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Citation: SCIENCE CHINA Information Sciences **65**, 200502 (2022); doi: 10.1007/s11432-022-3509-6

View online: https://engine.scichina.com/doi/10.1007/s11432-022-3509-6

View Table of Contents: https://engine.scichina.com/publisher/scp/journal/SCIS/65/10

Published by the Science China Press

SCIENCE CHINA
Information Sciences

October 2022, Vol. 65 200502:1–200502:7
https://doi.org/10.1007/s11432-022-3509-6

• **RESEARCH PAPER** •
Special Focus on Quantum Information

Hybrid quantum key distribution network

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Received 15 February 2022/Revised 26 April 2022/Accepted 9 June 2022/Published online 15 July 2022

Abstract Quantum key distribution (QKD) is now moving toward a scalable and secure QKD network, which establishes secret keys among network users. The continuous-variable (CV) and discrete-variable (DV) QKD systems are currently being developed in parallel and are all used in QKD networks. We propose here a hybrid QKD network, in which the CV QKD system is used to build metropolitan QKD networks, and the DV QKD system is used to connect metropolitan QKD networks. The hybrid QKD network takes advantage of high secret key rates for CV QKD systems and long distance for DV QKD systems. We also present a feasible hybrid measurement-device-independent (MDI) QKD network, which combines both CV and DV MDI QKD systems. The presented hybrid QKD networks meet the low cost and compact requirement of a realistic QKD network and provide a feasible solution for future real QKD networks by combining the advantages of both CV and DV QKD systems.

Keywords quantum network, quantum key distribution, hybrid quantum information, continuous variable, discrete variable

Citation Ren S Y, Wang Y, Su X L. Hybrid quantum key distribution network. Sci China Inf Sci, 2022, 65(10): 200502, https://doi.org/10.1007/s11432-022-3509-6

1 Introduction

Quantum key distribution (QKD) allows two legitimate parties, Alice and Bob, who are linked by a quantum channel and an authenticated classical channel, to establish a secret key only known by themselves. The QKD's security is guaranteed by quantum mechanics principles. After obtaining the secret key, the secure information transmission can be completed by encoding and decoding with the key in a one-time pad. QKD was first developed in the discrete variable (DV) regime and then was extended to the continuous variable (CV) regime, as the development of quantum information [1, 2]. Up to now, CV QKD and DV QKD have developed in parallel.

The implementations and device imperfections in the actual QKD system are a common problem, and quantum cryptography academic research has focused on this issue in the last ten years [3]. The decoy state QKD system, which is now widely used in QKD experiments, is used in DV QKD to overcome the photon number splitting attack [4–6]. Device-independent QKD provides security under a minimal set of assumptions and against a wide range of side-channel attacks [7, 8]. However, the protocol requires high detection efficiency and very low channel loss, so it is technically impossible in the short term. Since side-channel attacks mostly occur in the measurement process, a measurement-device-independent (MDI) QKD protocol is proposed [9–11]. Long-distance DV MDI QKD has been demonstrated by several groups [12, 13] and its transmission distance has been extended to 404 km [14]. Recently, a new protocol called twin-field QKD has been proposed [15] and the sending-or-not-sending twin-field QKD has been experimentally demonstrated over 605 km [16] and 830 km [17].

Continuous quantum variables of the light field, such as amplitude and phase quadratures, are used as information carriers in CV QKD protocols [2]. Usually, CV QKD uses Gaussian quantum resource

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state, such as entangled state, squeezed state, modulated coherent state, as the resource state, plus reconciliation and privacy amplification procedure to distill the secret key [2]. CV QKD protocols have been shown to be unconditionally secure, that is, secure against arbitrary attacks [18] and have been proved to be unconditionally secure over long distance [19]. In recent years, the CV QKD exploited coherent state [20, 21] and entangled state [22–25] has been experimentally realized, and transmission distance has been extended to 80 km [20], 100 km [21], and 202 km [26], respectively. The CV MDI QKD is also proposed and demonstrated in the proof-of-principle experiment [27–31]. Recently, CV MDI QKD in a 10 km fiber channel has been demonstrated [32]. When compared with the DV QKD system, it is difficult to extend the distance of the CV QKD system due to excess noise in the quantum channel, and the efficiency of the data reconciliation is complicated. However, the advantage of the CV QKD system is that it is compatible with the present communication system. Because the light sources and the detectors used in CV QKD are routinely developed in classical optical communications, the CV approach offers implementation based only on mature telecom components.

A quantum network is a fundamental construction for quantum communication and quantum computation, which enables one to accomplish some impossible tasks in the classical realm. With the gradual maturation of QKD devices and technologies in recent years, the application of QKD is becoming more and more widely. Several QKD networks have been proposed and demonstrated [33–41], but a large amount of them are extensions of the point-to-point QKD protocol. Most of these QKD networks are established with the DV QKD system. In China, more than 2000 km of QKD networks has been built in Beijing, Jinan, Hefei, and Shanghai. A real-life fiber-based multi-user DV MDI QKD network was realized in 2015 [42] and the satellite-to-ground QKD has also made essential progress [43, 44]. CV QKD system has been applied in point-to-point communication in the SECOQC network and Tokyo network, which does not embody the advantages of CV QKD. In 2016, a CV QKD network with Gaussian modulated coherent state was built in Shanghai [41], which demonstrates the feasibility of the CV QKD network in the metropolitan area. However, it is unclear how to efficiently adopt CV and DV QKD systems in QKD networks.

In the optical quantum information processing, DV [1, 3] and CV systems [2, 45–47] were previously developed in parallel. Recently, hybrid quantum information processing, which bridges these two types of quantum information processing approaches, has been developed [48]. The intrinsic individual limitations of both DV and CV systems are overcome in the hybrid quantum information processing, and advantages of both DV and CV systems are taken to implement quantum information processing. Several experimental progress has been made in hybrid quantum information processing, for example, hybrid quantum teleportation [49, 50], hybrid entanglement distillation [51, 52], and hybrid quantum computation [53–55].

Here, motivated by the idea of hybrid quantum information processing [48], we propose a hybrid QKD network, which combines both the DV and CV QKD systems. The CV QKD systems are used to establish metropolitan networks, and the DV QKD system is used to connect metropolitan CV QKD networks. In this case, the hybrid QKD network uses the advantage of both the higher secret key rates of CV QKD systems and the long distance of DV QKD systems. A hybrid MDI QKD network that is immune to the side-channel attacks is also proposed. In a hybrid QKD network, the advantage of intrinsic compatibility with conventional fiber-optic networks for CV QKD systems reduces the overall network cost when compared with a QKD network consisting only of DV QKD systems. A hybrid QKD network can achieve long-distance transmission when compared with a QKD network consisting only of CV QKD systems. The presented hybrid QKD networks provide a feasible structure for the future QKD network.

2 The principle of hybrid QKD networks

Figure 1 shows the schematic of hybrid QKD networks. In Figure 1(a), a general hybrid QKD network is presented. Two star-shape metropolitan QKD networks A and B are established by the CV QKD systems. There is one user in each CV QKD network that is equipped with both the CV and DV QKD systems. The DV QKD systems are used for communication between two metropolitan networks. In this hybrid QKD network, only one DV QKD system is used, which reduces the number of single photon detectors. The secret key rates and secure transmission distance in the metropolitan networks are limited by the CV QKD system. While the secret key rates and secure transmission distance between two metropolitan networks are limited by the DV QKD system. Considering the practical application, we use the mature coherent state system for the CV QKD system and the decoy state protocol for the DV QKD system

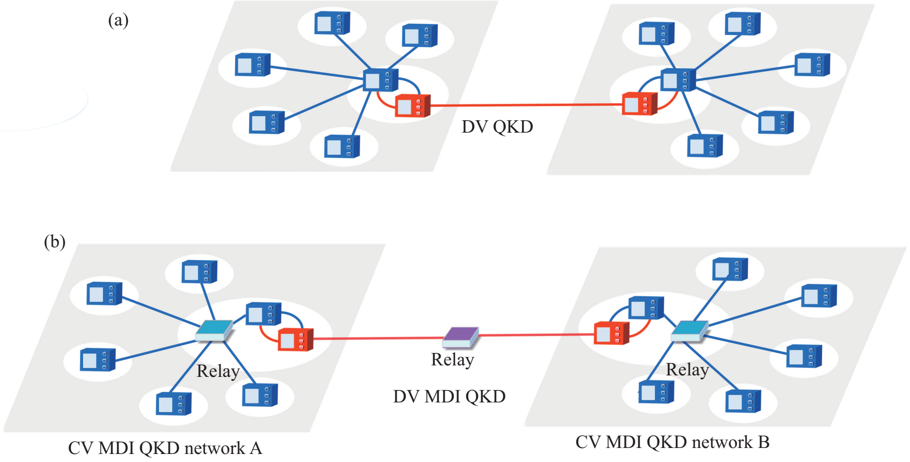

Figure 1 (Color online) Schematic of the hybrid QKD networks. (a) A general hybrid QKD network with conventional CV and DV QKD systems. (b) A hybrid MDI QKD network with CV and DV MDI QKD systems. Blue boxes: CV QKD systems. Red boxes: DV QKD systems.

(Figure 1(a)).

A hybrid MDI QKD network consisting of CV and DV MDI QKD systems is also proposed, as shown in Figure 1(b). In each CV MDI QKD networks, the measurement is performed in the CV relay. Here, we assume the user who owns both the CV and DV QKD systems is close to the CV relay. The two CV MDI QKD networks are connected by DV MDI QKD system. A DV relay is placed between two metropolitan networks, where the measurement of DV MDI system is performed.

3 Results

3.1 Results of the general hybrid QKD network

We analyze the secret key rates and secure transmission distance of the hybrid QKD networks in the following. In the metropolitan CV QKD networks of Figure 1(a), Alice prepares and sends the Gaussian modulated coherent states to Bob. Bob performs homodyne (or heterodyne) detection on the received coherent states. The security analysis of the CV QKD with modulated coherent state can be achieved by using the equivalent QKD with entangled state model, where one of the EPR entangled states is homodyne measured. The secret key rate of CV QKD with homodyne detection and reverse reconciliation considering finite-size effects is given by [56]

$$R_{\text{finite}} = \frac{n}{N}[\beta I_{\text{AB}}^{\text{hom}} - \chi_{\text{BE}}^{\text{hom}} - \Delta(n)], \tag{1}$$

where N and n denote the sampling length and the block length for final key estimation, respectively, β denotes the reconciliation efficiency, $I_{\text{AB}}^{\text{hom}}$ is the mutual information of Alice and Bob with homodyne detection, $\chi_{\text{BE}}^{\text{hom}}$ is the Holevo bound on the information between Bob and Eve, and $\Delta(n)$ is related to the security of the privacy amplification.

In the DV QKD system, we consider the decoy state QKD protocol. The secret key rate of DV QKD with infinite decoy state is given by [5]

$$R \geqslant q\left\{-Q_{\mu} f H_2\left(E_{\mu}\right) + Q_1\left[1 - H_2\left(e_1\right)\right]\right\}, \tag{2}$$

where q depends on the implementation of the protocol, μ denotes the intensity of the signal states, Q_{μ} is the gain of the signal states, E_{μ} is the overall quantum bit error rate (QBER), Q_1 is the gain of single-photon states, e_1 is the error rate of the single-photon states, f is the bidirectional error correction efficiency, and $H_2\left(x\right)$ is the binary Shannon information function. The details of the calculation for secret key rates of the CV and DV QKD systems can be found in Appendixes A and B.

The main parameters of the CV and DV QKD systems are listed in Table 1. For the CV QKD system, $\eta = 60\%$ and $\eta = 98\%$ represent detection efficiencies of practical and ideal homodyne detectors, respectively, ϵ represents the excess noise in the channel, and β is the reconciliation efficiency. For the

Table 1 Main parameters of four kinds of QKD systems

Types of QKD	η	ϵ	β	Y_0	f	e_d
CV QKD	60% (98%)	0.01	95.6%	–	–	–
CV MDI QKD	97% (98%)	0.01	97%	–	–	–
DV QKD	66% (93%)	–	–	1.7×10^{-6}	1.22	0.33%
DV MDI QKD	66% (93%)	–	–	10^{-6}	1.16	0.1%

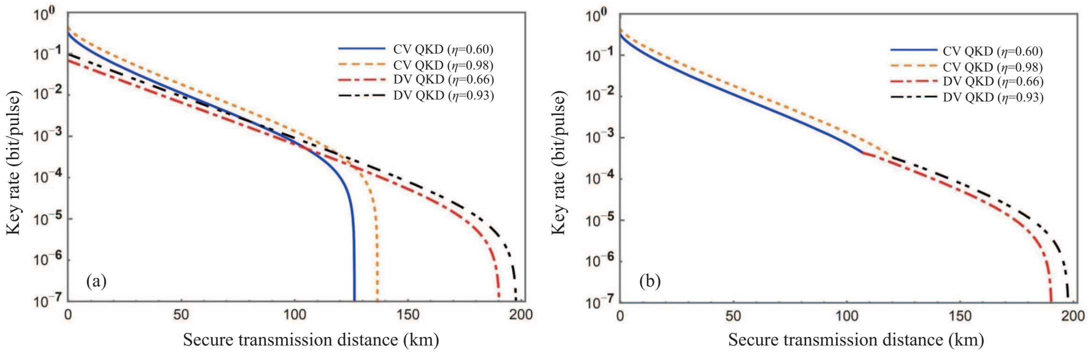

Figure 2 (Color online) (a) Comparison of secret key rates for CV and decoy-state DV QKD systems. DV QKD with detection efficiencies $\eta = 66\%$ and $\eta = 93\%$ represents advanced superconducting nanowire single photon detectors operating at 2.05 K and below 2 K in a cryogenic system, respectively. CV QKD with detection efficiencies of $\eta = 60\%$ and $\eta = 98\%$ represents practical and ideal homodyne detectors, respectively. (b) Secret key rates for the hybrid QKD networks for practical and ideal cases. The parameters can be found in Table 1 and Appendixes A and B.

DV QKD system, $\eta = 66\%$ and $\eta = 93\%$ represent detection efficiencies of advanced superconducting nanowire single photon detectors operating at 2.05 K and below 2 K in a cryogenic system, respectively, Y_0 is the dark count rate, f represents the error correction efficiency and e_d is the intrinsic error rate. The detailed parameters can be found in Appendixes A and B.

Figure 2(a) shows the secret key rates for the decoy-state DV QKD BB84 protocol and CV QKD system based on coherent state with different detection efficiencies. The secret key rate of the CV QKD system taking into account the finite size effects is higher than that of the decoy-state DV QKD protocol in the transmission distance shorter than around 100 km, while it is below that of the decoy-state DV QKD protocol when the distance is longer than 100 km. This confirms the advantage of the CV QKD is high secret key rate in short distance and the advantage of the DV QKD in long distance. The higher secret key rates of the CV QKD come from the nature of infinite-dimension Hilbert space which enables encoding a lot of information. The limitation distance of CV QKD is because the CV system is sensitive to loss and noise in the quantum channel. The secret key rate of the CV QKD system is higher than both the practical and cryogenic decoy-state DV QKD systems. In the proposed hybrid QKD network, both the advantages of the CV and DV QKD systems are used, as shown in Figure 2(b). It is obvious that the high secret key rate is obtained in the metropolitan distance smaller than 100 km and the communication between two metropolitan networks is determined by the DV QKD system in the presented general hybrid QKD network.

3.2 Results of the hybrid MDI QKD network

In the CV MDI QKD network shown in Figure 1(b), two distant parties, Alice and Bob, prepare and send two coherent states modulated by a Gaussian distribution to an untrusted CV relay, which is placed at the center of the star shape CV MDI QKD metropolitan network. Here, we assume that Alice is close to the relay and the CV Bell measurement is performed in the CV relay, and Bob refers to any user in the metropolitan network. The measurement results are then communicated to Alice and Bob via classical public channels. In this way, the secret key can be established between Alice and other users in the CV MDI QKD network. The DV MDI QKD system is used to connect two remote CV MDI QKD networks. Two users belonging to two metropolitan networks send decoy-state weak coherent pulses to the DV relay, where the DV Bell measurement is performed. The details of the calculation for secret key rates of CV and DV MDI QKD systems can be found in Appendixes C and D. The main parameters of CV and DV MDI QKD systems are shown in Table 1, and the detailed parameters can be found in Appendixes C and D.

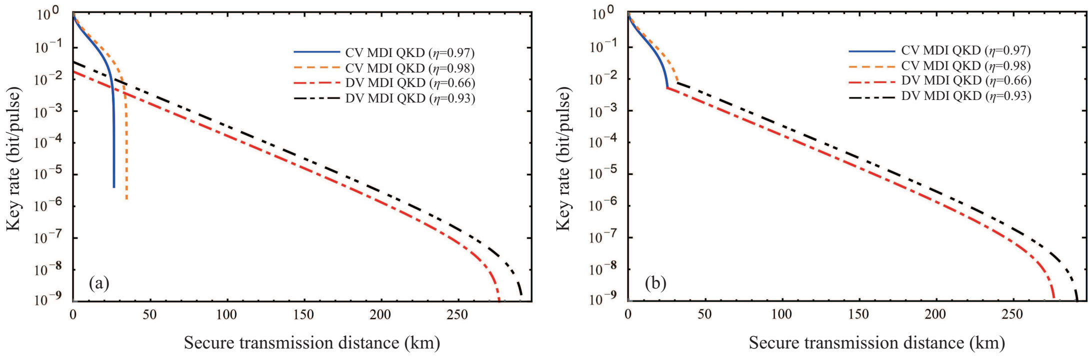

Figure 3 (Color online) (a) Comparison of secret key rates for CV and DV MDI QKD systems. DV MDI QKD with $\eta = 66\%$ and $\eta = 93\%$ represent advanced superconducting nanowire single photon detectors operating at 2.05 K and below 2 K in a cryogenic system, respectively. CV MDI QKD with $\eta = 97\%$ and $\eta = 98\%$ represent practical and ideal homodyne detectors, respectively. (b) Secret key rates for the hybrid MDI QKD networks for practical and ideal cases. The parameters can be found in Table 1 and Appendixes C and D.

The distance of the CV MDI QKD network depends on the distance between the sender (Alice) and the relay [29–31]. When the relay is close to Alice, i.e., the asymmetric configuration, the distance of the CV MDI QKD network can reach around 25 km. When the relay is placed in the middle of the sender and the receiver, i.e., the symmetric configuration, the distance of the CV MDI QKD network is limited to around 5 km. Since we assume Alice is close to the relay, the secret key rate of the CV MDI QKD taking into account the finite size effects is higher than that of the DV MDI QKD in a range of 25 km as shown in Figure 3(a), which corresponds to the case with detection efficiency of 97% as obtained in [32]. The secret key rates for the hybrid MDI QKD network are presented in Figure 3(b), which clearly shows the advantage of the combination of both CV and DV MDI QKD systems. The higher secret key rate is obtained in the metropolitan distance around 25 km and the long distance is achieved with the DV MDI QKD system in the presented hybrid MDI QKD network.

4 Discussion and conclusion

It has been shown that the finite size effects lead to the decrease of secret key rates of both CV [21] and DV [57, 58] QKD. In our calculation, the secret key rates of CV QKD considering finite size effects are compared with those of DV QKD without considering the finite size effects. As shown in Figures 2 and 3, the secret key rates of CV QKD in a short distance are higher than those of DV QKD in this case. When the finite size effects on DV QKD are also considered, the advantage of higher secret key rates of CV QKD over short distances remains.

For the application, the proposed hybrid QKD network can be applied to establish a wide area QKD network, where the CV QKD system is applied to establish the metropolitan network in a city, and the DV QKD system is applied to the communication between two cities. For a city with an urban area smaller than 25 km, the CV MDI network can be applied to the metropolitan network, so a hybrid MDI QKD network can be established. While for a city with an urban area in a range of 25 to 100 km, the conventional CV QKD system can be applied in the metropolitan network, so a general hybrid QKD network can be established. The proposed hybrid QKD networks can, of course, be extended to a wide area network involving more than two cities.

In summary, we present the hybrid QKD networks that combine the advantages of both CV and DV QKD systems, where the CV QKD system is used to build a star shape metropolitan QKD network, and the DV QKD system is used to complete the communication between two metropolitan networks. By comparing the secret key rate and transmission distance of the CV and DV QKD systems, we confirm the feasibility of establishing hybrid QKD networks. The presented hybrid QKD networks provide a higher secret key rate at metropolitan distance and enable long-distance QKD between two cities, which provides a feasible QKD network structure in the future.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 11834010, 11504024) and the Fund for Shanxi "1331 Project" Key Subjects Construction.

Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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