Highly Secure and Reliable 7-Core Fiber Optical OFDM Access System Based on Chaos Encryption Inside Polar Code

Yu Bai, Bo Liu, Jianxin Ren, Yaya Mao, Zhipeng Qi, Shuaidong Chen, Xiumin Song, Suiyao Zhu, Lingzhi Yuan, Shun Han, and Rahat Ullah

***Abstract*—A highly secure and reliable optical orthogonal frequency division multiplexing passive optical network (OFDM-PON) based on the chaos encryption inside polar code scheme is proposed. The 3-dimensional Chua's circuit model is adopted to realize chaotic encryption during polar encoding with low complexity. The three chaotic sequences generated by Chua's circuit model are used to encrypt information index bit matrix, frozen bits (during polar encoding) and subcarrier sequence, respectively. The BER and security performance of the optical transmission system are enhanced by our method. A 70 Gb/s polar encoded encrypted 16 quadrature amplitude modulation OFDM signal transmission over a 2 km seven-core fiber is further experimentally demonstrated. The experimental results show that the polar encoded encrypted 16 QAM-OFDM obtains a 2.1 dB gain in receiver sensitivity at a BER of 10^{-3} under the same bit rate compared to the normal 16 QAM-OFDM without FEC. Moreover, the key space of the proposed scheme is 10^{84}, which is large enough to guard against any malicious attacks from illegal ONUs effectively. The combined superiority of BER and security performance enable such OFDM-PON based on chaos encryption inside polar code, to have a high prospect of application in low-cost and reliable optical access system.**

***Index Terms*—Chaos encryption inside polar code, OFDM-PON, seven-core fiber, Chua's circuit model.**

I. Introduction

THE emergence of large-scale commercial communication networks has been in urgent need for high security and reliability of high-speed optical communication systems [1]. With the development of network service such as virtual reality, HD video and cloud computing, there is a high demand for large bandwidth as well as increased supported users of optical access system. The OFDM PON is capable of meeting the requirement of rapid growth of the bandwidth, which is hence considered as a promising candidate for optical access system [2]. However, the capacity of the PON based on standard single mode fiber is limited. In order to further increase the bandwidth and the number of users, the space division multiplexing has been proposed [3], [4]. The OFDM-PON with multi-core fiber is expected to provide larger bandwidth and number of users in the foreseeable future.

Reliability and security are two crucial characteristics in the OFDM-PON system. Due to high spectral efficiency, cost effective, compatible constellation and polarization mode dispersion (PMD) robustness, the optical orthogonal frequency division multiplexing (OFDM) has attracted much attention [5]–[8]. In the optical communication system, the loss and noise could affect the quality of information transmission significantly, so that it is necessary to adopt error-correction coding to code and modulate the signal. The soft-detection forward error correct (FEC) is regarded as one of the most promising solutions, which can achieve both power reduction and cost efficiency [9]. In 2009, polar code, a new FEC scheme, was proposed by Arikan [10], [11]. The polar code is based on the theory of channel polarization, which can be divided into two processes: channel coupling and channel splitting. With the infinite increase of code length, some sub-channels tend to be noiseless, and the others tend to be pure noise. Theoretically, polar code can achieve the Shannon limit with relatively low complexity decoding. The error correct performance and complexity advantages of polar code becomes more obvious with the increase of code length. Moreover, relevant studies [9], [12], [13] have verified that the polar code using list-cyclic redundancy check (CRC) decoding shows better performance in short block length than the one based on low density parity code (LDPC). Most researches on polar code are mainly concentrated on decoding [14]–[18], while the study on the encryption security and frozen bits is few. Considering the excellent performance of polar code, it is necessary to further study its performance in OFDM optical access system.

Manuscript received August 27, 2021; revised October 4, 2021; accepted October 21, 2021. Date of publication October 27, 2021; date of current version November 18, 2021. This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFB1800905, in part by the National Natural Science Foundation of China under Grants 61775098, 61822507, 61835005, 61875248, 61727817, U2001601, 62035018, 61975084, 61720106015, 61935011, and 61935005, in part by Open Fund of IPOC (BUPT), Opened Fund of the State Key Laboratory of Integrated Optoelectronics under Grant IOSKL2020KF17, and in part by Jiangsu team of innovation and entrepreneurship, The Startup Foundation for Introducing Talent of NUIST. *(Corresponding author: Bo Liu.)*

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Digital Object Identifier 10.1109/JPHOT.2021.3122909

On the other hand, due to the broadcasting of OFDM-PON, downlink singles can be received by all optical network units (ONUs), making it difficult to keep the security of transmitted information [19], [20]. At present, physical layer encryption is widely used in digital signal processing (DSP) owning to its low cost, high flexibility and compatibility. The physical layer encryption based on chaotic system that is ergodic, pseudorandom and parameter sensitivity can protect transmitted information from violent attacks. The current researches on physical layer chaos encryption mainly focus on the encryption methods of frequency domain, time domain and modulation format [21]–[26], using one-dimensional or multi-dimensional encryption to achieve higher security of transmission. There are few researches on joint chaotic encryption based on error-correction coding. Although the group has realized a high security optical transmission system with large key space by using Chua's circuit model, the transmission reliability has not been improved [27]. Recently, Xiao *et al* also used physical layer encryption to encrypt subcarriers in Polar coded optical OFDM system, whose encryption mode is single and easy to crack [28]. The proposed scheme uses multi-dimensional encryption during polar encoding. The close combination of Polar code and chaos encryption not only makes signals more difficult to be cracked illegally, but also improves the reliable performance of optical transmission system. And there is still lack of encryption coding modulation methods to guarantee the reliability and security of multi-core OFDM-PON.

In this paper, a highly secure and reliable 16QAM-OFDM-PON applied in optical access system based on chaos encryption inside polar code, is proposed and demonstrated in the 2 km seven-core fiber transmission experimentally. The 3D Chua's circuit model is adopted to realize chaotic encryption during polar encoding, BER improvements and security performance enhancement simultaneously. The chaotic sequences, generated by Chua's circuit model, are used for the perturbation encryption of information index bit matrix, frozen bits (during polar encoding) and subcarrier sequence (during subcarrier modulation). Compared with the normal 16 QAM-OFDM without FEC, the experimental results show that the polar encoded encrypted 16 QAM-OFDM obtains a 2.1 dB gain in receiver sensitivity at a BER of 10^{-3} under the same bit rate. In addition, the key space of the proposed scheme is 10^{84}.

II. Principles

The principle of the proposed highly secure and reliable OFDM-PON based on chaos encryption inside polar code is illustrated in Fig. 1. In order to reduce the complexity of polar coding, the original data stream is transformed into a relative short multi-channel parallel data stream after serial/parallel conversion, and then sent to polar encoding module. During polar coding, two groups of chaotic sequences, generated by chaotic system, are used to encrypt the information index bit matrix and frozen bits to improve the security. Meanwhile, another chaotic sequence is used to encrypt the subcarrier sequence after QAM module. Then the polar encoded encrypted 16 QAM-OFDM signal is transmitted in a seven-core fiber. At the receiving end, the ONUs with all keys will decrypt correct information. Compared with traditional 2-dimensional encryption, the 3-dimensional Chua's circuit model has better encryption effect and is more difficult to be cracked. So, the 3-dimensional Chua's circuit model [29] is adopted in this scheme to generate chaotic sequence for encryption, which can be expressed as:

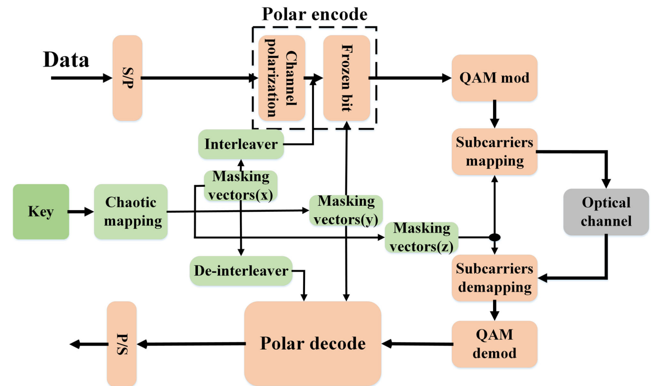

Fig. 1. The schematic diagram of highly secure and reliable OFDM-PON based on chaos encryption inside polar code.

$$\begin{cases} \partial x/\partial t = \alpha(y - x - f(x)) \\ \partial y/\partial t = x - y + z \\ \partial z/\partial t = -\beta y \\ f(x) = bx + 0.5(a-b)(|x+1| - |x-1|) \end{cases} . \quad (1)$$

where x, y, z are chaotic sequences generated by the chaotic system, and a, b, α, β are constants of Chua's model. Fig. 2 shows the phase diagram and bifurcation process of Chua's model. It is obviously shown in the bifurcation diagram that x becomes chaotic when α is bigger than 8.8. Here, the value of a, b, α, β are set as -1.27, -0.65, 10 and 14.87. The initial values (x_0, y_0, z_0) are set as 0.3, -0.8, 0.5. Three groups of chaotic sequences (x, y, z) will be obtained simultaneously after initial value and iteration time being set. Then, x and y are used for the perturbation encryption of information index bit matrix and frozen bits during the polar encoding process, while z is used for perturbation encryption of subcarrier sequence.

The polar coder used in the scheme is shown in the Fig. 3. The pseudo-random binary U is coded by the systematic polar encoder to form the code-word X, acting as the input data stream. The Gaussian approximation is used for the construction of polar code to obtain the capacities of different bit channels [30], [31]. The information bits are assigned to bit channels with high reliability at the output side, which is recorded by a set of indexes known as information index bit matrix. Oppositely, the frozen bits are set to 0 or 1 and assigned to bit channels with low reliability at the input side. In each code unit, the code-word X can be defined as:

$$\begin{cases} G_N = B_N \cdot F^{\otimes n}, \quad n = \log_2 N \\ X_N = U_N \cdot G_N = U_N \cdot B_N \cdot \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}^{\otimes n} \end{cases} \quad (2)$$

where N is the code length, B_N is the bit-reversal permutation matrix and $\otimes n$ represents the n^{th} ($n = \log_2 N$) Kronecker power of the matrix. It has been demonstrated that systematic polar

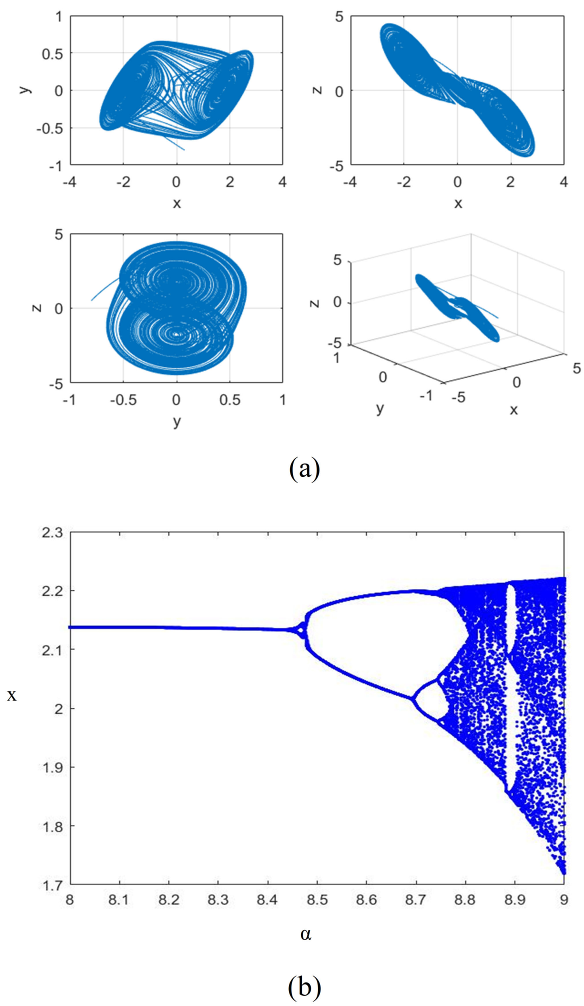

Fig. 2. The phase diagram: (a) and bifurcation process and (b) of Chua's model.

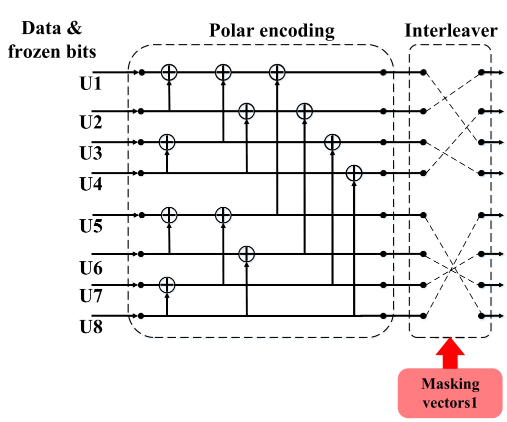

Fig. 3. Schematic of polar encoder. The input side consists of information and frozen bits.

code has excellent performance in BER performance. The information index bit matrix and frozen bits are very important for receiver to decode correctly. Therefore, it is necessary to improve the security of the optical transmission system based on the combination of polar code with chaotic encryption.

Considering decoding complexity and encoding gain [9], [13], [18], the code length N and encoding rate are set to 256 and 0.5, respectively. The joint chaos encryption with the polar encoding scheme is proposed, adopting chaotic sequences x and y to encrypt the information index bit matrix and frozen bits. If the information index bit matrix is stolen, transmitted information will be easily decoded by illegal ONUs. It is necessary to protect optical communication system from threats by chaotic sequences. For the encryption of information index bit matrix, the generated scrambled sequence is illustrated as follows:

$$\inf\_bite\_new = f_x\{\inf\_bite(sort(\mathrm{mod}(x_n, 1)))\} \quad (3)$$

where inf_*bite_new* (inf_*bite)* represents information index bit matrix, $f_x\{\}$ is the rule to scramble information index bit matrix. During the encryption, selecting chaotic sequence x as the label of the information indexes, which equals in length to the information index bit matrix. By ordering the label sequence x in a special rule, the information index bit matrix will be scrambled.

For the traditional polar code, its frozen bits are fixed to either 0 or 1, which is easily cracked. So, the chaotic sequence y is used to determine the frozen bit of each block group. The length of y is equal to the number of block groups. It has become more and more difficult for illegal ONUs to crack the information with the increase of block group numbers. The chaotic sequence y is multiplied by 10^{15} and divided by 2 to find the remainder, and the results will be the number of frozen bits. The generation rule is as follows:

$$l\_frozen = floor(\mathrm{mod}(y_n \cdot 10^{15}, 2)) \quad (4)$$

where *l_frozen* represents frozen bits, with a value of 0 or 1.

After polar encoding, chaotic sequence z is used to scramble and encrypt subcarriers in order to further improve the security of optical transmission system. Similar to the encryption of information index bit matrix, chaotic sequence z is selected as the label of OFDM subcarriers. Then, the perturbation scramble of subcarriers is realized by ordering the label sequence z, in a certain rule. The perturbation scramble process for subcarrier sequence is similar to information index bit matrix. The generated scrambled sequence can be illustrated as follows:

$$subcarriers\_new = f_z\{subcarriers(sort(\mathrm{mod}(z_n, 1)))\} \quad (5)$$

where *subcarriers_new* (subcarriers) represents the subcarrier sequence, $f_z\{\}$ is the rule to scramble subcarrier sequence. After the interweaving polar encoding and chaotic encryption, the security and reliability of optical transmission system are improved significantly. The ONUs, which owns all the keys, can accurately restore the original information.

III. Experimental Setup and Results

To verify the BER and security performance of the proposed OFDM-PON based on chaos encryption inside polar code, an experiment setup is carried out as shown in Fig. 4. In the optical line terminal (OLT), the encrypted OFDM single is generated via offline DSP processing in the electrical domain. And a total of 128 subcarriers are used to carry the encrypted 16QAM coded data (entropy is 4 bits/symbol), while other 128

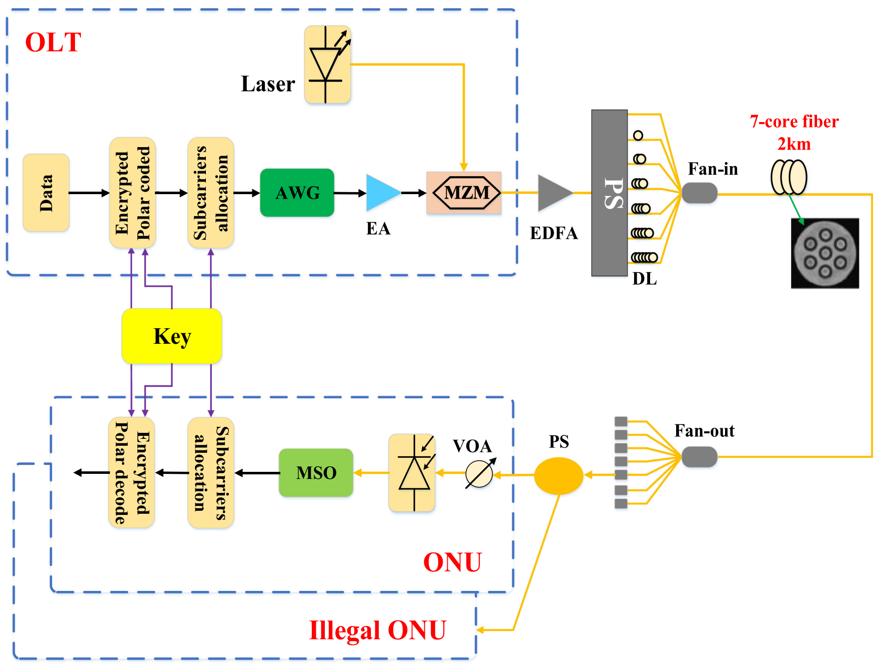

Fig. 4. Experimental setup (AWG: arbitrary waveform generator; EA: electrical amplifier; MZM: Mach-Zehnder modulator; PS: power splitter; VOA: variable optical attenuator; PD: photodiode; MSO: mixed signal oscilloscope; DL: delay line).

subcarriers are adopted to carry the corresponding complex conjugates to fulfil Hermitian symmetry so as to ensure the output of real values of the signal, which are then used for intensity modulation and direct detection. The size of IFFT is 512. The 1/4 of the OFDM symbol length is added as cyclic prefix (CP) to avoid inter-symbol interference (ISI). And the generated digitally-encrypted 16QAM-OFDM encoded signal undergoes digital-to-analog converting procedure by an arbitrary waveform generator (AWG, TekAWG70002A) with 12.5GSa/s. After transmitting through the electrical amplifier (EA), electrically encrypted 16QAM-OFDM encoded signal is injected into Mach-Zehnder modulator (MZM) for intensity modulation to generate modulated optical signal for 2 km seven-core fiber transmission. With the amplification (EDFA) and power splitting (PS), the polar encoded encrypted 16QAM signal is sent to a seven-core fiber by Fan-in device. The fibers used in the experiment exhibit consistent and low attenuation characteristics, and the attenuation coefficient are measured less than 0.3 dB/km at 1550 nm. In addition to the transmission loss, the misalignment between the multicore fiber and the Fan-in/Fan out device is another cause for the additional insertion loss. Consequently, the accuracy of the core pitch and the accurate alignment of each connection point are the key to solving the problem. The signals are multiplexed spatially through a Fan-in device consisting of seven thin cladding fibers wrapped by glass capillaries, and the average insertion loss of each fiber core is about 1.5 dB. The crosstalk between adjacent cores is less than -50 dB. The ONUs with all the keys can decrypt the correct information after the transmission through the 7-core fiber.

In the experiment, a continuous wave (CW) laser with the wavelength of 1550 nm and the optical power of 14.5 dBm is emitted from the light source. In the ONU, a variable optical attenuator (VOA) is adopted to adjust the received optical power for the further optical signal detection by photodiode (PD) to obtain the electrical 16QAM-OFDM encoded signal. Following the analog-to-digital converting functioned by a mixed signal oscilloscope (MSO, TekMSO73304DX), the offline DSP reversed to the OLT performs signal demodulation and decryption to recover the original information. As far as OFDM signal is concerned, the total bit rate can be tantamount to the expression of (subcarrier number $\times$ entropy $\times$ AWG sampling rate/IFFT size/(1+CP)). A 70 Gb/s (10 Gb/s $\times$ 7) the encrypted 16QAM-OFDM signal transmission over 2 km seven-core fiber is experimentally demonstrated to verify the feasibility of the proposed scheme.

The joint polar decoding method of cyclic redundancy (CRC) and successive cancellation list (SCL) has better performance in short codes than LDPC codes [9], [13], [18]. In the report [9], it is verified that polar codes show better performance with the increase of code length. Moreover, the performance of SCL decoder is related to decoding list size (L). With the decoding list size increasing, the systematic performance becomes better at the cost of larger complexity. However, the improvement in BER performance at $L = 32$ is negligible compared with $L = 16$. Overviewing the performance and complexity of the system, the SCL decoder is adopted and L is set as 16.

Fig. 5 shows the comparison of BER performances between the proposed polar coded encrypted 16QAM-OFDM, only polar coded and without coded unencrypted 16QAM-OFDM. It is obviously observed that the BER performances of different cores are very close to each other, and the maximum differences of received optical powers between seven cores is about 1 dB at BER of 10^{-3}. Considering the randomness of transmission system, the constellation diagram in Fig. 5(b) and Fig. 5(c) shows

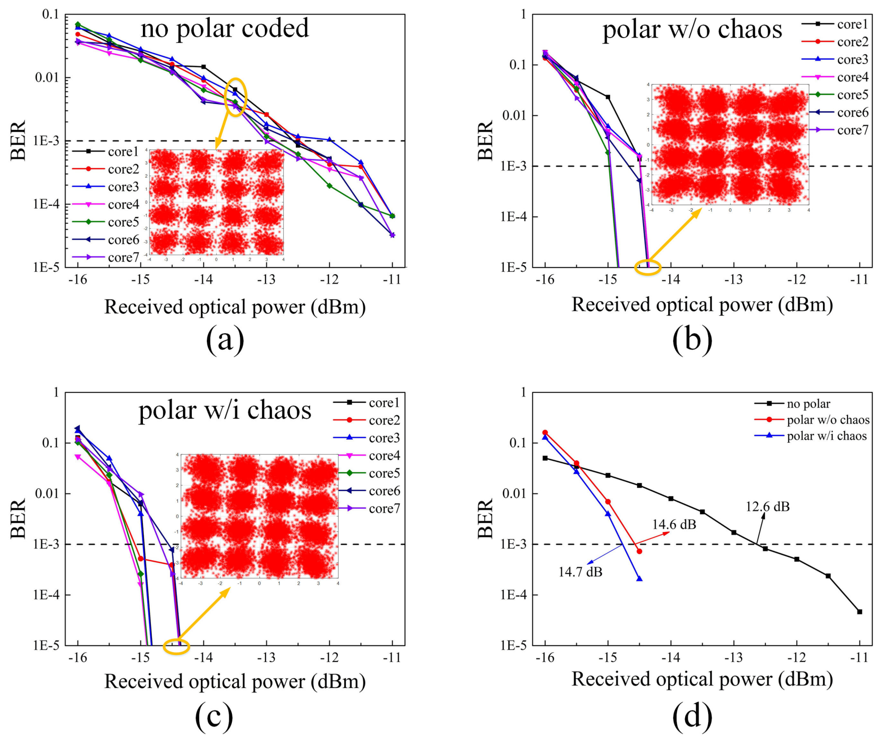

Fig. 5. BER curves of no polar coded 16QAM-OFDM, polar coded without encrypted 16QAM-OFDM, and polar coded encrypted 16QAM-OFDM under the same bit rate after 2 km 7-core fiber transmission.

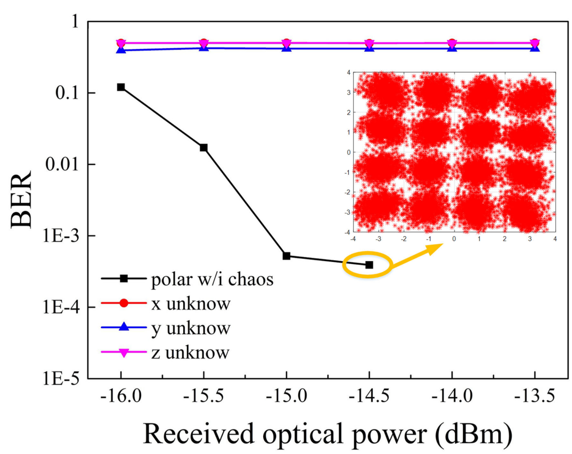

Fig. 6. BER curves of legal ONU and illegal ONU after 2 km transmission.

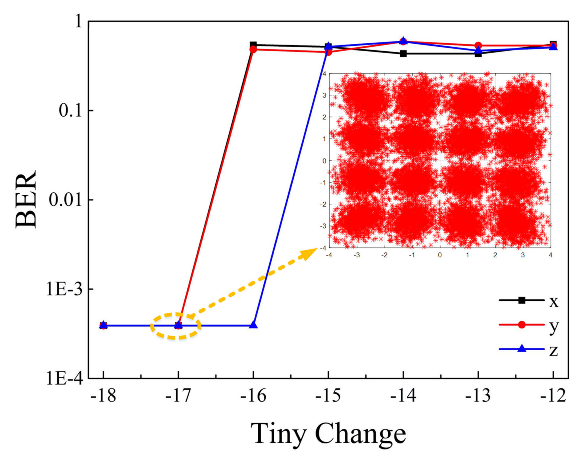

Fig. 7. BER curves of various ONUs with a tiny change in initial value.

no differences compared with Fig. 5(a). This is attributed to the fact that polar code is a kind of external codes. Furthermore, the averaged BER performances of seven cores are shown in Fig. 5(d). At BER of 10^{-3}, a nearly 2.1 dB gain is obtained in the receiver sensitivity compared with no FEC coded 16QAM-OFDM. In addition, the proposed scheme improves transmission security with the increase of received optical power (ROP) at no costs of reliability.

At last, we further verified the anti-attack capability of such OFDM-PON based on chaos encryption inside polar code. Fig. 6 depicts the BER curves of legal ONU and illegal ONU under the circumstance that only two initial values out of {x, y, z} are breached. It shows that the BER fluctuates at around 0.5, indicating original information cannot be deciphered even though the received constellation is clearly viewed.

For the illegal ONU, violent attack is the most common way to crack information. In our scheme, the security of joint chaos encryption with polar coding transmission is further studied and the influence of small disturbance of the keys on receiver is analyzed, as shown in Fig. 7. For x or y, when the initial value changes to 10^{-17} or smaller, there is no change in BER compared to the original correct parameter value. Once the initial value changes to 10^{-16} or larger, the BER curves dramatically increase. The smallest change for z is 10^{-16} with no obvious BER change.

For our system, the total of seven key parameters (a, b, α, β, x_0, y_0, z_0) can achieve a key space of 10^{84}, ensuring that violent cracking takes longer time than the keys updating.

IV. Conclusion

A highly secure and reliable OFDM-PON scheme based on chaos encryption inside polar code is proposed, realizing the enhancement of both BER and security performance in optical access system. Furthermore, a 70 Gb/s polar coded encrypted 16QAM-OFDM signal transmission over 2km in seven-core fiber is experimentally verified. Compared with the transmission system without FEC, the proposed polar coded encrypted 16QAM-OFDM, with SCL (L = 16) decoder, brings about 2.1 dB receiver sensitivity gain at a BER of 10^{-3} under the same bit rate. When it comes to the security enhancement, a key space of the proposed scheme is 10^{84}. It proves that the proposed scheme is effective in preventing transmission signals from being stolen by illegal ONUs. Experimental results indicate that the polar coded encrypted OFDM-PON scheme based on chaos encryption inside polar code could improves both BER and security performance in optical access system.

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