Assessing the Impact of Patterning Effect on Quantum Key Distribution

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Abstract: We assessed the impact of patterning effect on SKR in QKD while considering statistical fluctuations. Through numerical simulations, compared to WCS, HSPS demonstrated superior resistance to patterning effect and can transmit over longer distances.

1. Introduction

The decoy state scheme enhances the performance of practical quantum key distribution (QKD) systems, resulting in improved secret key rate (SKR) and extended secure distances. Most decoy state QKD systems employ three intensity levels with average photon fluxes μ, ν, and ω ($\mu>\nu>\omega\approx 0$), termed as signal, decoy and vacuum pulses. In practical QKD systems, these are generated using an intensity modulator (IM). practical modulators and electrical drivers are band limited (which is common in optical communication as well), electrical signal distortion causes intensity fluctuation of individual pulses as well as intensity correlation between the optical pulses, a phenomenon known as the patterning effect. The former affects the estimation of the single-photon parameter, while the latter may introduce a side channel that provides additional information to potential eavesdroppers. This is a concern because current decoy-state security analysis assumes independent and identically distributed signals.

To mitigate the impact of patterning effect, post-processing methods can be used to discard pulses affected by severe patterning effect [1], but this significantly reduces SKR. Another method is to use a Sagnac interferometer to adjust the intensity of two vertices [2], but the structure of the Sagnac interferometer constrains systems frequency. Additionally, multi-path Mach-Zehnder interferometer (MMZI) structures or IQ modulators can be employed [3,4], but MMZI requires independent intensity and phase control in each of its optical paths, and IQ modulators cannot flexibly control the decoy to signal intensity ratio. In practice, QKD systems employing different light sources exhibit noteworthy variations in their resistance to patterning effect, offering valuable insights for QKD systems design.

We conducted a comprehensive analysis of the impact of the patterning effect on SKR in decoy state QKD, considering statistical fluctuations. The simulation results reveal that heralded single-photon sources (HSPS) excel in decoy state QKD, attributed not only to their larger upper bound of transmission distance compared to the conventional weak coherent sources (WCS) but also to their heightened resistance to the patterning effect. In the realm of decoy state QKD experiments, Employing HSPS as a countermeasure against pattern effects is a judicious decision.

2. Decoy state QKD with patterning effect and statistical fluctuations

Considering the decoy state QKD systems based on the BB84 protocol using different light sources [5,6], the optical injection-based technique can yield optically stable pulse sources [7] and IM can be used to prepare the required intensity states (μ, ν, and ω) for the decoy state method. This study predominantly assesses the impact of imperfections in the IM on the key rate of decoy state QKD, while positing that the principal source of intensity fluctuations in QKD originates from the patterning effect.

The patterning effect can lead to intensity correlations between optical pulses and intensity fluctuations in individual pulses. The former disrupts the condition of independent and identical distribution of the signal. However, in article [8], the security of a QKD protocol is proven under practical assumptions about the source that accommodate fluctuations in phase and intensity modulations. As long as assumptions hold, it does not matter at all how the phase and intensity distribute or whether or not their distributions over different pulses are independently and identically distributed, and demonstrates that the actual source can be safely employed in QKD experiments. The latter can significantly impact single-photon parameter estimation. We calculate the impact of the patterning effect on SKR in decoy-state QKD when using various light sources, while considering statistical fluctuations, using the method described in [9].

In the numerical simulation, for WCS, it follows a Poisson distribution, and the average number of photons for each pulse is set to 0.479, 0.127, and 0. For HSPS, after phase randomization, the photon number distribution follows a thermal distribution. The detection efficiency at the sender is 0.5, and the dark count rate is 5×10^{-5}. The average number of photons for each pulse is set to 5.325×10^{-3}, 0.577×10^{-3}, and 0 [10]. The heralding efficiency is set to 0.77 [11]. The jitter for the decoy state is set within the range of 2% to 20%, while the signal state jitter is fixed at 2%. For simplicity, we make the assumption that the vacuum state serves as an accurate source without any intensity jitter, as described in reference [10]. The jitter of the decoy state is greater than that of the signal state because the decoy state is generally in the linear region of the intensity modulator. Other simulation parameters are shown in Table 1.

Table 1. Simulation Parameters

η_d	e_d	$\alpha(\mathrm{dB/km})$	p_{dc}	e_0	P_u	P_v	P_ω	Fec	q	N
7.5%	1%	0.2	8×10^{-6}	0.5	50%	25%	25%	1.22	0.5	10^{10}

η_d is the detection efficiency of the single-photon detector at Bob's end, e_d is the basis misalignment error due to imperfect polarization state preparation and detection, α is the optical fiber loss, p_{dc} is the dark count rate of the detector, e_0 is the bit error rate caused by dark counts, P_u,P_v,P_ω are the proportions of the signal state, decoy state, and vacuum state sent, Fec is the error correction efficiency, q is the base efficiency, and N is the finite block size. $R(\delta, L, p_{\mathrm{cor}})$ represents SKR of QKD using HSPS with QKD decoy state intensity jitter δ, transmission distance L, and heralding efficiency p_{cor}. We define ξ as the impact of patterning effect on SKR of decoy state QKD [10]:

$$\xi = \frac{R(\delta, L, p_{\mathrm{cor}})}{R(0.02, L, p_{\mathrm{cor}})} \tag{1}$$

For WCS, there is no heralding efficiency. At this time, ξ is:

$$\xi = \frac{R(\delta, L)}{R(0.02, L)} \tag{2}$$

3. Simulation results

Figure 1(a) illustrates the impact of the patterning effect on SKR of decoy state QKD using HSPS with a maximum transmission distance of 151 km. The blue region in the graph indicates scenarios where the transmission distance exceeds 151 km, and as a result, the key cannot be successfully transmitted. In Figure 1(b), we depict the impact of the patterning effect on the SKR of decoy state QKD using WCS with an upper limit of a 116 km transmission distance. Beyond this distance, the key transmission becomes unfeasible. Within the 116 km range, there is a smaller blue region indicating that, due to the patterning effect, QKD cannot transmit the key. This results in the appearance of a trapezoidal shape in the graph. Figure 1(c) demonstrates the impact of the patterning effect on the key rate of decoy-state QKD using HSPS with different heralding efficiencies at a 100 km transmission distance. Figure 1(d) showcases the combined impact of statistical fluctuations and the patterning effect on the SKR of decoy state QKD. This is examined using HSPS with a heralding efficiency of 0.77, WCS, and an ideal HSPS under the same experimental conditions. The signal state jitter is set to 2%, while the decoy state jitter is set to 5%.

Figures 1(a) and (b) demonstrate that the impact of patterning effect on SKR of decoy state QKD using WCS cannot be ignored, especially as the transmission distance approaches the upper limit. HSPS proves to be a favorable choice for decoy state QKD experiments. It not only has a larger transmission distance limit compared to WCS, but also is more resistant to patterning effect, and the impact of patterning effect on SKR is essentially negligible, with ξ approximately equal to 1. Figure 1(c) illustrates that different heralding efficiency of HSPS all have good resistance to patterning effect. Figure 1(d) provides evidence that HSPS is a superior source for QKD experiments, offering a larger upper bound for the transmission distance and SKR. Additionally, in our simulations, we utilized a high-performance HSPS with a 77% correlation between photons (as reported in [11]), and its performance closely approximated that of an ideal heralded single-photon source.

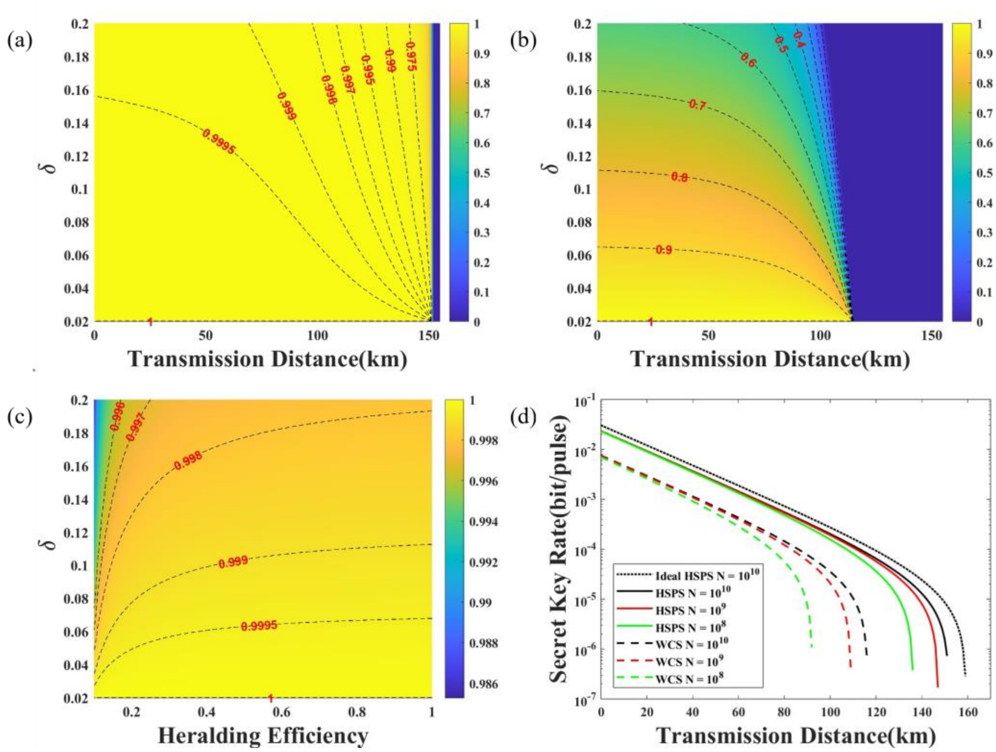

Fig. 1. (a) Impact of patterning effect on SKR of QKD using HSPS (b) Impact of patterning effect on SKR of QKD using WCS (c) Impact of patterning effect on SKR of QKD using HSPS with different heralding efficiency at a transmission distance of 100 km (d) SKR of QKD using HSPS and WCS considering patterning effect and statistical fluctuations

4. Conclusion

This study analyzes the impact of the patterning effect on SKR of decoy state QKD using different light sources, while taking statistical fluctuations into account. Numerical simulations demonstrate that HSPS outperform WCS in terms of resisting the patterning effect. The impact of the patterning effect on the SKR of decoy state QKD using HSPS is essentially negligible, as ξ approximately equals to 1. Furthermore, HSPS offers larger upper bound of transmission distance compared to WCS.

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