Basis Precoding Based on Probabilistic Constellation Shaping in QAM/QNSC

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Abstract—Quantum noise stream cipher (QNSC) is a physical-layer encryption approach for optical communications, and its security barrier is the “basis” that is used as the secret-key for symbol encryption. Regarding the fact that the basis is actually transmitted through the fiber, we propose a basis precoding scheme based on probabilistic constellation shaping, to better conceal the basis into the noise for security enhancement. Experimental results show our scheme can improve the security of the QAM/QNSC system in terms of Eve's symbol error ratio.

Keywords—quantum noise stream cipher, probabilistic constellation shaping, basis

I. INTRODUCTION

The optical network with high bandwidth and low delay meets the demand of abundant information transmission. In recent years, with the flourishing development of quantum computing, the encryption schemes based on mathematical complexity hardly meet the protection needs, and the security in optical networks faces greater challenges. Many researchers are engaged in the search for more secure encryption technologies. The physical layer security technology has become one of the current hot spots [1]. Y-00 quantum noise stream cipher (QNSC) is a popular physical layer security approach, which combines the advantages of both the ineluctable quantum noise and mathematical cryptography [2]. With Y-00, the original low-order plaintext signals at the legal transmitter are mapped to high-order ciphertext by coding with pre-shared secure keys, which is also referred to as the “basis”. Following the Y-00 coding protocol, the pre-shared key will be hidden in the quantum noise, and thus the ciphered signals can only be decrypted by the legitimate receiver with the pre-shared basis.

In the context of physical-layer security, capacity and security are two important metrics. Regarding the transmission capacity, experiments demonstrated a 10Tbit/s secure physical layer transmission using a combination of QAM/QNSC and injection-locked WDM techniques [3]. Focusing on the long-haul system without intermediate amplifiers, a 16 QAM/QNSC transmission system over 300km fiber was reported, and the product of distance and data rate has reached 10.2Tbit/s·km [4]. In addition, in terms of security, the fast correlation attack (FCK) can be prevented by maintaining a high-level noise mask and timely updating the seed keys [5]. In the above studies, the security degree of QNSC is evaluated in terms of the number of masked signals (NMS) or symbol error ratio (SER) for the eavesdropper (Eve). The larger NMS or the higher SER for Eve means a higher security level of the system. There are two typical ways to improve these two metrics, i.e., strengthening the noise effect of the system [6] and reducing the Euclidean distance between adjacent ciphertext signal symbols.

In fact, the above two metrics are valid only under the assumption that the pre-shared keys or the basis cannot be tracked by Eve. Otherwise, Eve will also be able to decrypt the ciphertext, just like a legitimate receiver. Therefore, the security of the basis is another fundamental factor for the overall security of a QNSC system. However, even though the QNSC system tries to hide the basis in the quantum noise, one risky fact is that the basis is actually coded into the ciphertext and transmitted through the fiber [7]. Therefore, the security of the basis itself is another important issue that needs to be addressed and it is worth exploring the approaches to enhance the security of the basis in QNSC.

Similar to the methodology for improving the security of the ciphertext symbols, one possible approach for securing the basis is to strengthen the noise's masking effect on the basis. In a traditional QNSC system, the basis with uniform distribution does not match noise so that the basis cannot be completely masked by noise. In this case, probabilistic constellation shaping (PCS), which can shape the probability distribution of signal symbols in the constellation [8], might be a promising technique for manipulating the distribution of the basis. Based on such advantages of PCS, this work investigates the ways for shaping the distribution of basis in the QNSC system, with the aim to tune the noise's masking effect on the basis. Besides, PCS improves the transmission performance of QNSC and reduces the performance loss caused by encryption algorithm.

This paper proposes a PCS-based basis encoding scheme to shape the distribution of basis to be matched with the distribution of noise and make the basis better masked with noise. We adopt the constant composition distribution matching (CCDM) algorithm to shape the basis following the desired distribution (e.g., Gaussian-like or Trapezoidal distributions). The proposed scheme is implemented in an 8.5Gbit/s (10Gb/s × 2 × 1/2 × (1-15%)) QAM/QNSC system over 300km ultra-low loss fiber (ULF). Experimental results show that our proposed scheme can improve the OSNR by 0.9 dB, Eve’s basis error ratio by 2.9E-4, and Eve’s SER by 5.8E-5 in the optimal condition.

II. QNSC WITH PCS-BASED BASIS SHAPING

This section introduces the CCDM algorithm briefly and designs the PCS-based basis shaping and Y-00 encryption schemes for the QNSC system.
A. PCS algorithm

CCDM is a famous PCS algorithm and it can convert independent and equiprobable binary bit sequences into a series of symbols with desired probability distributions. As a rule, output symbols of CCDM follow Maxwell-Boltzmann (MB) distribution, which is a Gaussian-like distribution. The usage of MB distributions can approximate the capacity limit of a channel with the additive white Gaussian noise, by gathering constellation points towards the center area. In contrast to the conventional PCS, which employs the half-MB distribution for amplitude with Trapezoidal distributions as two candidates to perform the PCS.

B. PCS-based Basis Shaping Scheme

Following the Y-00 protocol, the legitimate transmitter and receiver have the pre-shared keys. The shared keys are used to generate a set of origin keys using the pseudo-random number generator (PRNG). After CCDM encoding, the origin keys will be transformed into a set of symbols that follow the Gaussian-like or Trapezoidal shape distributions for amplitude with CCDM algorithm.

To verify the performance of the proposed scheme, we construct an experiment setup, as shown in Fig. 2. At the transmitter side, the arbitrary waveform generator (AWG) generates a signal with 300mV according to the output of DSP. An external cavity laser (ECL) is employed to maintain a stable laser with 10dBm of optical power at 1550nm. An I/Q modulator modulates electrical signal to optical signal. For the CCDM module inside the DSP part, we adopt the Gaussian-like and Trapezoidal distributions as two candidates to perform the PCS.
After encrypting the plaintext data with the shaped basis, a DFT-OFDM with 256-points DFT and 1024-points IDFT is adopted to reduce the peak-to-average power ratio of the system. Finally, the ciphertext symbols are dumped into a 300km of ULF channel without any intermediate amplifier. At the receiver side, the input power of the receiver is set to -5.3dBm. The sampling rate of the digital oscilloscope (OSC) is set to 40GSa/s. In the receiver’s DSP part, the CCDM module uses the same parameters as the transmitter to generate the same shaped basis for further decoding from ciphertext symbols to plaintext. We experimentally demonstrated an 8.5Gbit/s QAM/QNSC system and measured Eve’s basis error ratio and SER under various QAM orders, ranging from $2^{10}$ to $2^{20}$. We also measure the bit error ratio (BER) performance with the mapping space size (i.e., QAM order) fixed at $2^{20}$. Note that, with QPSK signal as the constellation with the Gaussian-like and Trapezoidal distribution, the Gaussian-like distribution achieves a higher basis error ratio and SER when the QAM order is lower than $2^{10}$. The Trapezoidal distribution achieves 0.9dB and 0.3dB OSNR improvement in terms of Eve’s basis error ratio and SER and achieve OSNR improvement. However, there’s a fly in the ointment: the order of basis is generally exceeding high to ensure security, which greatly increases the complexity of PCS algorithm. How to reduce the complexity of the algorithm is also the focus of our future work.

IV. CONCLUSIONS

This paper proposed a basis precoding scheme based on PCS in QAM/QNSC to conceal the basis in the noise for security enhancement. Experimental results show that the proposed scheme can improve OSNR by 0.9 dB with 15% overhead SD-FEC, while increase the basis error ratio of Eve by 2.9E-4 and the SER of Eve by 5.8E-5 in the $2^{20}$ QAM/QNSC system.

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