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The following publication X. Zhou et al., "112-Gbit/s PDM-PAM4 transmission over 80-km SMF using digital coherent detection without optical amplifier," 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Prague, Czech Republic, 2016 is available at https://doi.org/10.1109/CSNDSP.2016.7573937.

112-Gbit/s PDM-PAM4 Transmission Over 80-km SMF Using Digital Coherent Detection Without Optical Amplifier

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Abstract— **In this work, we experimentally demonstrated a 112 Gbit/s polarization-division-multiplexed (PDM) four-level pulse amplitude modulation (PAM4) transmission over 80-km single mode fiber (SMF) using digital coherent detection without optical amplifier and CD compensation for the short reach applications. Here, a signal-phase aided least-mean-square (SP-LMS) equalization algorithm is proposed to avoid the effects of carrier frequency offset and phase noise. Without additional carrier recovery algorithms, the PDM-PAM4 system shows good transmission performance. The received optical power (ROP) penalty is only about 0.2 dB after 80 km transmission comparing to back-to-back (BTB) transmission. A receiver sensitivity of -20dBm (at 7% FEC limit) can be reached after 80-km transmission.**

Keywords—polarization-division-multiplexing; pulse amplitude modulation; coherent detection; equalization; short reach systems.

I. INTRODUCTION

The ever-increasing broadband mobile communication and cloud computing services are requiring high data-rate transmission in datacenter and other optical interconnects. 100 Gbit/s or above per wavelength will be the trend to short reach systems in the near future [1]. Due to short reach applications desired to be low cost and simple implementation, some advanced modulation formats with intensity modulation and direct detection (IM-DD), including pulse amplitude modulation (PAM) [2-4], carrier-less amplitude modulation (CAP) [5] and discrete multi-tone (DMT) [6-7], have been widely investigated for short reach transmissions. However, due to CD-induced power fading impairments, these IM-DD systems are much difficult to reach a longer transmission range, as up to 80 km for ZR transmission. Recently, in order to increase the transmission distance, some advanced technologies were proposed to combat the power fading effect, such as orthogonal frequency division multiplexing (OFDM) with Stokes vector direct detection (SV-DD) [8], single-sideband (SSB) DMT [9], et al. However, there is still not a good solution for the short reach system over 80 km transmission without optical amplifier.

Considering that digital coherent detection is effective approach to solve the accumulated CD problem. It combined with intensity modulated transmitter will be a promising cost-effective solution for short reach systems. In this paper, we experimentally demonstrated a 112 Gbit/s PDM-PAM4 transmission over 80 km SMF at C-band without optical amplifier, where the electro-absorption modulated laser (EML)-based transmitter and intradyne coherent receiver (ICR) are employed. In order to avoid the use of carrier recovery algorithms in this IM coherent system, a SP-LMS equalization algorithm is proposed. Based on the novel SP-LMS algorithm, the PDM-PAM4 system is only about 0.2 dB ROP penalty and the receiver sensitivity at a BER of 3.8E-3 is -20dBm after 80 km SMF transmission. To the best of our knowledge, this is the first reported 100-Gbit/s above short reach transmission over 80km SMF without optical amplifier.

II. SP-LMS EQUALIZATION ALGORITHM

The least mean square (LMS) [10] algorithm is a classic equalization algorithm for the optical coherent systems. However, it is sensitive to phase distortions induced by carrier frequency offset and phase noise [11]. Hence, traditional LMS algorithm needs the assistance of carrier frequency offset estimation and phase recovery algorithms [12]. Considering that PAM signal does not encode data on carrier frequency or phase, it is costly to extract the phase errors by using extra carrier recovery algorithms for providing to LMS algorithm. In order to avoid the phase-induced influence simply, a SP-LMS algorithm is proposed. In the SP-LMS, the phase of the equalized signal is extracted directly and imposed it on the reference signal to calculate the error function (see Fig. 1).

The SP-LMS error functions of two polarizations are given by

$$\varepsilon_x = \exp\left(j\phi_x\right) d_x - x_{out}, \quad \varepsilon_y = \exp\left(j\phi_y\right) d_y - y_{out} \qquad (1)$$

where $d_{x(y)}$ denotes the PAM4-based reference signal, which can be provided by the training sequence in the first stage,

$\phi_{x(y)}$ is the phase of the output signal after equalization, which can be easily extracted by a phase angle operation,

$$\phi_x = \arg\left(x_{out}\right), \quad \phi_y = \arg\left(y_{out}\right) \qquad (2)$$

Using the error functions of Eq. (1), the tap coefficients of SP-LMS can be updated according to,

$$\begin{aligned} h_{xx} &= h_{xx} + \mu\varepsilon_x \bar{x}_{in}^* & h_{xy} &= h_{xy} + \mu\varepsilon_x \bar{y}_{in}^* \\ h_{yx} &= h_{yx} + \mu\varepsilon_y \bar{x}_{in}^* & h_{yy} &= h_{yy} + \mu\varepsilon_y \bar{y}_{in}^* \end{aligned} \qquad (3)$$

where μ is a convergence parameter, $(.)^*$ is the complex conjugate operation, $\bar{x}_{in}$ and $\bar{y}_{in}$ denote the input signal vectors of X-pol and Y-pol respectively.

It is worth noting that the training sequence-based adaptive algorithm would not be used for whole equalization processing. Until the equalizer is converged properly, the SP-LMS algorithm will be switched from the training mode to the decision-directed mode. In this case, the reference signal will be replaced to the decision value of the equalized PAM4 signal, as

$$d_x = \text{Decision}\left(\left|x_{out}\right|\right), \quad d_y = \text{Decision}\left(\left|y_{out}\right|\right) \qquad (4)$$

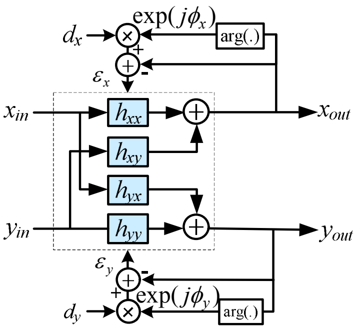
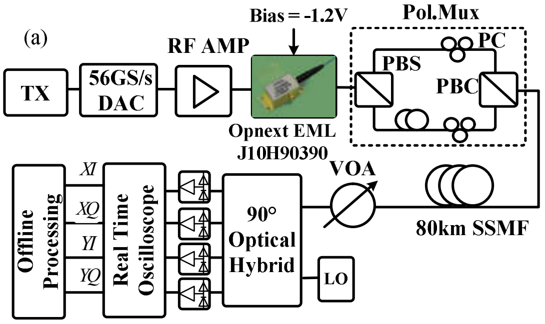


Fig. 1. Block diagram of the SP-LMS-based equalization

III. EXPERIMENTAL SETUP AND RESULTS

Fig. 2 shows the experimental setup. In the transmitter, a DAC with a sampling rate of 56-GSam/s and 3dB bandwidth of 12GHz is used to generate the driving signal. The electric driving signal is boosted to a 1.7V peak-to-peak by a RF linear amplifier. Commercial electric absorption modulated laser (EML) was used to modulate the PAM4 signal on to the optical carrier. The bias voltage is optimized to be -1.2V. The center wavelength of the EML is 1546.1nm. Then the single polarization PAM4 signal is fed into a polarization multiplexer, which is split and recombined in orthogonal polarizations after delaying one of the split signals to de-correlate it from another split signal. The power of output optical signal is around 1 dBm.



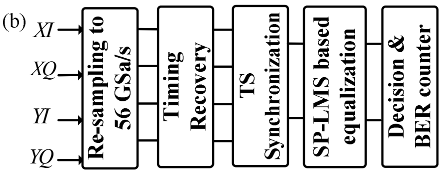


Fig. 2. Experimental setup for 112Gbit/s PDM-PAM4 system, offline DSP.

At receiver side, the transmitted signal is detected by a ICR with a 3dB bandwidth of 18GHz. The detected signal is sampled by a real-time scope with a sampling rate of 80GS/s and a bandwidth of 30GHz. The captured data is processed offline as shown in Fig.2 (b). Firstly, the digital samples are re-sampled to two samples per symbol. After timing recovery by using Digital Square and filter algorithm, the correlation between the received samples and the training symbols is calculated to find the starting point of the training sequence from the coming data. This processing is called TS synchronization, and note that the correlation calculation needs to be implemented on the power of the received samples so as to avoid the influence induced by carrier frequency offset and laser linewidth. Next, the SP-LMS based equalizer is employed to de-multiplex polarization, and compensate inter-symbol interferences induced by CD, PMD and the narrowband filtering effect. Finally, the BER is measured by a bit error counter after symbol decision.

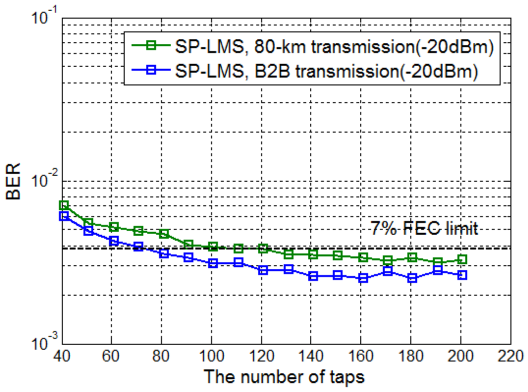


Fig. 3. BER as a function of the number of taps.

In order to find the best performance point for the SP-LMS algorithm, its optimal number of taps are investigated and shown in Fig. 3. Here, two transmission scenarios of BTB and after 80km SSMF transmissions are considered at a ROP of -20dBm. Besides, the training mode is used in the whole equalization processing. It can be seen that the basically stable BER performance can be achieved by the number of taps larger than 101. Furthermore, there is a similar change tendency of BER for BTB and after 80 km transmission, which indicates that the narrowband filtering effects from DACs and detectors should be the dominant impairment instead of fiber dispersion. In this case, the extra CD compensation is not used before the adaptive equalization in our system. All the kinds of ISI are compensated by using the adaptive butterfly equalizer.

In practice, the equalization processing cannot always depend on the training sequence. After the equalizer is converged properly, the training mode will be switched to the decision-directed mode. In order to investigate how many training symbols are required to reach the switching condition, BER performances are measured as a function of the number of training symbols from 1500 up to 8000. Here, the reference signal of SP-LMS will be replaced with the decision values as long as the training symbols are used up. It can be seen from Fig.4, the number of taps and line dispersion both have the influence to the convergence speed of equalization. Here, the maximum number of training symbols is about 4200 for 80 km transmission by using 131 taps.

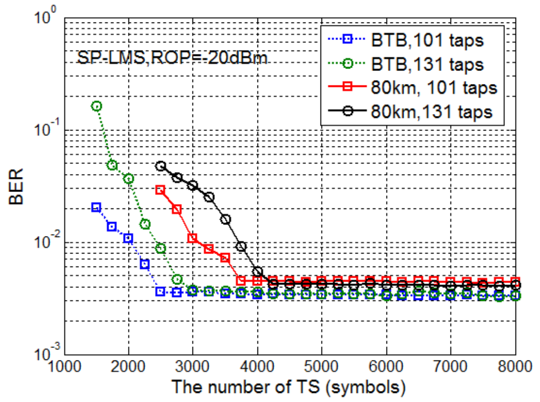


Fig. 4. BER as a function of the number of training symbols

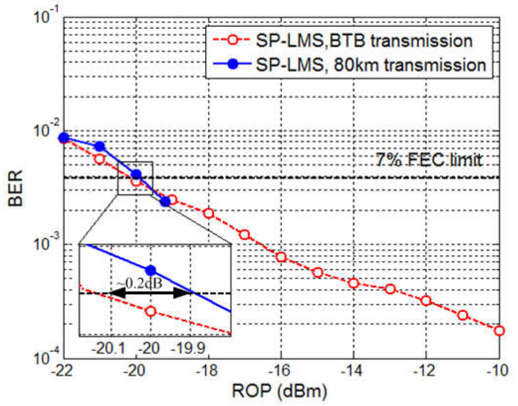


Fig. 5. BER as a function of the received optical power.

The measured BER performances as a function of the received optical power are shown in Fig.5 by using SP-LMS for the BTB transmission and after 80km SSMF transmission. Here, 131 taps are used for equalization, and 6000 training symbols are used at the first stage of training mode equalization. Due to no optical amplifier used in the whole experimental system, the maximum ROP can be only achieved about -19.2 dBm after 80km transmission. As shown in Fig. 5, the BER reaches the hard-decision FEC threshold of 3.8E-3 at about ROP of -20 dBm based on the SP-LMS algorithm. Comparing to BTB situation, there is only about 0.2 dB ROP penalty after 80-km transmission.

IV. CONCLUSION

In this paper, 112-Gbit/s PDM-PAM4 signal over 80-km SMF was experimentally demonstrated by using digital coherent detection without optical amplifier and CD compensation. Based on our proposed SP-LMS algorithm, there are negligible differences in ROP requirements between BTB and transmission scenarios, and the receiver sensitivity at a BER of 3.8E-3 (7% FEC limit) is -20 dBm after 80 km SMF transmission.

Acknowledgment

This work was supported by project H-ZG3Y of Huawei Technologies Co. Ltd, National Natural Science Foundation of China (61401020, 61377093, 61435006), Beijing Natural Science Foundation (4154080), Hong Kong Government General Research Fund (GRF) PolyU 152109/14E PolyU 152248/15E and PolyU 152079/14E, Hong Kong Scholar Program (XJ2013026) and Fundamental Research Funds for the Central Universities (FRF-TP-15-028A2).

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