FFE: feed forward equalizer; S-VNE: Sparse-Volterra nonlinear equalizer; TL-DNN: transfer-learning deep neural network; (c) Electrical spectra of the transmitted PDM signals. $S_x(t)$ and $S_y(t)$ are the transmitted polarization-multiplexed signals. (d) Electrical spectra of the six received photocurrents. $i_k(t)$ (k=1~6): received photocurrents. (e) Transmitted and received optical spectra of PDM signals.

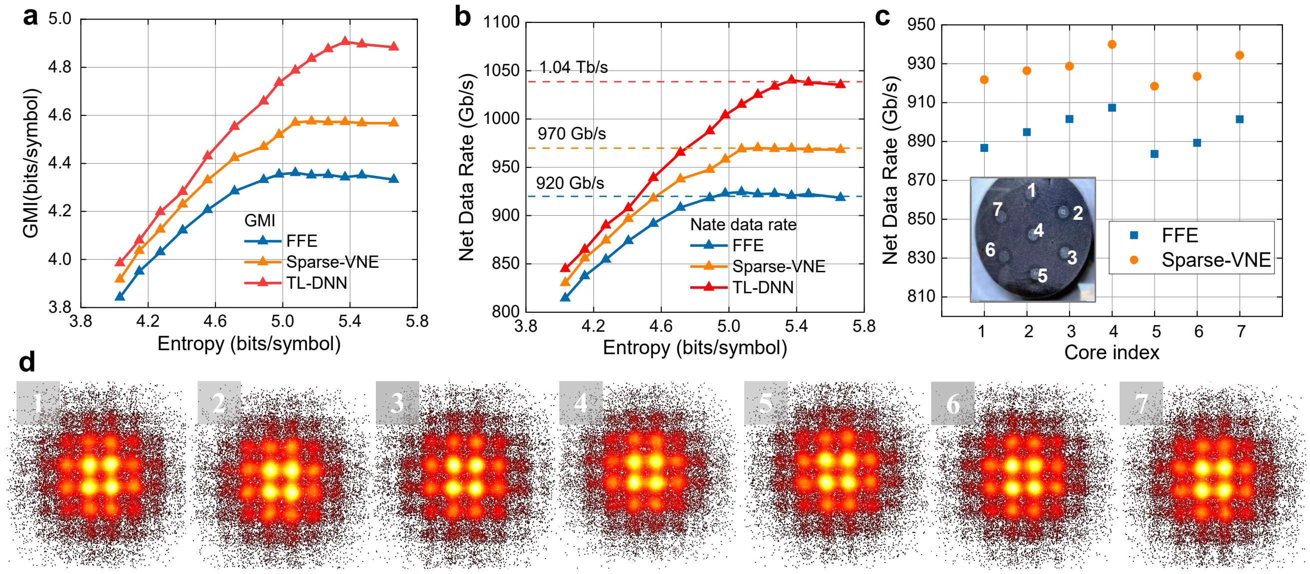

Fig. 4. (a) Net data rate and (b) GMI versus entropy of signal source in SMF. (c) Net data rates of the seven cores. The cross-sectional image of the 7-core fiber is shown in the inset. (d) Constellations of the seven cores of MCF with Sparse-VNE.

domain is realized using the Fourier Processor function of a wave-shaper (II-IV 4000A). After the photoelectric conversion of single-ended photodetectors (PD, XPD3210R), the 6 tributaries of electrical waveforms are captured by 6 channels of two synchronized 256 GSa/s real-time oscilloscopes (RTO, UXR0594AP) operating in the multi-scope mode.

B. *Digital Signal Processing at the Recevier*

The electrical spectra of captured waveforms are displayed in Fig. 3(d). They are then digitally filtered to realize a rectangular receiver bandwidth of 56.5(=3+53.5) GHz. The signals are resampled to 3 samples-per-symbol (159 GSa/s) to avoid spectral overlapping. After frame synchronization, a MIMO equalizer is used to perform optical full-field recovery, polarization demultiplexing, and channel equalization simultaneously. Here, three kinds of equalizers are tested including a linear feed-forward equalizer (FFE, 91 taps), a 3-order sparse Volterra nonlinear equalizer (Sparse-VNE, 91+21+1 taps) with diagonal kernels only, and a four-layer transfer learning-assisted deep neural network (TL-DNN, See Appendix of [14]). The nonlinear Sparse-VNE and DNN aim to mitigate the signal-to-signal interference (SSBI) generated in the photoelectric conversion. For FFE and Sparse-VNE, the filter taps are updated by the recursive least square algorithm based on 2000 training symbols. For TL-DNN, 5000 training symbols are required for convergence and polarization tracking [14]. After the digital subcarrier demultiplexing, generalized mutual information (GMI) is calculated as system performance metrics since it predicts the post-FEC system performance reliably [10-11].

IV. Results and Discussion

A. *Transmission Results in 40-km SMF*

For 40-km SMF transmission, we optimize the entropy of PS-64QAM to maximize the achievable information rate in terms of GMI. The net data rate is calculated as 53×2(bands)×GMI×2(pols.) Gb/s. The results with different equalization schemes are plotted in Fig. 4(a). It shows that a net data rate of 920 Gb/s can be reached using a simple linear FFE, which proves that the I/Q components of PDM signals are retained in the photocurrents and can be extracted using adaptive equalization. In addition, 970 Gb/s is successfully achieved with a Sparse-VNE with 22 diagonal kernels for SSBI mitigation. To further approach the capacity limits of this system, we adopt a fully-connected TL-DNN with a ReLU activation function for efficient SSBI mitigation. The maximum bitrate of this 56.53-GHz receiver is 1.04 Tb/s. The achieved GMI with respect to the source entropy is depicted in Fig. 4(b). The highest GMI is 4.9 bits/symbol at an entropy of 5.07 bits/symbol. To the best of our knowledge, it achieves the highest net ESE of 18.4 b/s/Hz among the existing DD systems.

B. *Transmission Results in 42-km MCF*

In the 42-km MCF transmission case, the entropy of PS-64QAM is set to 5.07 bits/symbol, according to the optimization results in the SMF. The losses of fiber cores vary from 10 to 12 dB consisting of both fiber propagation loss and insertion loss of multiplexers. The cross-sectional image of the 7-core fiber is shown in the inset of Fig. 4(c). The achieved net data rates in each of the 7 cores are displayed in Fig. 4(c). The net data rates of 6.25 Tb/s and 6.49 Tb/s can be achieved using the linear FFE and Sparse-VNE, respectively. Compared with the results in 40-km SMF, the amplified spontaneous emission (ASE) noise introduced by the excess attenuation of MCF slightly degrades the system performance. The constellations of the received signal in each of the 7 cores are displayed in Fig. 4(d). The constellations show marginal distortion, which validates the capability of the 4-D Jones space receiver to recover the full-field of phase- and polarization diverse optical signals.

C. *Practical Implementation Concerns*

From the perspective of practical implementation, the linear FFE is more suitable due to lower complexity. Using only linear equalization, we achieve a single-wavelength net data rate of 920 Gb/s over 40 km of SMF with a record ESE of 16.3 b/s/Hz, and a single-wavelength net data rate of 6.25 Tb/s over 42 km of MCF. We also note that the frequency offset estimation and carrier phase recovery are eliminated thanks to direct detection, which benefits the design of DSP ASICs with reduced complexity as well as lower power consumption. Additionally, the proposed scheme facilitates monolithic integration since an LO is saved at the receiver [19].

V. CONCLUSION

We achieve the highest single-wavelength net data rate of 1.04-Tb/s over 40-km SMF at a record ESE of 18.4 b/s/Hz via a 4-dimensional Jones-space direct detection receiver within 56.5 GHz bandwidth. Using a 42-km weakly-coupled 7-core MCF, single-wavelength 6.4-Tb/s transmission is successfully demonstrated for higher-capacity optical interconnects. The LO-free advantage of this receiver renders it suitable for monolithic photonic integration, offering a spectrally-efficient and cost-effective candidate for large-scale and low power-consumption data center interconnects.

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