Core and Wavelength Allocation of Sending-or-not-sending Quantum Key Distribution for Future Metropolitan Networks over Multicore Fiber

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Abstract: We propose core and wavelength allocation schemes of SNS-QKD for future metropolitan transmission over multicore fiber. Experiments verify that the proposed schemes can suppress noise photons up to 57.54% compared to conventional channel allocation. © 2021 The Author(s)

OCIS codes: (270.5565) Quantum communications; (060.2330) Fiber optics communications.

1. Introduction

Quantum key distribution (QKD) ensures that remote parties generate secure keys based on the basic principles of quantum mechanics, and guarantees the information-theoretic security [1]. Recent research on twin-field-QKD (TF-QKD) protocol has promoted the development of long-distance QKD [2], and some improved TF-QKD-based protocols have been derived, such as sending-or-not-sending-QKD (SNS-QKD) [3], etc. SNS-QKD can tolerate a wider range of error rates caused by interference. Meanwhile, with the increasing demand for 5G beyond (B5G) in terms of capacity and security, it is a development trend by adopting QKD on multi-core fiber (MCF) to ensure the security of B5G metropolitan networks. However, it will also bring many problems: On one hand, the typical power of the classical signals is 0 dBm per channel, while the weak quantum signal is about -80 dBm. Such a huge power difference makes the noises generated from classical signals degrade the performance of QKD, such as inter-core crosstalk (ICXT) noises. On the other hand, the classical signals and the quantum signals have the relationships of resource competition, such as core and wavelength resources. Therefore, adopting QKD over MCF to ensure the security of metropolitan networks faces two major challenges: 1) How to reduce noise interference to quantum signals from classical signals; 2) How to extend the secure transmission distance of the future metropolitan networks in a resource-limited scenario.

Previous research studied the allocation schemes of core, frequency slot and time slot, and solved the problem of resource allocation based on BB84-QKD network. For example, authors in Ref. [4] proposed an integer linear programming formulation and a heuristic algorithm to allocate network resources. However, previous studies mainly performed allocation of classical channels and quantum channels for BB84-QKD-based links or networks, and new QKD protocols have not been considered in resource allocation schemes.

In this paper, we propose core and wavelength allocation schemes based on the SNS-QKD, and compare the proposed schemes with conventional channel allocation. Experimental results show that the proposed schemes have the advantages up to 57.54% in suppressing noise photons. Simulation results show that the proposed scheme can extend the secure transmission distance up to 78.8%.

2. Proposed core and wavelength allocation schemes

The proposed schemes aim to minimize the noises on quantum channels and maximize the secure transmission distance. For core distribution, two schemes are selected: (1)**DC**: Classical signals and quantum signals are allocated in different cores; (2)**SC**: Classical signals and quantum signals are allocated in the same core. In the DC schemes, the noise interference on quantum channels is mainly dark counts, ICXT noises, inter-core spontaneous Raman scattering (ICSpRS) noises and inter-core four-wave mixing (ICFWM) noises from the classical signals in other cores. However, in the SC scheme, in addition to the inter-core noises, the quantum channels are also affected by the intra-core FWM and intra-core SpRS noises from the classical signals in the same core.

As shown in Fig. 1, in actual networks, upstream and downstream classical channels are usually allocated in different wavebands, so we consider the two cases where forward classical channels and backward classical channels do not overlap. There are M forward classical channels: $f_1^f, f_2^f \dots f_M^f$, N backward classical

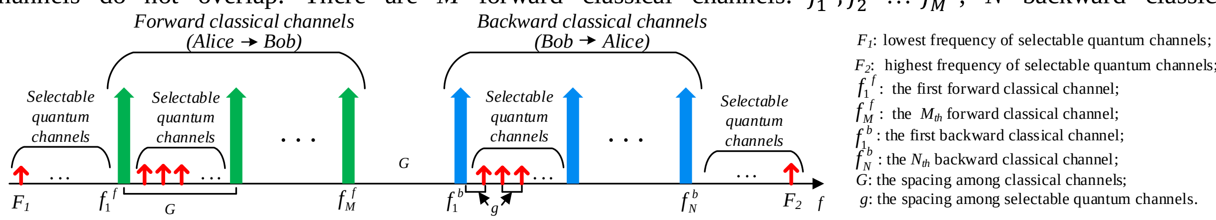


Fig. 1. Schematic diagram of the wavelength allocation in all cores.

channels: $f_1^b, f_2^b \ldots f_N^b$, and Q quantum channels: $f_1^q, f_2^q \ldots f_Q^q$. The allocation of quantum channels adopts quantum equal frequency spacing (qEFS) and quantum unequal frequency spacing (qUFS). The detailed schemes are as follows.

qEFS scheme: In the schemes, the allocation of quantum channels and the classical channels adopts frequency interleaving strategy, which can completely suppress the influence of intra-core FWM and ICFWM noises. Also, the channel management is convenient. Furthermore, the quantum channels are preferentially allocated at the high frequency to avoid the Stokes side of the Raman spectrum.

(1) When $f_1^b > f_M^f, f_1^b - f_M^f = G = t_0 * g$ in Fig. 1. The frequency of the first quantum channel is higher than f_{N-1}^b about $t * g$ $(t \in [1, t_0 - 1])$. The i_{th} quantum channel is as shown in equation (1).

(2) When $f_N^b < f_1^f, f_1^f - f_N^b = G = t_0 * g$ in Fig. 1. The frequency of the first quantum channel is higher than f_{M-1}^f about $t * g$ $(t \in [1, t_0 - 1])$. The j_{th} quantum channel is as shown in equation (2).

$$f_i^q = f_N^b - (t_0 - t)g - (i-1)G \quad (1) \qquad f_j^q = f_M^f - (t_0 - t)g - (j-1)G \quad (2)$$

Due to the allocation restriction of equal interval, quantum channel management is convenient. However, the quantum channel may not be the channel with the least noises, so the qUFS scheme is proposed below.

qUFS scheme: The qUFS scheme can select the quantum channel with the largest secure key rate within a band. The qUFS scheme is divided into five steps, as follows:

Step 1: Determining the channel range $[F_1, F_2]$ of selectable quantum channels, and the spacing g among quantum channels. Therefore, the number of selectable quantum channels is $K_{DC} = K_{SC} = \left\lfloor \frac{F_2 - F_1}{g} \right\rfloor - M - N + 1$.

Step 2: Calculating the noise power on selectable quantum channels. The noise powers of selectable quantum channels in the DC and SC schemes are P_{DC} and P_{SC}. $P_{DC} = [P_{DC}^1, P_{DC}^2, \ldots P_{DC}^{K_{DC}}]$, $P_{SC} = [P_{SC}^1, P_{SC}^2, \ldots P_{SC}^{K_{SC}}]$.

Step 3: Calculating the secure key rate on selectable quantum channels. $R_{DC} = [R_{DC}^1, R_{DC}^2, \ldots R_{DC}^{K_{DC}}]$, $R_{SC} = [R_{SC}^1, R_{SC}^2, \ldots R_{SC}^{K_{SC}}]$.

Step 4: Selecting candidate quantum channels. Eliminate selectable channels with secure key rate of 0, and sorting the elements of candidate quantum channels in descending order of secure key rate to R'_{DC} and R'_{SC}.

Step 5: Allocating quantum channels. The quantum channels under DC scheme: $f_1^q = ch(R'_{DC,1})$, $f_2^q = ch(R'_{DC,2}), \cdots$. The quantum channels under SC scheme: $f_1^q = ch(R'_{SC,1}), f_2^q = ch(R'_{SC,2}), \cdots$.

$ch(\cdot)$ indicates the function for acquiring channels. The qEFS scheme has uniform channel spacing and convenient channel management, but the selected quantum channel may not be the minimum noisy, and the secure key rate may not be maximized. On the contrary, the qUFS scheme can choose the quantum channel with the highest secure key rate, but the quantum channels may be uneven.

3. Simulation and experimental results

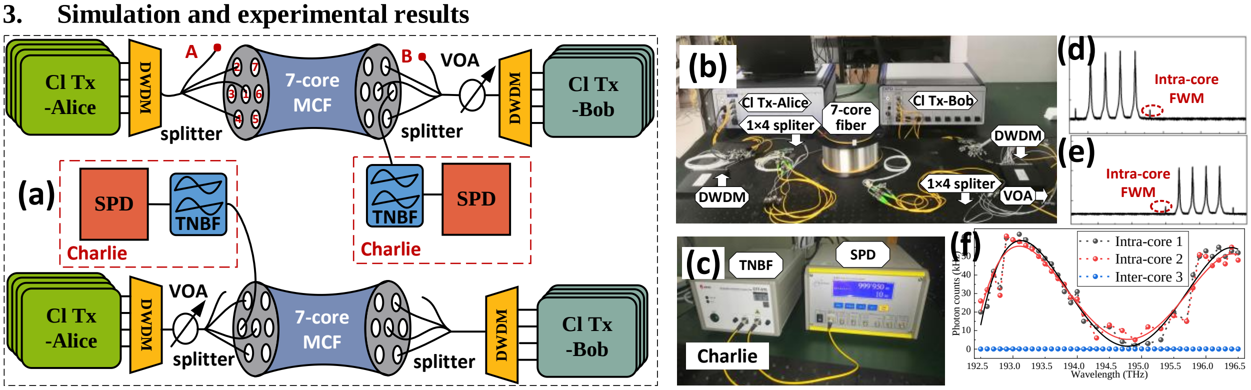


Fig. 2. (a) Experimental setup (Cl Tx-Alice/Cl Tx-Bob: the classical transmitter in Alice/Bob end; DWDM: dense wavelength division multiplexer; VOA: variable optical attenuation; TNBF: tunable narrow bandpass filter; SPD: single photon detector); (b) Experimental setup of classical transmitters in Alice and Bob ends; (c) Experimental setup of Charlie; (d) The spectrum at point A; (e) The spectrum at point B; (f) Experimental measurement of Raman noise spectrum (The black solid line and the red solid line are the corresponding fitting results).

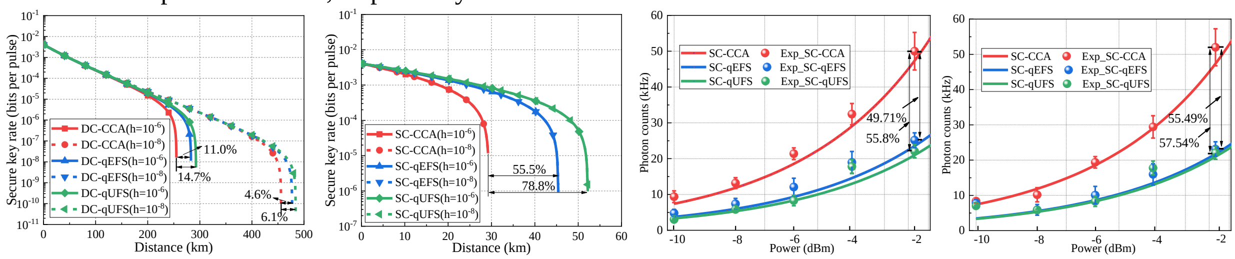
Fig. 2(a) shows the experimental setup. The classical wavelengths transmitted from Alice to Bob are 194.2 THz, 194.4 THz, 194.6 THz and 194.8 THz, and the classical wavelengths from Bob to Alice are 195.0 THz, 195.2 THz, 195.4 THz and 195.6 THz. The distances from Alice to Charlie and Bob to Charlie are symmetrical. Since we only have a 10 km 7-core fiber, we first put the 10 km MCF in the section of Alice to Charlie, and use VOA to simulate Bob to Charlie, then have an exchange measurement. The experimental photos are shown in Fig. 2(b) and Fig. 2(c). Fig. 2(d) and Fig. 2(e) show the spectrum at points A and B in Fig. 2(a), respectively. The intra-core FWM noise can be observe. For the 10 km homogeneous 7 core fiber, each core of the fiber is designed with a step-index profile at a core pitch of 42.4 μm, and the core diameter is 8.4 μm.

In Fig. 2(c), the TNBF is used to select the quantum channel, and the bandwidth is 0.12 nm. The noise level on the quantum channel is measured by a SPD and expressed in photon count rate, and the gate duration, detector efficiency and detection probability of dark counts are 1 *ns*, 20% and 7×10^{-6}, respectively. Next, since the FWM noise is avoided in the qEFS scheme and the qUFS scheme, Raman noise is the main source of interference. We measure the spectrum of Raman scattering noise, as shown in Fig. 2(f). Affected by the spectrum width of classical signals, the measurement results of the Raman spectrum is not smooth enough. We can also observe that the ICSpRS noise interference is small, which is in the same order of magnitude as the dark count noise.

Next, Taking the four-strength decoy state as an example, the calculation of the secure key rate per pulse in SNS-QKD is as follows [3]:

$$R_{pulse} = 2\epsilon(1-\epsilon)\mu_Z e^{-\mu_Z} s_1[1 - H(e^{ph_1})] - S_Z f H(E^Z) \qquad (3)$$

ϵ is the proportion of light pulses sent when Alice and Bob select signals windows. μ_Z is the signal state intensity. S_Z and E^Z are the the total gain and error rate in signals windows, respectively. s_1 and e^{ph_1} are the single photon count rate and phase error rate, respectively.



(a) (b) (c) (d)

Fig. 3. Performance evaluation of the proposed schemes. (a)Simulation results in DC schemes; (b)Simulation results in SC schemes; (c)Experimental results of Alice-Charlie; (d)Experimental results of Bob-Charlie.

The performance evaluation of the proposed schemes is shown in Fig. 3, adopting the conventional channel allocation (CCA) scheme as the benchmark [5]. In Fig. 3(a), when the power coupling coefficient is 10^{-6}, the secure transmission distance in DC-qEFS scheme is extended by 11.0% compared to the DC-CCA scheme. Furthermore, the DC-qUFS scheme presents advantages of 14.7%. When the power coupling coefficient is 10^{-8}, the DC-qEFS scheme and the DC-qUFS scheme can extend secure transmission distance of 4.6% and 6.1%, respectively. Fig. 3(b) shows the performance evaluation in SC schemes. Intra-core noises are the dominant noises, so the influence of the coupling coefficient is weak. The SC-qEFS scheme and the SC-qUFS scheme can extend the secure transmission distance up to 55.5% and 78.8%, respectively.

Finally, experimental evaluations in the proposed SC scheme are shown in Fig. 3(c) and Fig. 3(d), and the two links of Alice-Charlie and Bob-Charlie both are experimentally evaluated. In different powers of classical signals, the SC-qUFS scheme always presents the best performance, and as the classical power increases, the noise suppression of the proposed schemes becomes more significant. The experimental measurement results and the simulation results match well. When the classical power of each channel is -2 dBm, the proposed schemes have the best noise suppression effect. Compared with the SC-CCA scheme, the maximum noise suppression can be up to 57.54%. This research can promote the deployment for simultaneous transmission of classical and quantum signals in the future B5G metropolitan networks.

4. Conclusion

In this paper, we propose core and wavelength allocation schemes based on SNS-QKD for long-distance transmission. The proposed schemes have advantages compared to the CCA scheme in different power coupling coefficients of MCF. The simulation results show that the proposed schemes can extend the secure transmission distance up to 14.7% in the DC core distribution and 78.8% in the SC core distribution. The experimental results show that the proposed schemes can suppress the noises up to 57.54%.

Acknowledgments This work is partly supported by National Natural Science Foundation of China (61971059) and Fundamental Research Funds for the Central Universities (2019XD-A02).

References

[1] H. Bennett, et al., "Quantum cryptography: public key distribution and coin tossing," Computers, Systems and Signal Processing, 1984.
[2] L. Marco, et al., "Overcoming the rate–distance limit of quantum key distribution without quantum repeaters." Nature, 2018.
[3] X. B. Wang, et al., "Twin-field quantum key distribution with large misalignment error," Phys. Rev. A , 2018.
[4] E. E. Moghaddam, et al., "Resource allocation in space division multiplexed elastic optical networks secured with quantum key distribution," IEEE J Sel Area Comm, 2021.
[5] J. N. Niu, et al., "Optimized channel allocation scheme for jointly reducing four-wave mixing and Raman scattering in the DWDM-QKD system," Appl Opt, 2018.