European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Space-wavelength-division-multiplexing-based Synergistic Transmission in Quantum Key Distribution Coexisting with Classical Communications

Weiwen Kong [(1)], Yongmei Sun [(1,*)], Xueqin Ren [(1)], Yaoxian Gao [(1)], Yuefeng Ji [(1)]

[(1)] The State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Haidian District, Beijing, 100876, China, ymsun@bupt.edu.cn

Abstract *We propose a synergistic core and wavelength allocation (SCWA) scheme to simultaneously improve the performance of classical optical communication and quantum key distribution. The experimental results show that SCWA scheme can improve the synergistic degree up to 0.57 compared to quantum unequal frequency spacing scheme. ©2022 The Author(s)*

Introduction

With the development of 5G and artificial intelligence, data transmission security is a focused issue. Quantum key distribution (QKD) can generate secure keys for remote parties based on the basic principles of quantum mechanics, combined with one-time pad technology to ensure the security of information theory[1]. In order to meet the requirements of high security and large capacity such as 5G and artificial intelligence, it is a development trend to transmit QKD and classical signals in space division multiplexing multicore fiber (MCF)[2-3].

However, it will bring some problems. On the one hand, the power of the classical signal is generally 0 dBm per channel, the power of the quantum signal is usually lower than -80 dBm, and the noises generated from the classical signal, such as spontaneous Raman scattering (SpRS) noise and four-wave mixing (FWM) noise, will degrade the QKD performance[4]. On the other hand, the addition of quantum channels will form a resource competition relationship with classical channels[5], which limits the performance of classical systems. Therefore, how to realize the synergistic and win-win performance of classical systems and QKD systems with limited resources is the challenge facing the simultaneous transmission of QKD and classical optical communication.

In the previous simultaneous transmission of QKD and classical optical communication, the focus was on improving the performance of QKD, but the performance of classical systems was not considered. For example, in Ref. [6], the classical channels are distributed in equal frequency spacing ways, and the low noise channels are allocated in unequal frequency spacing quantum channels (qUFS) ways to improve the secure key rate of QKD, but the classical channels are also affected by the FWM noise generated from classical signals in the same core and the inter-core crosstalk (ICXT) noise generated from the other cores, and they weaken the performance of classical optical communication.

In this paper, we define the concept of synergistic degree, and propose a synergistic core and wavelength allocation (SCWA) scheme to simultaneously improve the performance of classical optical communication and QKD. Finally, the performance of the proposed scheme is evaluated experimentally, and the synergistic degree can be improved up to 0.57 compared to qUFS scheme.

Synergistic Core and Wavelength Allocation Scheme

In order to simultaneously evaluate the performance of classical optical communication and QKD, the criterion of synergistic degree is defined. Each parameter corresponds to a parameter order degree, and the parameter includes the evaluation index of classical systems and QKD systems. Suppose the value range of the parameter is $[\alpha,\beta]$, the actual parameter is *e*, and the order degree of the parameter can be expressed as:

$$U^{i}_{c(q)} = \begin{cases} \frac{e-\alpha}{\beta-\alpha}, \text{index that needs to be improved} \\ \frac{\beta-e}{\beta-\alpha}, \text{index that needs to be reduced} \end{cases} \quad (1)$$

Set the order degree of the classical optical communication system U_c and QKD system U_q, which can be expressed as:

$$U_{c(q)} = \sum_i \omega_i U^{i}_{c(q)} \quad (2)$$

ω_i is the weight of each parameter. Therefore, the synergistic degree between classical optical communication and QKD system can be expressed as:

$$C = sig(\cdot)\sqrt{\left|U^{pro}_{c} - U^{ben}_{c}\right| \cdot \left|U^{pro}_{q} - U^{ben}_{q}\right|} \quad (3)$$

$U^{pro}_{c(q)}$ represents the order degree of the classical or QKD system of the proposed scheme, and $U^{ben}_{c(q)}$ represents the order degree of the classical or QKD system of the benchmark scheme. $sig(\cdot)$ is:

$$sig(\cdot) = \begin{cases} 1, U^{pro}_{c} - U^{ben}_{c} \geq 0 \ and \ U^{pro}_{q} - U^{ben}_{q} \geq 0 \\ -1, \ other\ cases \end{cases} \quad (4)$$

To improve the synergistic degree between the classical system and the QKD system, we propose space-wavelength-division-multiplexing -based SCWA scheme. For classical channels, mainly reduce intra-core FWM noise and avoid ICXT noise to improve optical signal noise ratio (OSNR). For quantum channels, mainly reduce intra-core FWM noise, intra-core SpRS noise, inter-core FWM noise, inter-core SpRS noise to reduce quantum bit error rate (QBER).

SCWA Scheme-1 Classical Channels and Quantum Channels Allocation

Input: The number of required *Fch*, *Bch* and *Qch*, that is R_f, R_b and R_q; The number of candidate *Fch*, *Bch* and *Qch*, that is C_f, C_b and C_q; *Fch*, *Bch* and *Qch* are distributed different wavelength ranges;

Output: The assigned *Fch, Bch* and *Qch.*

$i \in [1, C_{f/b}]$; $S_{f/b} \in \left\{1, \left\lceil \frac{1+C_{f/b}}{2} \right\rceil, C_{f/b}\right\}$;
for all candidate *Fch* and *Bch* **do**
  for $i \notin S_{f/b}$ do
    $FWM_i = \sum_{j=1}^{C_{f/b}} FWM_j(i, S_{f/b})$;
  end
  $i_{opt} = arg\{\min[FWM_i]\}$;
  $S_{f/b} \leftarrow i_{opt}$;
  if $length(S_{f/b}) = R_{f/b}$ **then**
    $S_f' = right\_shift(S_f, 0.5)$;
    $S_b' = right\_shift(S_b, 0.5)$;
  else
    continue;
  end
end
for all candidate *Qch* **do**
  Calculate the $QBER_k$ of k_{th} *Qch* in the C_q candidate *Qch*;
  Arrange the elements of *QBER* in ascending order, named *QBER'*;
  $f_1 = ch(QBER_1'), f_2 = ch(QBER_2'), \ldots f_{R_q} = ch\left(QBER_{R_q}'\right)$;
end

Fch/Bch and *Qch* denote the classical forward/backward channels, and quantum channels. $FWM_i = \sum_{j=1}^{C_{f/b}} FWM_j(i, S_{f/b})$ represents the FWM noise calculation in the entire candidate *Fch/Bch.* $S_{f/b} \leftarrow i_{opt}$ represents saving i_{opt} to $S_{f/b}$. $right\_shift(S_f, 0.5)$ means to shift S_f right by 0.5 frequency spacing.

There are normal scheme and shift scheme for the classical forward channel, S_f and S_f', denoted as 1F and 2F. There are also normal scheme and shift scheme for the classical backward channel, S_b and S_b', denoted as 1B and 2B. The core allocation in the SCWA scheme is introduced, as shown in Fig. 1. The core allocation is suitable for N-core fibers with any cores in which the cores are distributed in a regular hexagon, and approximately symmetrical scenarios of forward and backward classical communication.

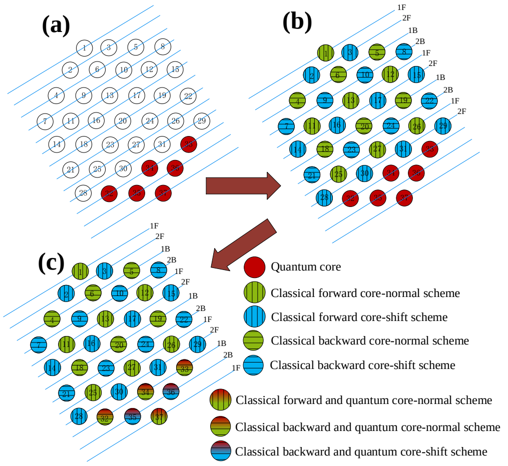

Fig. 1 Core allocation in SCWA scheme.

SCWA Scheme-2: Classical Cores and Quantum Cores Allocation

Step 1: Make priority grouping line *l*. Select the core of any vertex of the regular hexagon, number it as core 1. Make a tangent along the outermost side of core 1 and translate it downward so that it passes through the center of the circle of core 1, and name it the priority grouping line *l*. When *l* is translated down so that it passes through multiple cores for the first time, it is called the second *l*... and so on, until *l* passes through the last core, and all *l* divisions are over.

Step 2: Number the core. The core numbers on each *l* are continuous, and the numbering priority order in each *l* is: $P_{left} > P_{right} > P_{middle}$.

Step 3: Allocate quantum cores. Quantum cores are allocated in descending order of core numbers, as shown in Fig. 1(a).

Step 4: Allocate classical cores. Plan 4 types of classical signals. The cores in first *l* are served for *1F*, the cores in second *l* are served for *2F*..., as shown in Fig. 1(b). Classical forward cores and classical backward cores are allocated in ascending order of core numbers, as shown in Fig. 1(b).

Step 5: When the sum of the required classical cores and the required quantum cores exceeds *N*, continue to assign classical signals in the quantum cores according to the principle in step 3 as shown in Fig. 1(c).

Experiments and Results

Experiments are carried out to verify the scenario of classical channel and quantum channel transmission in the same core. Fig. 2(a) shows the experimental architecture of SCWA scheme. According to the SCWA scheme, Alice-Bob's classical channels are 194.2 THz, 194.4 THz, 194.7 THz and 195.1 THz, and Bob-Alice's classical channels are 195.2 THz, 195.4 THz, 195.7 THz and 196.1 THz (shift wavelength and

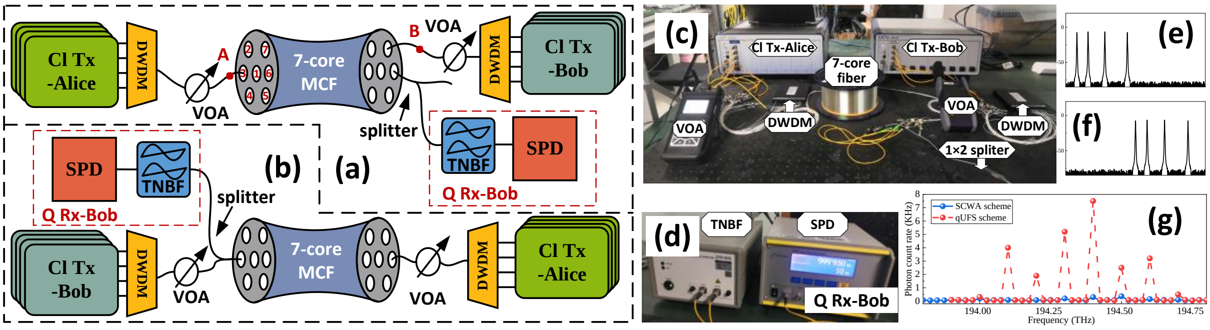

Fig. 2 (a) Experimental architecture of SCWA scheme (Cl Tx-Alice/Cl Tx-Bob: the classical transmitter in Alice/Bob end; DWDM: dense wavelength division multiplexer; VOA: variable optical attenuation; TNBF: tunable narrow bandpass filter; SPD: single photon detector; Q Rx-Bob: the quantum receiver in Bob end); (b) Experimental architecture of qUFS scheme; (c) Experimental setup of classical transmitters in Alice and Bob ends; (d) Experimental setup of quantum receiver in Bob end; (e) The spectrum at point A; (f) The spectrum at point B; (g) Experimental measurement of intra-core FWM noise spectrum.

quantum channel are not in the same core, not transmitted in the experiment). The quantum channels are chosen to be 197.0 THz, 197.1 THz, 197.2 THz and 197.3 THz. The 10 km and 1 km homogeneous MCFs are adopted in the experiments. Fig. 2(b) shows the experimental architecture of qUFS scheme. Fig. 2(c) and Fig. 2(d) show the experimental setup. Fig. 2(c) and Fig. 2(d) show the optical spectrum of point A and point B in Fig. 2(a).

Fig. 2(g) shows the intra-core FWM noise in different schemes. The bandwidth of TNBF is 0.12 nm, the gate width of SPD is 1 ns, the efficiency is 10%, and the dark count is 3×10^{-7}. Since the SpRS noise is broad, the experimental measurements also include SpRS noise. It can be seen from the spectral data that the FWM noise on the classical channel in the qUFS scheme is heavy when the each classical signal is -8 dBm, but most of the FWM noise in the SCWA scheme is suppressed, and the count of noise photons does not exceed 500.

Fig. 3 shows the simulation and experimental results, the line is the simulation result, and the stars and error bars are the calculation from the experimental data. The synergistic degree between the SCWA scheme and the qUFS scheme is based on the conventional channel allocation scheme as the benchmark[4]. In DC allocation, the synergistic degree first increases to a peak, which is mainly due to the simultaneous increase of the OSNR and reduction of QBER compared with the benchmark, the synergistic degree then decreases because the QBER increases sharply. The synergistic degree of the qUFS scheme is negative when it is less than 60 km, mainly because the OSNR is lower than the benchmark scheme. At 1 km, the synergistic degree improves by 0.57 relative qUFS scheme through experimental data.

Fig. 3(b) shows OSNR and QBER versus classical signal power. The qUFS scheme aims to maximize the secure key rate, and the QBER of the SCWA scheme is close to that of the qUFS scheme, but the OSNR of the SCWA scheme is much larger than that of the qUFS scheme. The classical power of each channel exceeds -5.8 dBm, and the secure key cannot be generated in SC transmission.

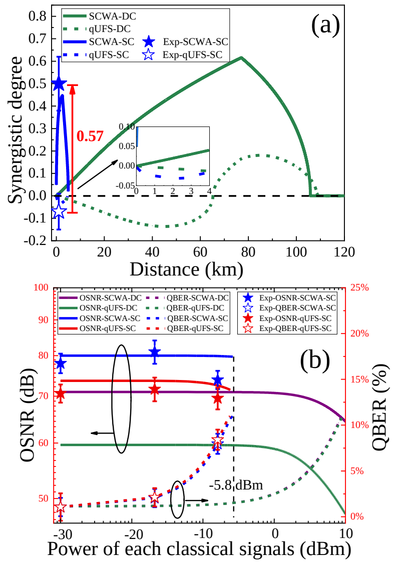

Fig. 3 (a) Synergistic degree vs distance; (b) OSNR and QBER vs power(DC: Classical and quantum channels are distributed in different cores; SC: Classical and quantum channels are distributed in same core).

Conclusions

We define the system synergistic degree index to evaluate the performance of QKD coexisting with classical channels, and propose a SCWA to improve system synergistic degree. The experiment is carried out on MCF, and the results show that SWCA scheme improves the system synergistic degree up to 0.57. The proposed scheme can provide a reference for the design of space-wavelength-division-multiplexing optical network secured by QKD.

Acknowledgements

This work is partly supported by National Natural Science Foundation of China (62150032, 61971059), Fundamental Research Funds for the Central Universities (2019XD-A02) and BUPT Excellent Ph.D. Students Foundation (CX2022304).

References

[1] Bennett Charles H., Gilles Brassard. "Quantum cryptography: Public key distribution and coin tossing ." *Theoretical Computer Science*, vol. 560, no. p1, pp. 7-11, 2014. DOI:10.1016/j.tcs.2014.05.025.

[2] Davide Bacco, Beatrice Da Lio, Daniele Cozzolino, Francesco Da Ros, Xueshi Guo, Yunhong Ding, Yusuke Sasaki, Kazuhiko Aikawa, Shigehito Miki, Hirotaka Terai, Taro Yamashita, Jonas S. Neergaard-Nielsen, Michael Galili, Karsten Rottwitt, Ulrik L. Andersen, Toshio Morioka, Leif K. Oxenløweet. "Boosting the secret key rate in a shared quantum and classical fibre communication system," *Communications Physics*, vol. 2, no. 1, pp. 1–8, 2019. DOI:10.1038/s42005-019-0238-1.

[3] Xavier Guilherme B, Lima Gustavo. “Quantum information processing with space-division multiplexing optical fibres,” *Communications Physics*, vol. 3, no. 1, pp. 1–11, 2020. DOI: 10.1038/s42005-019-0269-7.

[4] Jianing Niu, Yongmei Sun, Chun Cai, Yuefeng Ji. “Optimized channel allocation scheme for jointly reducing four-wave mixing and Raman scattering in the DWDM-QKD system,” *Applied Optics*, vol. 57, no. 27, pp. 7987–7996, 2018. DOI: 10.1364/AO.57.007987.

[5] Elham Ehsani Moghaddam, Hamzeh Beyranvand, Member Jawad A. Salehi. “Resource Allocation in Space Division Multiplexed Elastic Optical Networks Secured with Quantum Key Distribution,” *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 9, pp 2688-2700,2021. DOI: 10.1109/JSAC.2021.3064641.

[6] Weiwen Kong, Yongmei Sun, Yaoxian Gao, Yuefeng Ji. “Core and Wavelength Allocation of Sending-or-not-sending Quantum Key Distribution for Future Metropolitan Networks over Multicore Fiber” in *Optical Fiber Communication Conference(OFC)*. Optical Society of America, pp. Th2A.37, 2022. DOI:10.1364/OFC.2022.Th2A.37.