Research Article

ADVANCED PHOTONICS NEXUS

100 Gb/s coherent chaotic optical communication over 800 km fiber transmission via advanced digital signal processing

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Abstract. Chaotic optical communication has shown large potential as a hardware encryption method in the physical layer. As an important figure of merit, the bit rate–distance product of chaotic optical communication has been continually improved to 30 Gb/s × 340 km, but it is still far from the requirement for a deployed optical fiber communication system, which is beyond 100 Gb/s × 1000 km. A chaotic carrier can be considered as an analog signal and suffers from fiber channel impairments, limiting the transmission distance of high-speed chaotic optical communications. To break the limit, we propose and experimentally demonstrate a pilot-based digital signal processing scheme for coherent chaotic optical communication combined with deep-learning-based chaotic synchronization. Both transmission impairment recovery and chaotic synchronization are realized in the digital domain. The frequency offset of the lasers is accurately estimated and compensated by determining the location of the pilot tone in the frequency domain, and the equalization and phase noise compensation are jointly performed by the least mean square algorithm through the time domain pilot symbols. Using the proposed method, 100 Gb/s chaotically encrypted quadrature phase-shift keying (QPSK) signal over 800 km single-mode fiber (SMF) transmission is experimentally demonstrated. In order to enhance security, 40 Gb/s real-time chaotically encrypted QPSK signal over 800 km SMF transmission is realized by inserting pilot symbols and tone in a field-programmable gate array. This method provides a feasible approach to promote the practical application of chaotic optical communications and guarantees the high security of chaotic encryption.

Keywords: chaotic optical communication; physical layer security; deep learning; digital signal processing.

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1 Introduction

As one of the main schemes of physical layer encryption, chaotic optical communication has the advantages of a noise-like, wide spectrum and compatibility with existing optical communication systems and has been continuously studied in recent years.[1] Since the realization of chaotic synchronization, many chaotic secure communication schemes have been proposed in the past few decades.[2–6] Due to the difficulty of synchronizing chaotic hardware, most research on chaotic optical communication remains in numerical simulation[7–9] and digital chaos.[10] There is a certain gap between numerical simulation and real experiments, and digital chaos requires additional key distribution. Therefore, the research progress of high-speed and long-distance chaotic optical communication is limited. In 2005, the first field trial of 2.4 Gb/s amplitude-encrypted chaotic optical communication was successfully demonstrated over a 120 km fiber transmission distance in Athens' metro network.[11] In 2010, the first 10 Gb/s phase-encrypted chaotic optical communication over a 120 km fiber link was successfully demonstrated in Besançon, France.[12] As reported in 2018, Ke et al.[13]

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demonstrated a 30 Gb/s chaotically encrypted duobinary signal transmission over a 100 km single-mode fiber. At the same time, many researchers have proposed some new chaos-based encryption schemes to improve communication performance.[14,15] In order to simplify the complexity of chaotic synchronization, we have proposed using deep-learning-based chaotic synchronization in the digital domain to replace chaotic hardware synchronization in the optical domain and experimentally demonstrated 32 Gb/s chaotic optical communication over 20 km fiber transmission, proving the feasibility of deep learning for chaotic synchronization.[16] The transmission distance is only 20 km because it is limited by the impairment compensation capability of algorithms in the direct detection system. Fiber transmission impairments can be well compensated by coherent detection in classic optical communication systems,[17] and the numerical simulation has proved that coherent detection is capable of extending the transmission distance of a 10 Gb/s chaotic optical communication to 1000 km.[18] With the help of coherent optical communication, the chaotic optical communication bit rate–distance product is increased to the 500 Gb · km/s level.[3,19,20] By combining coherent detection with blind digital signal processing (DSP) algorithms and deep-learning-based chaotic synchronization, we have experimentally demonstrated 30 Gb/s phase-encrypted chaotic optical communication over 340 km fiber transmission,[21] which is the record bit rate–distance product of chaotic optical communications. Further, improving the bit rate–distance product of chaotic optical communication is limited by the capability of the blind constant modulus algorithm equalization and phase-recovery algorithm. More powerful algorithms are needed to further improve the transmission performance and reduce the gap between chaotic optical communication and deployed coherent optical communication systems. As an important figure of merit, the bit rate–distance product of chaotic optical communication has been continually improved, but it is still far from the requirement for a deployed optical fiber communication system, which is currently beyond 100 Gb/s × 1000 km.

In this paper, we propose and experimentally demonstrate a pilot-based DSP scheme for coherent chaotic optical communication via deep-learning synchronization, which significantly increased bit rate–distance product of chaotic optical communication from 30 Gb/s × 340 km to 100 Gb/s × 800 km. A pilot tone is inserted in the spectrum of a chaotic encrypted carrier and serves as a good frequency offset (FO) indicator. The FO estimation and compensation are implemented by determining the location of the pilot tone. Then a pilot symbols-based multiple-input multiple-output equalizer is adopted for joint adaptive equalization and carrier phase estimation, which can mitigate the polarization-mode dispersion and achieve a reliable tracking of the time-varying single-mode fiber (SMF) channel variation. More important, the well-trained deep-learning model can synchronize various types of chaotic systems, and the DSP module can be used as the fiber channel compensation algorithm for any modulation format signals. So our proposed scheme is not only fully compatible with commercial optical communication systems but also greatly enhances the application scenario of chaotic optical communication.

2 Experimental Setup

The experimental setup of the chaotic transmitter is shown in Fig. 1(a). The light with a power of 14 dBm generated by a continuous wave laser (CW1) is injected into a Mach–Zehnder modulator (MZM1) with a 3 dB bandwidth of 20 GHz and a half-wave voltage of 4.1 V. The output light of MZM1 is the chaotic carrier $c(t)$ divided into two parts through an optical coupler (OC1), where one part is mixed with the quadrature phase-shift keying (QPSK) message $m(t)$ from MZM2 for security, and the other part is collected as a data set for a neural network (NN). The variable optical attenuator (VOA1 and VOA2) is used to adjust the mixing ratio of message $m(t)$ and chaos $c(t)$. MZM2 is driven by a 25 Gb/s QPSK message generated by an 80 GS/s arbitrary waveform generator (AWG). The power ratio of the signal to the chaotic carrier is 1.5:1, which has been proven safe in our previous work.[16] The encrypted carrier $m(t) + c(t)$ is divided into two parts, where one part is sent back to the feedback loop driving MZM1 to create chaos with 15 GHz bandwidth. In the feedback loop, the encrypted carrier is first delayed by the delay line (DL), attenuated by VOA3, then converted into a photodetector (PD1) with a 3-dB bandwidth of 20 GHz, and finally amplified by an electrical amplifier (EA)

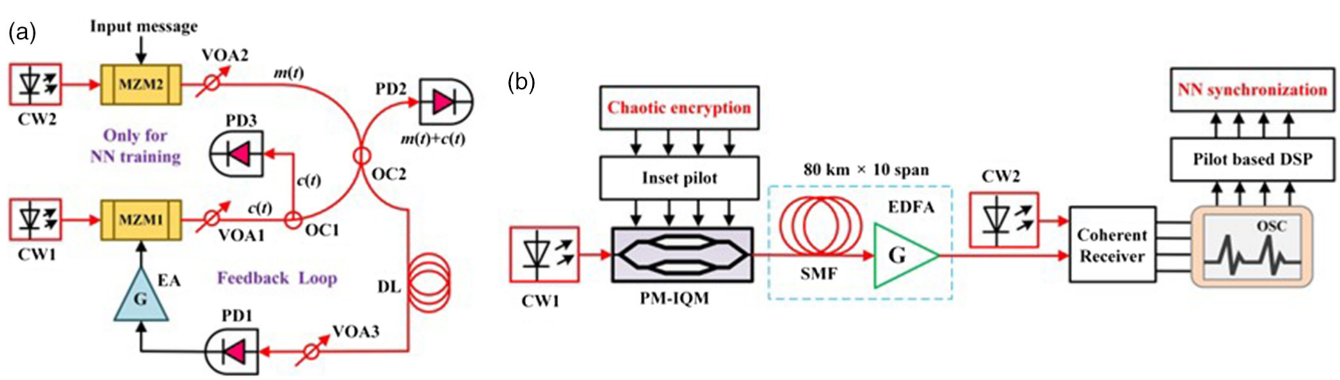

Fig. 1 Experimental setup. (a) Chaotic transmitter and (b) the offline pilot-based chaotic coherent fiber transmission system. CW, continuous wave laser; MZM, Mach–Zehnder modulator; OC, optical coupler; DL, optical delay line; VOA, variable optical attenuator; PD, photodiode; EA, electrical amplifier. PM-IQM, polarization multiplexing-in-phase/quadrature modulator; SMF, single-mode fiber; EDFA, erbium-doped fiber amplifier; OSC, oscilloscope; DSP, digital signal processing; and NN, neural network.

with a 3-dB bandwidth of 50 kHz to 15 GHz and a peak-to-peak voltage of 12 V.

The encrypted carrier $m(t) + c(t)$ and chaotic carrier $c(t)$ are received by PD2 and PD3, respectively, and collected by an oscilloscope (OSC) with the 100 GSa/s sampling rate. We first train the NN in the back-to-back case in the digital domain. In order to balance performance and complexity, we use a four-layer fully connected NN structure. The numbers of neurons in the first three layers is 201, 128, and 64, while the output layer has one node, corresponding to the desired chaotic signal after the time delay T. Chaos synchronization can be realized by extracting chaotic carrier $c(t)$ from encrypted carrier $m(t) + c(t)$. The principle of chaos synchronization via NN and the security of the system has been introduced and studied in detail in our previous work.[16,18] Here we focus on further improving the transmission performance of chaotic optical communication through coherent detection and pilot-based DSP algorithms. When the NN has been well trained, we remodulate the chaotic encrypted electrical signal to the optical domain for offline pilot-based fiber transmission experiments.

Figure 1(b) shows the chaotic coherent transmission structure. The wavelength of the CW1 is set to 1550 nm, and the nominal linewidth is 100 kHz. Pilot symbols and pilot tone are inserted into the chaotic encrypted signals first. The encrypted digital signals were uploaded to an AWG with a sampling rate of 80 GSa/s and modulated by a polarization-multiplexing in-phase/quadrature modulator (PM-IQM). The chaotic encrypted signal is modulated into the four channels of the PM-IQM to achieve a fourfold increase in the transmission rate. Then the 100 Gb/s chaotic encrypted optical signals are transmitted over the SMF with 0 dBm launch power. The transmission link consisted of 10 spans of SMF, and the length of each span was around 80 km. The total transmission distance was 800 km. After each span, an erbium-doped fiber amplifier (EDFA) with a 5-dB noise figure was used to compensate for the fiber loss. Afterward, the transmitted optical encrypted signals were received by the coherent receiver, and a CW2 with a nominal linewidth of 100 kHz was used as the local oscillator. The outputs of four electrical signals were captured by a real-time digital storage OSC with a sampling rate of 100 GSa/s.

The pilot structure at the transmitter and the pilot-based DSP module at the receiver are shown in Fig. 2. The security level of the NN-based chaos synchronization was analyzed in our previous work.[16] We consider three well-known attacks: brute-force attack, free cyphertext attack, and plaintext attack. We concluded that if the eavesdropper does not have physical access to the transmitter, the eavesdropper cannot train the NN and further decrypt the message. Even if the eavesdropper extracts the pilot, it will not affect security performance. The frame structure of pilot symbols is shown in Fig. 2(a). In order to balance the communication rate and algorithm performance, a pilot sequence of length $N_p = 1024$ is inserted at the beginning of the chaotic symbol stream, followed by equally spaced pilot symbols with a pilot rate of $1/N_S = 1/32$. The sequence length of the AWG is 2,[19] so the overhead is about 3.51%. The pilot sequence guarantees a fast convergence of the equalization algorithm. The pilot symbols will be used for joint equalization and phase-noise compensation, and both pilot sequence and pilot symbols are QPSK symbols. Figure 2(b) shows the spectrum of the pilot tone and the chaotic encrypted carrier. Pilot tones are inserted as single-frequency probes at the frequency of $f_0 = 16$ GHz. Figure 2(c) illustrates the principle of the FO compensation intuitively, where the semiellipses denote the spectrum of the chaotic encrypted carrier and the arrows denote the spectrum of the pilot tone. Under the effect of the carrier FO, both the spectra of the pilot tone and the chaotic encrypted carrier shift in frequency. And the frequency shift equals the carrier FO. So FO can be estimated easily by determining the location of the pilot tone in the spectrum of the pilot tone. Figure 2(d) shows the pilot-based DSP module at the receiver. Normalization and deskew correction are first applied to compensate the receiver IQ impairments, followed by chromatic dispersion (CD) compensation in the frequency domain. Then pilot tone-FO compensation and frame synchronization are carried out. Afterward, pilot symbols equalization and carrier phase recovery (CPR) are employed. Pilot symbol-based

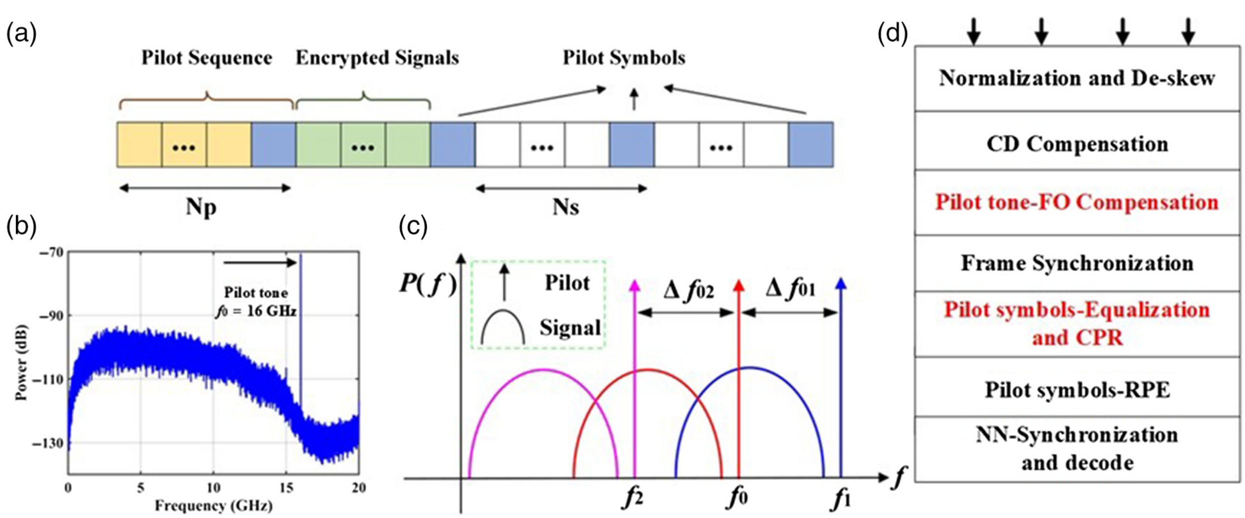

Fig. 2 Pilot structure at the transmitter and the DSP module at the receiver. (a) Frame structure of pilot symbols; (b) pilot tone structure of chaotic encrypted carriers; (c) principle of FO compensation by pilot tone; and (d) receiver pilot-based DSP module. CD, chromatic dispersion; CPR, carrier phase recovery; RPE, residual phase estimation; and NN, neural network.

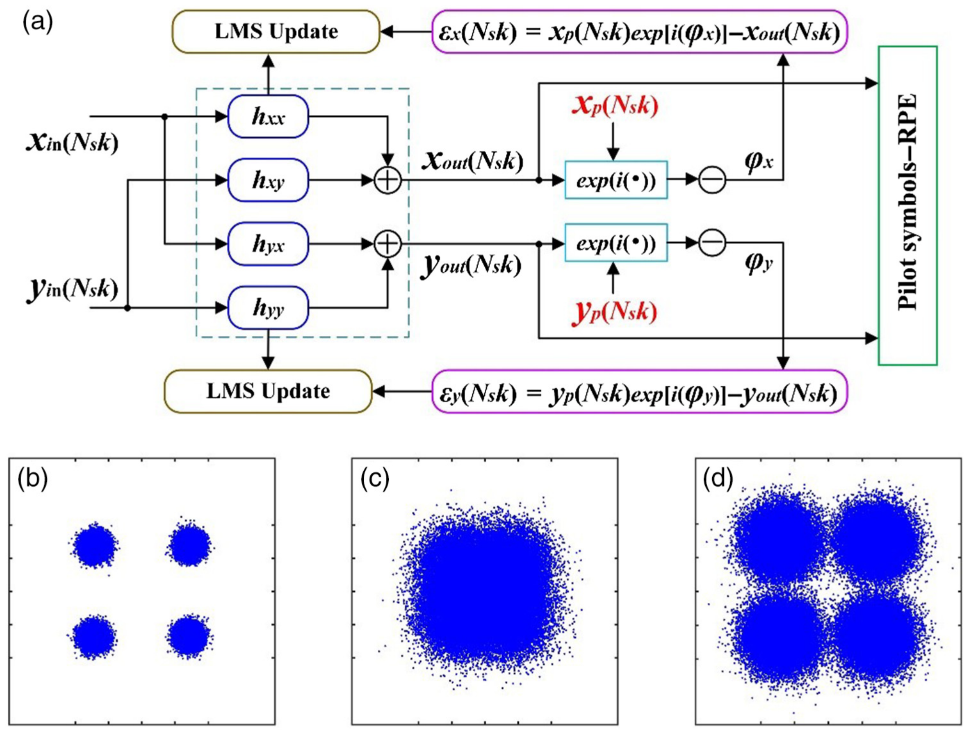

Fig. 3 Equalization algorithm process and constellations of the encrypted and decrypted QPSK signal. (a) Jointly LMS equalization and phase noise compensation by pilot symbols; (b) constellation of decrypted QPSK signals in the back-to-back case; (c) constellation of chaotic encrypted carrier; (d) constellation of decrypted QPSK signal by NN after 800 km fiber transmission.

residual phase estimation further compensates for phase noise by the V–V algorithm.[22] Finally, NN synchronization and decoding are conducted. The detailed joint least mean square (LMS) equalization and CPE operation of the pilot-based 2×2 equalizer are shown in Fig. 3(a). $x_{\mathrm{in}}(N_S k)$ and $y_{\mathrm{in}}(N_S k)$ are the input pilot symbols after frame synchronization. h_{xx}, h_{xy}, h_{yx}, and h_{yy} are the tap coefficients of the LMS filter. The recursive least square algorithm by pilot sequence brings the equalizer to a convergence. Then at each pilot symbol position $N_S k$, the CPE block adopted the pilot symbols $x_p(N_S k)$ and $y_p(N_S k)$, and recovered symbols $x_{\mathrm{out}}(N_S k)$ and $y_{\mathrm{out}}(N_S k)$ to estimate the current phases φ_x and φ_y. Then the phase is used to modify the error function of the LMS equalizer,

$$\begin{cases} \varepsilon_x(N_S k) = x_p(N_S k)\exp(i\varphi_x) - x_{\mathrm{out}}(N_S k) \\ \varepsilon_y(N_S k) = y_p(N_S k)\exp(i\varphi_y) - y_{\mathrm{out}}(N_S k) \end{cases}. \tag{1}$$

Finally, we apply the LMS updating rules, and the updated tap weights are used for the following chaotic encrypted carrier payload symbols as well.[23] Once this process converges, the equalizer can continuously track the fiber channel changes throughout the symbol stream with the filters only modified at pilot symbol positions, corresponding to the calculation complexity of $1/N_S$.

3 Results

The constellation of 100 Gb/s QPSK signal after chaotic encryption and decryption is shown in Figs. 3(b)–3(d). The decoded QPSK constellation of the chaotic encrypted signal after NN synchronization in the back-to-back case is shown in Fig. 3(b). The signal-to-noise ratio (SNR) of the decoded QPSK signal is 17.4 dB, and the bit error rate (BER) is 0. Figure 3(c) shows the constellation of the encrypted chaotic carrier. It can be seen that the constellation is completely noisy. After 800 km fiber transmission and DSP processing, the decoded QPSK constellation is shown in Fig. 3(d). After NN synchronization, the SNR of the decoded QPSK signal is 9.9 dB, the correlation coefficient is 0.9, and the BER is 1.8×10^{-3}, which is lower than the hard-decision forward-error-correction threshold. Due to the improvement of the performance of the pilot-based algorithm, compared to our previous work,[21] the chaotic synchronization correlation coefficient remains similar, but the transmission rate and distance have been greatly improved.

In order to enhance system security and ensure the continuous and nonrepetitive characteristics of the chaotic optical carrier, we propose to insert pilot symbols and pilot tone in real time through a field-programmable gate array (FPGA), which can not only ensure high-speed and long-distance transmission but also preserve the continuity aperiodicity of optical chaotic carriers. Figure 4(a) shows the experimental structure of the real-time pilot-based chaotic coherent fiber transmission system. The chaotic transmitter is roughly the same as the device in Fig. 1(a), but the bandwidth of the EA is in the range of 30 kHz to 10 GHz with a peak-to-peak voltage of 10 V. To simplify the difficulty of the experiment, the chaotic encrypted carrier collected by PD2 is divided into two channels by an electrical coupler, one of which is delayed by an electrical delay line. The two-channel electrical signals are input into two

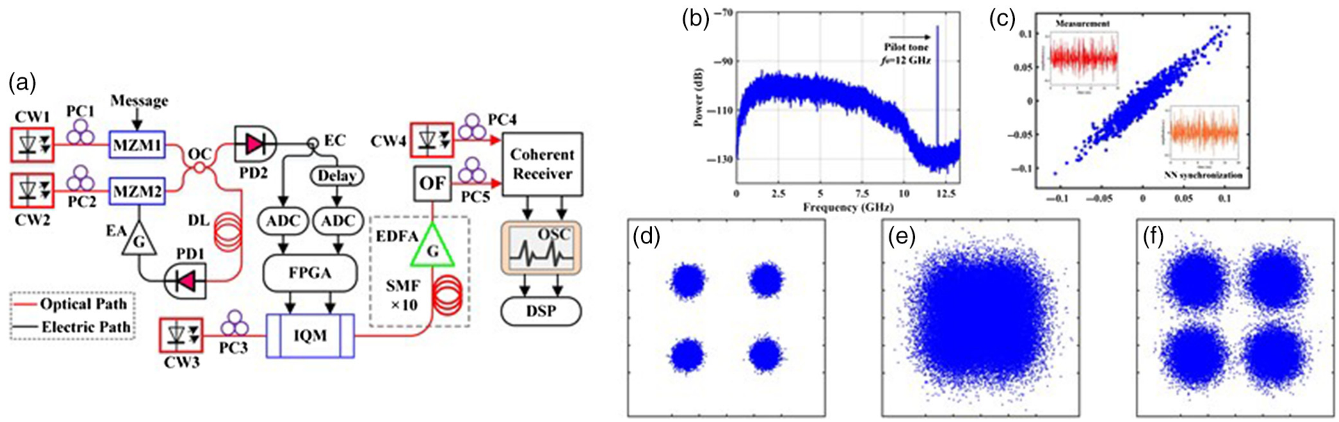

Fig. 4 Experimental setup and results of real-time pilot-based coherent chaotic fiber transmission system. (a) Experimental setup; (b) pilot tone structure of chaotic encrypted carriers; (c) plot of chaotic time series collected from PD2 and NN synchronization; (d) constellation of decrypted QPSK signals in the back-to-back case; (e) constellation of chaotic encrypted carrier; and (f) constellation of decrypted QPSK signal by NN after 800 km fiber transmission.

analog-to-digital converters (ADCs) with a 30 GSa/s sampling rate. After sampling, real-time pilot insertion of electrical encrypted signals via FPGA is realized. The FPGA is constantly buffering and sending encrypted signals. In order to reduce the computational complexity of the FPGA, the periodic sequence length of the pilot symbols is 2,[15] which corresponds to a 6.25% redundancy. Due to the limitation of FPGA's sampling rate, the bandwidth of the chaotic carrier is 10 GHz for 20 Gb/s QPSK signal encryption. The electrical encrypted signals are modulated to the IQM through the two digital-to-analog converters built in the FPGA to realize the 40 Gb/s chaotic encryption, and the 800 km encrypted transmission experiments are carried out.

The pilot tone structure of chaotic encrypted carriers is shown in Fig. 4(b). The bandwidth of the chaotic carrier is 10 GHz, so the position of the pilot tone is at $f_0 = 12$ GHz. The synchronization plot between chaotic time series from PD2 sampled by ADC and NN synchronization is shown in Fig. 4(c). The results show the good performance of chaos synchronization. The constellation of 40 Gb/s QPSK signal after chaotic encryption and decryption is shown in Figs. 4(d)–4(f).

Figure 4(d) shows the decoded QPSK constellation of the chaotic encrypted signal after NN synchronization in the back-to-back case. The SNR is 17.6 dB, with BER = 0. Figure 4(e) shows the constellation of the encrypted chaotic carrier. The decoded constellation after 800-km fiber transmission is shown in Fig. 4(f), where the SNR of the decoded QPSK signal is 10.2 dB, and the BER is 9.3×10^{-4}.

4 Discussion

We also studied the BER performance of decrypted QPSK signal after 800-km fiber transmission with different lengths of N_p and the pilot rate of N_S. The pilot rate of N_S was fixed at 1/32; the BER performance of the decrypted signal with different lengths of N_p is shown in Fig. 5(a). N_p uses the known pilot sequence to quickly converge the tap coefficients of the LMS filter. In the experiment, as long as the filter can be converged, the equalization performance can be guaranteed. Excessively increasing the length of N_p will increase the redundancy cost of the system. Then we fixed the pilot sequence at $N_p = 1024$; the BER performance of the decrypted signal BER with different pilot rates of N_S is shown in Fig. 5(b). Increasing the proportion

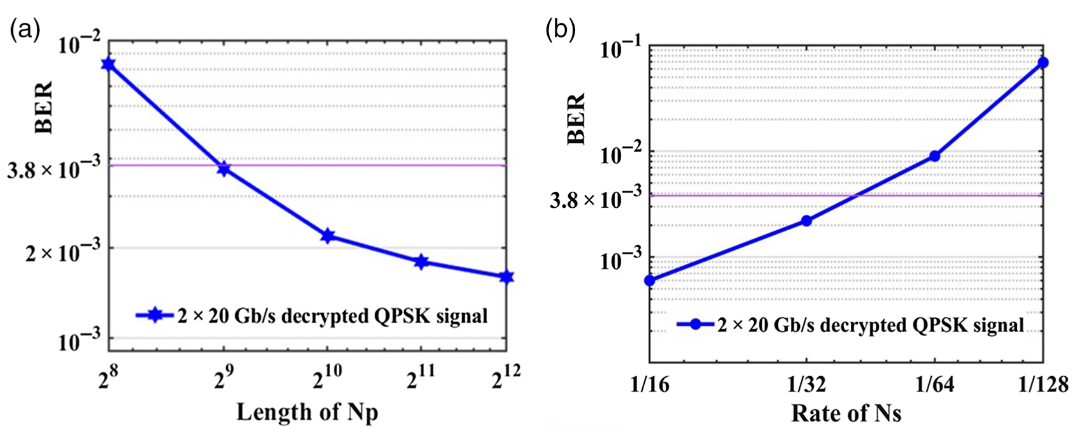

Fig. 5 BER performance. BER performance of decrypted QPSK signal after 800-km fiber transmission (a) with the length of N_p and (b) with the pilot rate of N_S.

of pilot rate will improve the system BER performance but greatly increase the redundancy of the system, so the proportion of pilot rate needs to be weighed in the experiment, which can not only achieve good equalization performance but also control the redundancy of the system within a reasonable range.

5 Conclusion

A pilot-based DSP scheme for coherent chaotic optical communication via deep-learning synchronization is proposed and experimentally demonstrated. The FO of transceiver lasers is estimated and compensated by a pilot tone. Channel equalization and phase noise compensation are jointly performed by the pilot symbols-based LMS algorithm. We realized 100 Gb/s chaotically encrypted QPSK signal over 800-km SMF transmission. And 40 Gb/s real-time chaotically encrypted QPSK signal over 800-km SMF transmission is achieved by inserting pilot symbols and tone in the FPGA. The proposed scheme is suitable for various chaotic optical communication scenarios and is a possible way to promote practical applications of chaotic optical communication systems and networks.

Disclosures

The authors declare no competing interests.

Code and Data Availability

The codes that support the findings of this study are available from the corresponding authors upon reasonable request. The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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References

1. A. Wang, Y. Wang, and H. He, "Enhancing the bandwidth of the optical chaotic signal generated by a semiconductor laser with optical feedback," *IEEE Photonics Technol. Lett.* **20**(19), 1633–1635 (2008).
2. Z. Gao et al., "32 Gb/s physical-layer secure optical communication over 200 km based on temporal dispersion and self-feedback phase encryption," *Opt. Lett.* **47**(4), 913–916 (2022).
3. L. Jiang et al., "Chaotic optical communications at 56 Gbit/s over 100-km fiber transmission based on a chaos generation model driven by long short-term memory networks," *Opt. Lett.* **47**(10), 2382–2385 (2022).
4. Y. Zhang et al., "Experimental demonstration of an 8-Gbit/s free-space secure optical communication link using all-optical chaos modulation," *Opt. Lett.* **48**(6), 1470–1473 (2023).
5. Y. Fu et al., "High-speed optical secure communication with an external noise source and an internal time-delayed feedback loop," *Photonics Res.* **7**(11), 1306–1313 (2019)
6. L. Wang et al., "Scheme of coherent optical chaos communication," *Opt. Lett.* **45**(17), 4762–4765 (2020).
7. Q. Li, "Numerical investigations of synchronization and communication based on an electro-optic phase chaos system with concealment of time delay," *Appl. Opt.* **58**(7), 1715–1722 (2019).
8. Y. Fu et al., "Analog-digital hybrid chaos-based long-haul coherent optical secure communication," *Opt. Lett.* **46**(7), 1506–1509 (2021).
9. S. Tang et al, "Message encoding and decoding through chaos modulation in chaotic optical communications," *IEEE Trans. Circuits Syst.* **49**(2), 163–169 (2002).
10. J. Zong et al., "Real-time secure optical OFDM transmission with chaotic data encryption," *Opt. Commun.* **473**, 126005 (2020).
11. A. Argyris et al., "Chaos-based communications at high bit rates using commercial fibre-optic links," *Nature* **438**(7066), 343–346 (2005).
12. R. Lavrov, M. Jacquot, and L. Larger, "Nonlocal nonlinear electro-optic phase dynamics demonstrating 10 Gb/s chaos communications," *IEEE J. Quantum Electron.* **46**(10), 1430–1435 (2010).
13. J. Ke et al., "Chaotic optical communications over 100-km fiber transmission at 30-Gb/s bit rate," *Opt. Lett.* **43**(6), 1323–1326 (2018).
14. L. Wang et al., "Experiment on 10-Gb/s message transmission using an all-optical chaotic secure communication system," *Opt. Commun.* **453**, 124350(2019).
15. N. Jiang et al., "Physical secure optical communication based on private chaotic spectral phase encryption/decryption." *Opt. Lett.* **44**(7), 1536–1539 (2019).
16. J. Ke et al., "32 Gb/s chaotic optical communications by deep-learning-based chaos synchronization," *Opt. Lett.* **44**(23), 5776–5779 (2019).
17. K. Kikuchi, "Fundamentals of coherent optical fiber communications," *J. Lightwave Technol.* **34**(1), 157–179 (2015).
18. Z. Yang et al. "Chaotic optical communication over 1000 km transmission by coherent detection," *J. Lightwave Technol.* **38**(17), 4648–4655 (2020).
19. A. Zhao et al., "Physical layer encryption for WDM optical communication systems using private chaotic phase scrambling," *J. Lightwave Technol*, **39**(8), 2288–2295 (2021).
20. Y. Wu et al., "60 Gb/s coherent optical secure communication over 100 km with hybrid chaotic encryption using one dual-polarization IQ modulator," *Opt. Lett.* **47**(20), 5285–5288 (2022).
21. Z. Yang, "Coherent chaotic optical communication of 30 Gb/s over 340-km fiber transmission via deep learning," *Opt. Lett.* **47**(11), 2650–2653 (2022).
22. G. Jacobsen, "Study of EEPN mitigation using modified RF pilot and Viterbi-Viterbi based phase noise compensation," *Opt. Express* **21**(10), 12351–12362 (2013).
23. S. J. Savory, "Digital filters for coherent optical receivers," *Opt. Express* **16**(2), 804–817 (2008).

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