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Intelligent performance monitoring for high-speed short-reach optical networks

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Abstract—**Performance monitoring approaches in 100/400/800 Gbit/s short-reach transmissions with advanced modulation formats are developed. The MSEs of the monitored OSNRs are less than 0.1 dB and accuracies of 100% have been achieved in MFI.**

Keywords-optical performance monitoring; advanced modulation formats; short-reach optical networks;

I. INTRODUCTION

Recently, the explosive growth in the traffic of inter- and intra-data centers has led to strong demand for high-speed and high-performance short-reach optical networks. In short-reach optical networks, the intensity modulation with direct detection (IM/DD) is more suitable than coherent detection in terms of cost, packaging and power consumption [1]. Therefore, advanced optical modulation formats for IM/DD with high spectral efficiencies have been widely studied to meet such requirements [2]. In terms of dispersion tolerance, spectral efficiency, digital signal process (DSP) complexity and cost, there are a lot of research works have to be carried out to explore the possibility of various advanced modulation formats in high-speed short-reach transmission such as pulse amplitude modulation (PAM), carrier-less amplitude phase (CAP) modulation, discrete multi-tone (DMT) modulation. It is very possible in future dynamic and heterogeneous short-reach optical networks that, different modulation formats are applied for different transmission scenarios. In dynamic optical networks, modulation format identification (MFI) and baud rate are variable, and advanced modulation formats lead to more complicated signal changes and higher difficulty in the optical performance monitoring (OPM).

In this work, we present in detail the generation process of four typical advanced modulation formats, including PAM-4, PAM-8, DMT and CAP16 and their asynchronous histograms. Meanwhile, we set up 100/400/800 Gb/s numerical short-reach transmission systems with various modulation formats in order to investigate the OPM of advanced modulation formats using ANN. It is shown that an MFI accuracy of 100% can be achieved for four considered modulation formats. Besides, the OSNR monitoring with a mean square error (MSE) less than 0.1 dB has been achieved in the OSNR range of 15-45 dB. Our work demonstrates that the OPM and the MFI, based on the ANN feature extraction and sharing, can still show excellent and stable performance even if the transmission rate is higher than 100 Gb/s.

II. DIGITAL SIGNAL PROCESSING FOR ADVANCED MODULATION FORMATS

A. DSP for PAM-8 signal

Figure 1 shows the DSP blocks for generating the PAM-8 signal at the transmitter. A Pseudo-Random Symbol Sequence (PRSS) with a pattern length of 2^{15}-1 was used to map bits to symbols and to produce the PAM-8 signal. After the binary coding, PAM-8 symbols are generated and fed into the 3-bit digital to analog convertor (DAC). The electronic PAM-8 signal is sent to a MZM at 1550 nm.

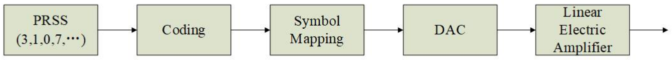

Figure 1. DSP process of PAM-8 transmitter.

B. DSP for PAM-4 signal

The PAM-4 signal generation process is similar to the generation of PAM-8 signal, except that the initial data stream is replaced with Pseudo-Random Binary Sequence (PRBS), as illustrated in Figure 2.

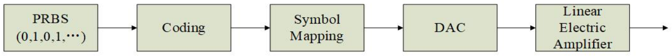

Figure 2. DSP process of PAM-4 transmitter.

C. DSP for CAP-16 signal

Figure 3 shows the generation of the CAP-16 signal. A data stream with is mapped into a 16-QAM constellation. The oversampling with 3 samples per symbol (or even higher) is implemented for the CAP signal. After the binary sequence mapping, the I and Q components can be extracted by taking real and imaginary parts of the signal.

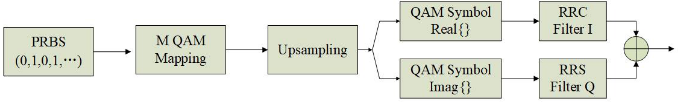

Figure 3. DSP process of CAP-16 transmitter.

D. *DSP for DMT signal*

DMT signal is a variant of the OFDM signal. The difference between the DMT and the OFDM lies in the operation of the data sequence before the IFFT. In the generation of the DMT signal, the corresponding conjugated sequence of the input data must be included before the IFFT to ensure the real values of the IFFT output. Figure 4 shows the DSP flow chart for the DMT system.

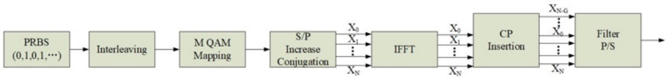

Figure 4. DSP process of DMT transmitter.

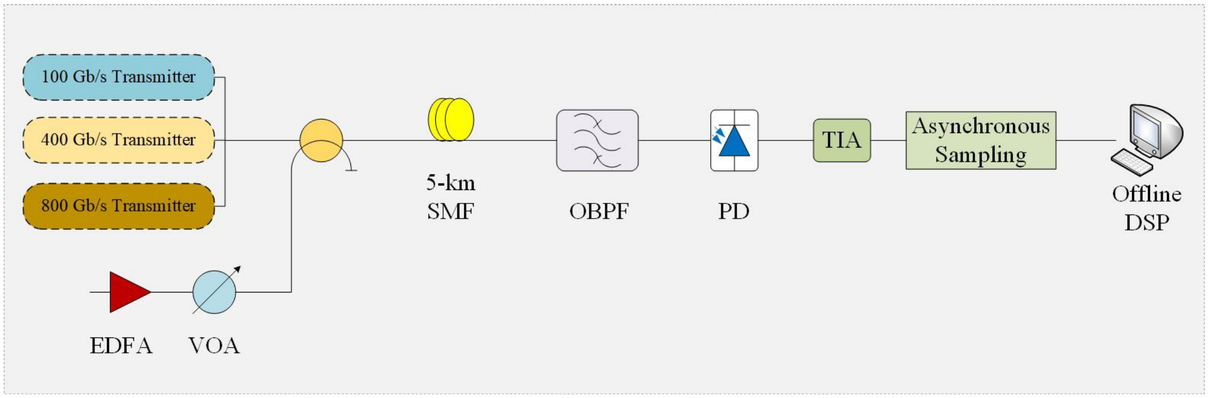

Figure 5. Schematic of numerical simulation system.

III. OPERATION PRINCIPLE AND RESULT FOR OPTICAL PERFORMANCE MONITORING

The high-speed short-reach transmission system diagram is shown in Fig. 5. These signals are generated from different transmitters as described in the previous section. The output power is fixed to 1 mW by an erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA). By adding noise to the input signal, the OSNR varies in the range of 15-45 dB with a resolution step of ~0.1 dB. At the receiver, an optical band-pass filter (OBPF) is used to remove the noise outside the signal bandwidth. A photodetector (PD) and a transimpedance amplifier (TIA) are used to convert the optical signal into the electrical signal. The received data are then processed by the offline DSP.

A. *Principle of Optical Performance Monitorings*

Recently, the application of machine learning technologies in optical communication systems becomes one of the hottest research topics [3]. In the area of OPM, popular machine learning algorithms such as convolution neural networks (CNN) and artificial neural networks (ANN) have demonstrated their outstanding performance [3-6]. Here the OPM based on asynchronous amplitude histograms (AAHs) trained ANN is employed to implement the OSNR monitoring and the MFI [7]. AAHs with 80 bins for four considered signal formats at different OSNRs are shown in Fig. 8. The abscissa of AAHs is the index of the bin, and the ordinate is the number of corresponding occurrences. It is clearly seen from Fig. 8 that AAHs reply on both modulation format and OSNR, and thus can be employed for the simultaneous operation of OSNR monitoring and MFI.

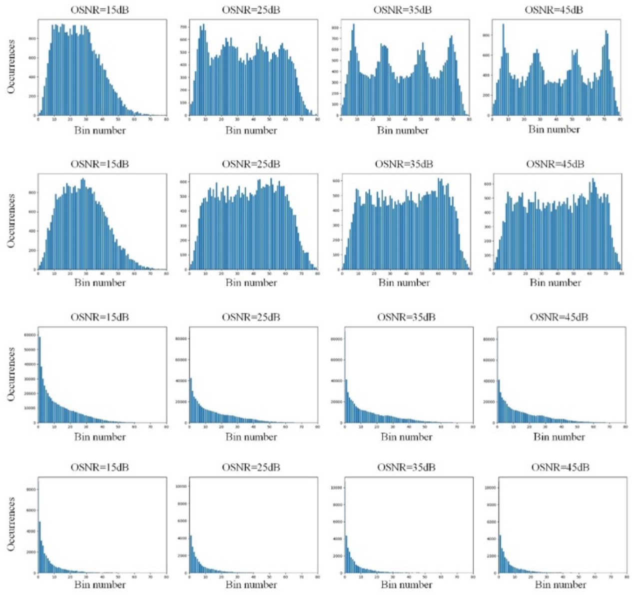

Figure 6. AAHs with 80 bins for PAM-4 (first row), PAM-8 (second row), CAP (third row) and DMT (fourth row) signals, at different OSNRs

B. *OSNR monitoring and MFI results*

The neural network employs a three-layer fully-connected layer structure with 120 hidden layer neurons, as shown in Fig. 7. The number of neurons in the input layer is 80, which is the same as the number of bins in the AAHs. The activation function of the NN is the Rectified Linear Unit (ReLU). The MSE between the predicted value and the true value is selected as the loss function to optimize the synapse weight. The optimization algorithm used in the training process is adaptive moment estimation (Adam) with a learning rate of 0.001, which incorporates the concepts of Gradient Descent, Momentum, Adagrad, RMSprop and their improved variants. The output layer selects Softmax as the activation function when the classification task (MFI) is carried out, but it does not employ any activation function when the regression task (OSNR Monitoring) is performed.

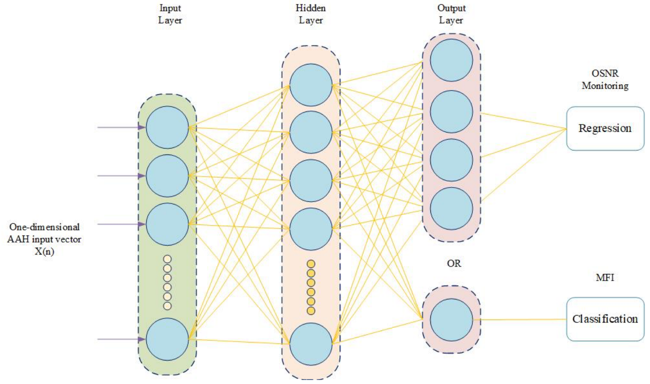

Figure 7. Structure of ANN for OPM

First, we have carried out the OSNR monitoring in 100G and 400G transmission systems. The data set used for ANN contains 400 one-dimensional vectors. The data set is divided into the training set, the validation set and the test set with a split ratio of 0.64:0.16:0.2. The final MSE results of the four modulation formats are presented in Table 1.

TABLE I. RESULTS OF MONITORING OF OSNR FOR THE 100G TRANSMISSION SYSTEMS

	28 Gb/s PAM8	***56 Gb/s PAM4***	***28 Gb/s DMT***	***56 Gb/s CAP16***
Average OSNR error(dB)	0.0241	0.0365	0.0684	0.0760
Training time(s)	125.9021	124.2013	377.5219	375.3440

Compared to the 100G transmission system, the signal quality in the 400G transmission system will be degraded more significantly due to the dispersion and the fiber loss. Therefore, for the same OSNR range, in the context of 400G transmission, the estimated results from the ANN will be worse when the OSNR value is low. The average MSE remains below 0.1 dB as shown in Table 2.

TABLE II. RESULTS OF MONITORING OF OSNR FOR THE 100G TRANSMISSION SYSTEMS

	96 Gb/s PAM8	***102 Gb/s PAM4***	***56 Gb/s DMT***	***96 Gb/s CAP16***
Average OSNR error(dB)	0.0482	0.04210	0.08658	0.0760
Training time(s)	122.8276	124.2759	373.6794	375.5445

For the 800G transmission system, the MSE in the OSNR monitoring for the 75 GBaud PAM4 signal is 0.0639 dB and the MSE in the OSNR monitoring for the 56 GBaud PAM8 signal is 0.0619 dB.

The data set includes four modulation formats and two transmission rates, and each modulation format contains 800 components. 6400 components are divided with the split ratio is 0.56:0.14:0.3. We have measured the accuracy of MFI for different epochs, as shown in Fig. 8.

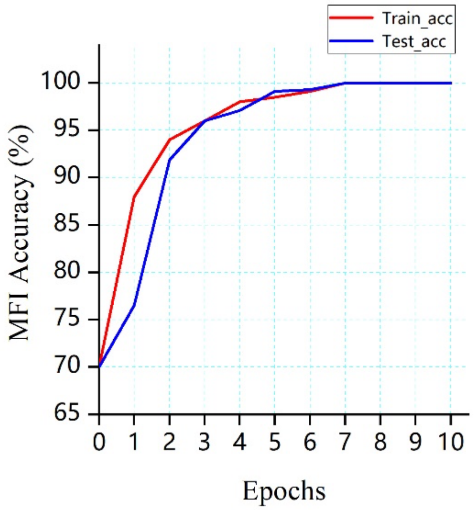

Figure 8. The MFI accuracies at different epochs

IV. CONCLUSION

In this work, we have presented the implementation of the OSNR monitoring and the MFI, based on the ANN, for next-generation heterogeneous high-speed short-reach optical networks. The DSP based generation of four modulation formats has been investigated in detail. The feasibility study of the asynchronous amplitude histogram is carried out, and AAHs of different modulation formats are also analyzed. Numerical setups for 100G/400G/800G short-reach transmission systems are implemented to evaluate the performance of the proposed monitoring approach. Our results show that the MFI accuracy achieves 100% in range of 15-45 dB. Besides, the MSE of OSNR estimation is less than 0.1 dB in 100G and 400G transmission systems. Our research provides a promising candidate to achieve intelligent signal analysis in next-generation dynamic heterogeneous short-reach optical networks.

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