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Effect of ADC parameters on neural network based chaotic optical communication

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The performance of traditional chaotic optical communications depends on the matching parameters of the chaotic transmitter and receiver. The chaotic receiver based on the neural network (NN) can solve the dependence on matching parameters, but the analog-to-digital converter (ADC) has an effect on the decryption performance. In this paper, the effects of sampling rate and digitalizing bit for ADC on NN-based chaotic optical communication systems with different feedback strengths at different bit rates are numerically studied. The results show that the requirements for ADC will be higher if the feedback becomes stronger. In order to achieve higher speed chaotic optical communications, the ADC with higher performance is needed. These results can give guidance for the applications of NN-based high-speed chaotic optical communication systems.

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With the rapid development of optical fiber communication technologies, the security of optical fiber communication systems becomes more and more important. Chaotic optical communication is a kind of physical layer encryption technology, which can guarantee the safety of the transmitted signal in optical fiber communication systems. Chaotic communication was proposed in the 1990s [1]. Due to the large bandwidth and noise-like characteristics of optical chaos, chaotic optical communication has great potential in high-speed secure optical fiber communication systems. There are mainly three kinds of schemes to realize chaotic optical communication, including all-optical feedback [2–4], optoelectronic feedback [5], and electro-optic feedback [6–9]. In all traditional schemes, chaos synchronization based on physical devices with matching parameters is needed for chaotic optical communication, and the requirement for the strict matching parameters of physical devices can provide high security for chaotic optical communication.

However, in practical applications, it is not easy to find the physical devices with strict matching parameters. The mismatched physical devices will bring about chaos synchronization error, which degrades the signal-to-noise ratio of the decrypted signal and cause the failure of decryption. Especially in high-speed optical communication systems, a high-speed signal is more sensitive to noise, and the tiny chaos synchronization error may lead to the failure of decryption. Besides, the precise dispersion compensation in the optical domain is needed for chaos synchronization [10], which complicates the fiber link. In order to solve the problem of parameter matching for physical devices, the neural network (NN) is proposed to realize chaos synchronization and decryption [11]. A 32 Gbps message encrypted by optical chaos can be decrypted by the NN after 20 km fiber transmission. Besides, the security of NN-based chaotic optical communication can also be guaranteed after analysis. The dispersion can also be accurately compensated in the digital domain, which can simplify the fiber link [12]. In NN-based chaotic optical communication systems, the analog-to-digital converter (ADC) is used for transformation between the analog and digital signals, and the output of the ADC is used for chaos synchronization and decryption by the NN in the digital domain. Therefore, the performance of the ADC has a strong effect on the bit error rate (BER) of the decrypted signal.

In this Letter, the effect of sampling rate and digitalizing bit for the ADC on NN-based chaotic optical communication systems with different feedback strengths are numerically studied. As the sampling rate and digitalizing bit increase, the BER performance of the system can be improved for the same feedback strength. Besides, the BER performance will be degraded for the same sampling rate and digitalizing bit when the feedback strength becomes stronger. Thus, the ADC with a high sampling rate and digitalizing bit is needed to realize chaos synchronization and decryption for the chaotic system with strong feedback strength. In other words, the high feedback strength can improve the security of system. In addition, chaotic optical communication systems with different feedback strengths and different bit rates of signals for the same sampling rate and digitalizing bit are studied. The increase for the bit rate of the signal and the feedback strength of the system can degrade the BER performance of NN-based chaotic optical communication systems. Therefore, the sampling rate and digitalizing bit of the

ADC, the feedback strength of system, and the bit rate of the signal need to be considered simultaneously in applications of NN-based chaotic optical communication systems. Limited by the experimental condition, although only simulation results are shown in this manuscript, we believe the results in this paper can provide useful guidance for real applications of the NN-based high-speed chaotic optical communication systems.

The simulation setup is shown in Fig. 1. The output light of a laser diode (LD1) with a power of P_1 is injected into a Mach–Zehnder modulator (MZM1) with a half-wave voltage of V_π. MZM1 provides nonlinear transfer function $\cos^2(x+\varphi)$, where φ is the bias of MZM1. MZM1 is driven by an electrical amplifier (AMP1) with gain G. The output light of MZM1 is chaos $c(t)$, which is divided into two parts through an optical coupler (OC1), where one part is used to train the NN, and the other part is mixed with the output light from LD2 modulated by MZM2 driven by the 16 quadrature amplitude modulation (QAM) message through OC2. The 16 QAM message is modulated by random data after serial-to-parallel conversion, which is generated by the Mersenne Twister algorithm. The 16 QAM message can be expressed as $m(t)$, and the output of OC2 can also be expressed as $m(t)+c(t)$. Therefore, the 16 QAM message is encrypted by the chaos signal, and the mixture ratio can be adjusted by a variable optical attenuator (VOA1). After that, the mixed light is divided into two parts through OC2, where one part is used for secure transmission, and the other part is sent back to the feedback loop for chaos generation. The feedback light is delayed by a delay line (DL), then the feedback light is converted into an electrical signal by a photodiode (PD1) with sensitivity. The feedback strength is controlled by VOA2. The output of PD1 amplified by AMP1 drives MZM1 again. Let $c_A(t)$ be the chaos signal of point A and $m_A(t)$ be the 16 QAM message of point A. The first-order bandpass filter is used to simulate the filter effect of the feedback loop, and the whole attenuation of the feedback loop is set as η. The process of chaos generation can be expressed as

$$\tau\frac{dc_A(t)}{dt}+c_A(t)+\frac{1}{\theta}\int_{t_0}^{t}c_A(\xi)\mathrm{d}\xi = P_1\eta SG\cos^2\left(\pi\frac{c_A(t-T)+m_A(t-T)}{2V_\pi}+\pi\frac{V_{DC}}{2V_\pi}\right), \tag{1}$$

where τ and θ are the high cut off response time and low cut off response time of the electronic feedback. V_{DC} is the direct current (DC) offset of MZM1. T is the delay time of the whole loop, which comprises the optical delay and electrical delay. The corresponding frequencies are $\nu_{hf}=(2\pi\tau)^{-1}$ and $\nu_{lf1}=(2\pi\theta)^{-1}$. Defining the normalized variable $c_A'(t)=\pi c_A(t)/(2V_\pi)$, Eq. (1) can be express as

$$\tau\frac{dc_A'(t)}{dt}+c_A'(t)+\frac{1}{\theta}\int_{t_0}^{t}c_A'(\tau)\mathrm{d}\tau = \beta\cos^2(c_A'(t-T)+m_A'(t-T)+\varphi), \tag{2}$$

where $\beta=\pi P_1\eta SG/(2V_\pi)$ represents the whole feedback strength in the emitter, and $\varphi=\pi V_{DC}/(2V_\pi)$ represents the normalized bias of MZM1. The above equation represents the process of chaos generation.

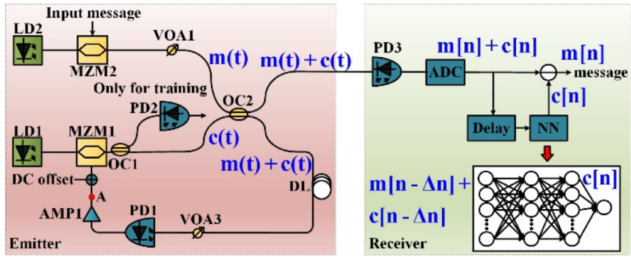

Fig. 1. Simulation setup. LD, laser diode; MZM, Mach–Zehnder modulator; VOA, variable optical attenuator; OC, optical coupler; DL, delay line; PD, photodiode; AMP, broadband radio frequency amplifier; ADC, analog-to-digital converter.

On the receiver side, the mixed light is received by PD3. After that, the output of PD3 is processed by the ADC, where the processing includes sampling, quantizing, and coding. Therefore, the sampling rate and digitizing bit are the key parameters of ADC. After being processed by the ADC, the analog signal $c(t)+m(t)$ is converted into a digital signal $c[n]+m[n]$. The output of the ADC is divided into two parts, where one part is processed by a delay module. After that, a trained NN module is used for chaos synchronization. The 16 QAM message $m[n]$ can be decrypted by the subtraction of the other output of the ADC and the chaos signal generated by NN. Therefore, the process of decryption can be express as

$$c[n-\Delta n]+m[n-\Delta n]\xrightarrow{NN}c'[n], \tag{3}$$

$$c[n]+m[n]-c'[n]=m'[n], \tag{4}$$

where $c'[n]$ is the chaos generated by the NN. Δn represents the delay module. If the chaos signal $c'[n]$ generated by the NN is equal to $c[n]$, which corresponds to the output PD2, $m'(t)$ will be equal to $m(t)$. Therefore, the 16 QAM message can be decrypted.

In simulation, the encrypted signal $m(t)+c(t)$ and PD2 output $c(t)$ can be achieved by solving Eq. (2) with the Runge–Kutta algorithm. The time step of simulation is 5 ps, and the duration of the simulation is 16 μs. The data from 0 μs to 12.8 μs is used for the training process, which corresponds to 2,560,000 points. Besides, the data from 12.8 μs to 16 μs is used for the testing process, which corresponds to 640,000 points. The characteristic time scales of the bandpass filter are $\tau=16$ ps for the high cut off and $\theta=3.18$ ns for the low cut off; therefore, the corresponding frequencies are $\upsilon_{hf}=10$ GHz and $\upsilon_{lf}=50$ MHz. The bias of MZM1 is set as $\pi/4$. The total delay time T is 30 ns. The 16 QAM signal is generated by quadrature modulation, the electrical carries frequency of the 16 QAM message is 5 GHz, and the symbol rates of 5 GBaud and 8 GBaud are studies, respectively, that corresponds to 20 Gbps and 32 Gbps. The 16 QAM message is filtered by a raised cosine digital filter with a roll off factor of 0.25 before it is injected to MZM2. Therefore, the bandwidth of the 16 QAM message is no more than 10 GHz, which means that the spectrum of the 16 QAM message can be masked by the chaos signal with a bandwidth of 10 GHz. The mask coefficient is defined as the ratio between the peak-to-peak value of the 16 QAM message and chaos signal. The mask coefficient is set as 0.6 in the simulation. In addition, in order to focus on the effect of ADC parameters, the noise in photoelectric devices and the dispersion and nonlinearity of the fiber are not considered in the simulation.

Before decryption, the encrypted signal and the output of PD2 are sampled and quantized by the ADC. The process of decryption includes the training stage and testing stage. In the training stage, the encrypted signal is used as the input of the NN, and the desired output of the NN is the output of PD2. After the training stage, the parameters of the NN will not be changed. Besides, there exists a delay time between the input signal and output signal of the NN. The loss function is the mean square error (MSE) between the output of PD2 and the output of the NN. The back-propagation (BP) algorithm and gradient descent algorithm are used to train the parameters of the NN. Specifically, the stochastic gradient descent (SGD) is used for training. The learning rate in the simulation is set as 0.01. It was noted that the input and output signals of the NN are digital signals processed by the ADC. In the testing stage, the output of PD2 is removed, while the encrypted signal is sent to the input of the NN. The output of the NN is the regenerated chaos. Therefore, the 16 QAM message can be decrypted by subtraction between the masked 16 QAM message and the regenerated chaos. The NN is the fully connected NN, which consists of the input layer with 71 neurons, the first hidden layer with 21 neurons, the second hidden layer with 11 neurons, and the output layer with 1 neuron. The activation function is $ReLU = \max(0, x)$. In addition, the hyper-parameters of the NN for decryption in training still need to be finely tuned to achieve the best performance of decryption for different feedback strengths, sampling rates, digitalizing bits, and bit rates of the 16 QAM message. The hyper-parameters are searched according to the MSE between the output of PD2 and the output of the NN, where1000 epochs are used in every training process.

First, chaos synchronization based on the NN is studied. The feedback strength β is five. The sampling rate and digitalizing bit of the ADC are 100 GS/s and 8 bits, respectively. The bit rate of 16 QAM is 32 Gbps. The chaotic time series from PD2 sampled by the ADC is shown in Fig. 2(a), the chaotic time series generated by the NN is shown in Fig. 2(b), and the synchronization plot is shown in Fig. 2(c). The results show the good performance of chaos synchronization. In order to quantitatively evaluate the performance of chaos synchronization, the normalized correlation coefficient is defined as

$$C = \frac{\langle [x(t) - \langle x(t)\rangle]\,[y(t) - \langle y(t)\rangle]\rangle}{\sqrt{\langle [x(t) - \langle x(t)\rangle]^2\rangle \langle [y(t) - \langle y(t)\rangle]^2\rangle}}, \quad (5)$$

where $x(t)$ is the time trace of emitter, $y(t)$ is the time trace of the receiver, and $\langle\cdot\rangle$ denotes the average. The normalized correlation coefficient C in Fig. 2 is 0.9845.

The constellation of the digital coherent demodulated 16 QAM message decrypted by the NN is shown in Fig. 2(f). Compared with the original 16 QAM message shown in Fig. 2(d), the decrypted 16 QAM message is worse than the original one, because the chaos synchronization is not perfect, and the noise converted from the chaos synchronization error degrades the performance of decryption. The constellation of the encrypted 16 QAM message demodulated by the digital coherent method is shown in Fig. 2(e). Compared with the original 16 QAM message, it can be seen that the 16 QAM message is completely masked by the chaos signal.

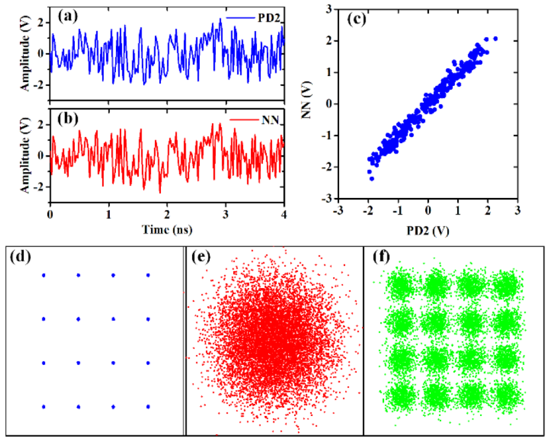

Fig. 2. Chaos synchronization and constellations of the original, encrypted, and decrypted 16 QAM message. (a) Chaotic time series collected from PD2 sampled by the ADC. (b) Chaotic time series generated by the NN. (c) Chaotic synchronization plot of the chaotic time series collected from PD2 and generated by the NN. (d) Constellation of the original 16 QAM message. (e) Constellation of the chaos-masked 16 QAM message. (f) Constellation of the 16 QAM message decrypted by the NN.

Then, the BER performance with different digitalizing bits and feedback strength is studied. The sampling rate is fixed at 100 GSa/s, and the digitalizing bit is set as 4, 6, 8, and 10 bits, while the feedback strength is set as 3, 4, 5, and 6. Figure 3 shows the relationship between the BER performance of the decrypted signal and the digitalizing bits of the ADC under different feedback strengths. When the feedback strength is fixed, the BER performance is improved as the digitalizing bit of the ADC increases. Therefore, the decryption performance of the NN becomes better. As the digitalizing bit increases, the quantization accuracy of the ADC is gradually improved, and the quantization error is gradually decreased, so the digital signal obtained by the ADC is closer to the analog signal in the system. Therefore, with the increase of the digitalizing bit, the performance of the decryption based on the NN can also be improved. In addition, under the same digitalizing bit, the BER performance will be degraded as the feedback strength becomes stronger. Because the nonlinearity of the system will also become stronger when the feedback strength increases, the quantization error is also amplified, which degrades the decryption performance of the NN. Therefore, the high digitalizing bit of the ADC is needed for the decryption when the feedback is strong.

The BER performance with different sampling rates and feedback strength is also discussed. The digitalizing bit is fixed at 8 bits. The relationship between the BER performance of the decrypted signal and the sampling rate of the ADC under different feedback strengths are shown in Fig. 4. As the sampling rate increases, the BER performance is improved gradually. Due to the increase in sampling rate of the ADC, the analog signal can be more accurately converted into a digital signal, which means that the input of the NN is closer to the real value of the signal in the system. Therefore, the NN can realize better performance of decryption. In addition, according to Fig. 4, when the sampling rate is fixed, as the feedback strength increases, the performance of the BER performance becomes worse. The reason can be explained as below: as the feedback strength increases, the nonlinearity of the system also becomes stronger, so the subtle

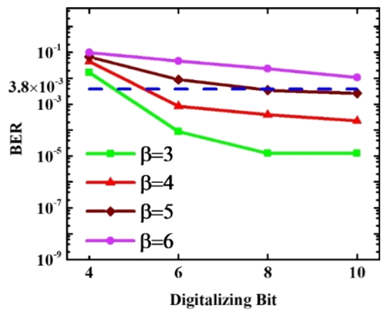

Fig. 3. BER performance of the decrypted signal with different digitalizing bits and feedback strength. The blue dashed line is the threshold of the hard decision feedforward error correction (HD-FEC).

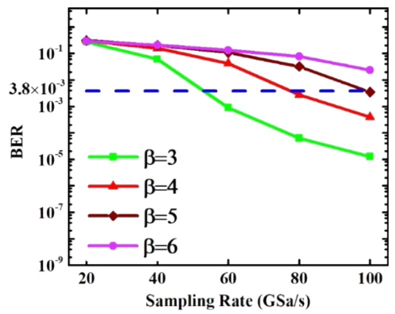

Fig. 4. BER performance of the decrypted signal with different sampling rates and feedback strength. The blue dashed line is the threshold of HD-FEC.

changes in the chaos waveform will be amplified by the feedback loop. If the sampling rate of the ADC is not sufficient at this time, the subtle changes of the waveform cannot be captured well, and the input of the NN loses some input information, which makes the NN unable to perform decryption operations well. Therefore, the BER of the decrypted signal increases. In real applications, when the feedback is strong, the ADC with a high sampling rate is needed in decryption.

In order to furtherly study the effect of feedback strength and ADC parameters on the bit rate of NN-based decryption, the sampling rate and digitalizing bit are fixed at 50 GSa/s and 8 bits, respectively. The NN-based decryption performance of 20 Gbps and 32 Gbps 16 QAM signals under different feedback strengths of the system is studied. Figure 5 shows the relationship between the BER performance of the decrypted signal and the feedback strength at different bit rates. The BER performance of the decrypted signal at the same bit rate will become worse as the feedback strength increases. Comparing the decryption performance of the signals with different bit rates, it can be seen that the decryption performance of the NN will become worse when the bit rate becomes higher. In addition, when the feedback strength β in Fig. 5 is greater than 3.5, the 16 QAM signals of 20 Gbps and 32 Gbps cannot be decrypted by the NN. Therefore, when the feedback strength becomes strong, the bit rate of the signal that can be decrypted by the NN is lowered. In real applications, the bit rate of the signal, the feedback strength of the system, and the parameters of the ADC need to be tuned carefully.

In conclusion, the sampling rate and digitalizing bit of the ADC have great influence on the BER performance of

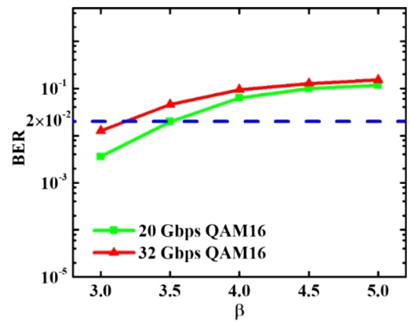

Fig. 5. BER performance of the decrypted signal with different feedback strengths and bit rates. The blue dashed line is the threshold of soft decision feedforward error correction (SD-FEC).

NN-based chaotic optical communication systems. The BER performance of the system can be improved by increasing the sampling rate and digitalizing bit of the ADC for the same feedback strength. Besides, the strong feedback strength will degrade the BER performance for the same sampling rate and digitalizing bit. Thus, the ADC with high sampling rate and digitalizing bit is needed to realize chaos synchronization and decryption for the system with strong feedback strength, while the security of the system can be improved by increasing the feedback strength of the system. Besides, the system with strong feedback will lower the bit rate of the signal that can be decrypted by the NN for same sampling rate and digitalizing bit. Therefore, in order to realize the decryption of the 16 QAM signal with a higher bit rate, the sampling rate and digitalizing bit of the ADC need to be increased. The research on NN-based decryption in this paper is focused on the offline mode, and the real-time NN-based receiver will be studied in the future. At present, these results can provide seful guidance for real applications of NN-based chaotic optical communication systems.

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