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Experimental demonstration of high-rate measurement-device-independent quantum key distribution over asymmetric channels

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Measurement-device-independent quantum key distribution (MDI-QKD) can eliminate all detector side channels and it is practical with current technology. Previous implementations of MDI-QKD all use two symmetric channels with similar losses. However, the secret key rate is severely limited when different channels have different losses. Here we report the results of the first high-rate MDI-QKD experiment over asymmetric channels. By using the recent 7-intensity optimization approach, we demonstrate >10x higher key rate than previous best-known protocols for MDI-QKD in the situation of large channel asymmetry, and extend the secure transmission distance by more than 20-50 km in standard telecom fiber. The results have moved MDI-QKD towards widespread applications in practical network settings, where the channel losses are asymmetric and user nodes could be dynamically added or deleted.

Quantum key distribution (QKD) promises information-theoretical security in communications [1, 2]. In practice, however, the realistic QKD implementations might introduce device imperfections [3], which deviate from the idealized models [4–9]. Among many protocols to resolve the device imperfections [10–12], the measurement-device-independent QKD (MDI-QKD) protocol [13] has attracted a lot of research interests due to its practicality with current technology and its nature advantage of immunity to all detector attacks. Experimental MDI-QKD [14–20] has advanced significantly up to a distance of 404 km in low loss fiber [21] and a key rate of 1 Mbits/s [22]. Many theoretical improvements have been proposed to guarantee the practical security [23–28]. Notably, the recent proposal of twin-field QKD has the capability to overcome the rate-distance limit of QKD [29].

The future of QKD is believed to be a quantum network in which many user nodes are connected together via quantum channels and centric servers, such as the star-type network illustrated in Fig. 1. MDI-QKD is well suited to construct such a centric QKD network even with an untrusted relay, i.e., the six users in Fig. 1 can securely communicate with each other, though Charlie is insecure. Such a MDI-QKD network, as demonstrated in [30], presents a huge advantage over traditional trusted-relay based QKD networks [31–33].

In a practical quantum network, it is inevitable that some users are further away from the central relay, while the others are closer to the relay. For instance, in Fig. 1, user 1 and user 3 are farther from Charlie than the other users. This topology has appeared naturally in previous field QKD networks [31–33]. Unfortunately, so far, all implementations to MDI-QKD have been performed either through near-symmetric channels [15–20] or through the deliberate addition of loss in one channel to balance the total losses in the two arms [14]. However, the assumption of near-symmetric channels is clearly an unsatisfactory situation in a practical MDI-QKD network. Adding loss in one channel will severely limit the key rate and the secure distance in the asymmetric setting [25], and it also means that the addition/deletion of a new node will inevitably affect every other existing node, which is highly inconvenient and limits the scalability of the network.

We for the first time demonstrate high-rate MDI-QKD over asymmetric channels and achieve substantially higher key rate over previous methods for MDI-QKD. Our experiment employs the 7-intensity optimization method proposed recently in [34]. We demonstrate that the 7-intensity method can be implemented in software only without having to physically modify any channel, and it is highly scalable that can be easily integrated into existing quantum network infrastructure.

In asymmetric MDI-QKD with two users, Alice and Bob have channel transmittances \( \eta_A \) and \( \eta_B \) (\( \eta_A \neq \eta_B \)). The main question is how to choose the optimal intensities of the weak coherent pulses for Alice and Bob, denoted by \( s_A \) and \( s_B \), so as to maximize the key rate [25].
efficiently choose the optimal parameters, we use a local
development method to decouple the decoy state estimation in
the $X$ and $Z$ basis (i.e., the phase error rate). Therefore, the optimal
parameters obtained using decoy state method, but has no effect to errors in
the $X$ basis from key generation in $Z$ basis. This is the key idea
of the 7-intensity optimization method proposed in [34].
Note that Ref. [28] also mentioned on passing the pos-
sibility of using different intensities for Alice and Bob,
but no analysis on this important asymmetric case was
performed.

In the 7-intensity optimization method [34], Alice
and Bob each selects a set of 4 intensities, namely
signal state $\{s_A, s_B\}$ in the $Z$ basis, and decoy states
$\{\mu_A, \nu_A, \omega\}$ and $\{\mu_B, \nu_B, \omega\}$ in the $X$ basis, respectively.
The parameters that Alice and Bob choose include 7
different intensities in total, as well as the proportions
to send them. The secret key is generated only from
the $Z$ basis, while the data in the $X$ basis are all used to
perform the decoy state analysis. The decoy state
intensities are chosen to compensate for asymmetry and
ensure good HOM visibility in the $X$ basis (and roughly
satisfy $\frac{\mu_A}{\mu_B} = \frac{\nu_A}{\nu_B} \approx \frac{\eta_A}{\eta_B}$, which maintains symmetry
of photon flux arriving at Charlie). On the other hand,
the signal state is decoupled from the decoy states,
and can be freely adjusted to maximize key rate in the $Z$ basis (and generally $\frac{s_A}{s_B} \neq \frac{\eta_A}{\eta_B}$). Overall,
Alice and Bob optimize 12 implementation parameters:
$\{s_A, \mu_A, \nu_A, P_A, \mu_A, \nu_A, s_B, \mu_B, \nu_B, P_B, \mu_B, \nu_B\}$. To
efficiently choose the optimal parameters, we use a local
search algorithm and follow the optimization technique
in [34], which converts the 12 parameters into polar
coordinate and searches them while locking the decoy
state intensities at: $\frac{\mu_A}{\nu_A} = \frac{\mu_B}{\nu_B}$ [37]. The optimization
technique is highly efficient, and takes less than 0.1s
for each run of full optimization on a common desktop
PC (with a quad-core Intel i7-4790k processor, using
parallelization with 8 threads).

To implement MDI-QKD over two asymmetric chan-
nels, we construct a time-bin-phase encoding MDI-QKD
setup in Fig. 2. Alice and Bob each possesses an internally
modulated laser which emits phase-randomized laser pulses at a clock rate of 75 MHz. The gain-switched
laser diode can naturally generate optical pulses with
random phases. AM1 (amplitude modulator) is used to
tailor the pulse shape by cutting off the overshoot rising
edge of laser pulses. AM2 and AM3 are employed to ran-
domly modulate the intensities of signal state and weak
decoy states. The time-bin encoding is implemented by
utilizing a combination of a Mach-Zehnder interferometer
(MZI), AM4 and a phase modulator (PM). For $Z$ basis,
the key bit is encoded in time bin $|0\rangle$ or $|1\rangle$ by AM4,
while for the $X$ basis, it is encoded in the relative phase
0 or $\pi$ by the PM. Alice and Bob send their laser pulses
through two standard fiber spools, $L_A$ and $L_B$, to Charlie,
who performs Bell state measurement (BSM). The
BSM includes a 50/50 beam splitter (BS) and two super-
conducting nanowire single-photon detectors (SNSPD1
and SNSPD2). The main system parameters character-
ized in the experiment are shown in Table I.

To compensate for the relative phase drift and estab-
lish a common phase reference, Alice employs a phase-
stabilization laser (PSL) and Bob employs a phase shifter
(PS) in one of the arms of his MZI and a single-photon avalanche photodiode. To properly interfere the two
pulses at Charlie, we develop a real-time polarization
feedback control system, an automatic time calibration
system and a temperature feedback control system [37].
Thanks to the feedback control systems, the observed vis-
ibility of the two photon interference is about 46% and
the system has a long-term stability over tens of hours.
This stability enables us to collect a large number of sig-
nal detections, thus properly considering the finite-key
effect [26].

| $Y_0$ | $\eta_d$ | $\epsilon_Z^X$ | $\epsilon_Z^X$ | $\alpha$ | $f$ | $\epsilon$ | $N$ |
|-------|---------|---------------|---------------|---------|------|----------|-----|
| 6.40 \times 10^{-8} | 46% | 0.5% | 4% | 0.19 | 1.16 | $10^{-10}$ | $10^{12}$ |

FIG. 1. An illustration of a star-type MDI-QKD network
providing six users with access to the untrusted relay, Charlie.
Inset: an example of the possible implementation by Charlie.
We implement the 7-intensity method over different choices of channel lengths [37]. First, we fix the distance between Alice and Charlie at 10 km, i.e., $L_A = 10$ km, while the distance between Bob and Charlie $L_B$ varies from 40 km to 90 km. At each channel setting, we use the system parameters listed in Table I to perform a numerical optimization on the implementation parameters, based on three optimization strategies: (i) 4-intensity method, where the same intensities and proportions for Alice and Bob are selected and optimized in the 4-intensity protocol [21, 28]; (ii) 4-intensity+fiber method, where the asymmetry of channels is first compensated by adding additional losses [14] and then the same intensities and proportions for Alice and Bob are selected; (iii) 7-intensity method. The results are shown in Fig. 3(a). 7-intensity method can substantially increase the key rate and maximum distance of MDI-QKD in the case of high channel asymmetry: at $L_B = 60$ km, the 7-intensity method can generate a secret key rate of over an order of magnitude higher than that of 4-intensity+fiber method, and extends the maximum distance for approximately 20 km compared to 4-intensity+fiber method, and 40 km compared to 4-intensity method alone.

Next, we demonstrate for the first time a “single-arm” MDI-QKD, as shown in the inset figure in Fig. 3(b), where we place Alice and Charlie at the same location, i.e., $L_A = 0$ km. $L_B$ varies from 40 km to 100 km. The results are shown in Fig. 3(b). Such a single-arm setup only uses one public channel, and could be highly useful in free-space QKD, where Alice and Bob typically have a single free-space channel, in the middle of which adding a relay is unfeasible (e.g., ship-to-ship or satellite-ground channel). In this case, adding fiber in the lab would also be inconvenient due to turbulence or moving platforms. Using “single-arm” MDI-QKD, however, Bob can place a relay in his lab, such that Alice and Bob can enjoy the security of MDI-QKD through this channel, and maintain satisfactory key rate.

We list the implementation parameters and the main experimental results for $L_A = 10$ km and $L_B = 60$ km in Table II. Note that the parameters in 7-intensity method are quite different from those two types of 4-intensity methods. We obtain a secret key rate of 343 bits/s with 7-intensity method, which is 13.5 times higher than that of 4-intensity+fiber method. By using the joint-bound analysis [28], the key rate can be further improved to 645 bits/s. Moreover, the 7-intensity optimization method can greatly extend the transmission distance by about 50 km fiber. Furthermore, we also tested an extreme case where $L_A = 0$ km and $L_B = 100$ km. 7-intensity produces a secret key rate of 0.049 bit/s. In contrast, no key bits can be extracted with either strategy of using 4-intensity method with/without fiber.

The method of asymmetric intensities and decoupled bases we demonstrated can be applied to general quantum information protocols. First, the asymmetric method is important to the future implementation of free-space MDI-QKD with a moving relay such as
FIG. 3. Simulation (curve) and experiment results (data points) for secret rate (bit/pulse) vs the total distance $L_{AB}$ in standard telecom fiber. (a) $L_A$ is fixed at 10 km, while $L_B$ is selected at 40, 60, 80, 90 km. (b) $L_A$ is fixed at 0 km, while $L_B$ is selected at 40, 60, 80, 100 km. The points (curves) in the figure indicate the experimental (simulation) results for (i) 4-intensity method shown in blue diamond points (blue dashed line), where the same intensities and proportions for Alice and Bob are selected and optimized in the 4-intensity protocol [21, 28]; (ii) 4-intensity+fiber method [14] shown in black circle points (black dot-dash line); (iii) 7-intensity method [34], shown in red square points (red solid line). As can be seen, for the 4-intensity methods, adding fibers improves the key rate in long distances, but it does not in short distances. In contrast, the 7-intensity method always achieves substantially higher key rate than any of the other two methods, especially when channel asymmetry is high.

satellite. For instance, the channel transmittances in satellite-based quantum communication are constantly changing with up to 20-dB channel mismatch [38]. Second, the asymmetric method can be readily applied to MDI quantum digital signature (QDS) [39–41] and twin-field (TF) QKD [29]. The key generation formula of MDI-QDS is similar to that of MDI-QKD, where the proposed method can be directly implemented [37]. TF-QKD relies on single-photon interference, where the intensity-asymmetry affects both the interference visibility and the single-photon gain [37]. Our methods of asymmetric choice of intensities and optimization of parameters can be implemented to improve the key rate for asymmetric TF-QKD [42]. However, we note that the two encoding bases are symmetric in TF-QKD, thus the method of decoupled bases might not be applicable [37]. Finally, other protocols that rely on single-photon or two-photon interference, such as comparison of coherent states [43] and quantum fingerprinting [44–46], can also be benefited from our methods when they are working in an asymmetric setting.

In conclusion, by using the recent 7-intensity method, we demonstrate an order of magnitude higher key rate and an extension of 20-50 km distance over previous best-known MDI-QKD protocols. While previous methods of adding fibers inconveniently require the modification of every existing node with the addition/deletion of a new node, our 7-intensity method implements the optimization in software only and provides much better scalability. Overall, our results have moved MDI-QKD towards a more practical network setting, where the channel losses can be asymmetric and nodes can be dynamically added or deleted.

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TABLE II. Example implementation parameters and experimental results for $L_A=10$ km and $L_B=60$ km. $s_1^{Z}$ is the estimated yield of single photons in the $Z$ basis and $e_1^{X}$ is the estimated phase-flip error rate of single photons in the $X$ basis. $Q_{ss}^{Z}$ and $E_{ss}^{Z}$ are the observed gain and QBER for signal states. $R$ is the secret key rate (bit/s). Ratio is the key rate advantage of the 7-intensity method over the given method.

| Parameters | 7-intensity | 4-intensity | 4-intensity+fiber |
|------------|-------------|-------------|-------------------|
| $s_A$      | 0.169       | 0.119       | 0.363             |
| $s_B$      | 0.614       | 0.119       | 0.363             |
| $\mu_A$    | 0.056       | 0.180       | 0.280             |
| $\mu_B$    | 0.465       | 0.180       | 0.280             |
| $\nu_A$    | 0.011       | 0.023       | 0.058             |
| $\nu_B$    | 0.089       | 0.023       | 0.058             |
| $p_{s_A}$  | 0.599       | 0.256       | 0.483             |
| $p_{s_B}$  | 0.600       | 0.256       | 0.483             |
| $p_{\mu_A}$| 0.030       | 0.035       | 0.045             |
| $p_{\mu_B}$| 0.031       | 0.035       | 0.045             |
| $p_{\nu_A}$| 0.254       | 0.490       | 0.320             |
| $p_{\nu_B}$| 0.248       | 0.490       | 0.320             |
| $s_1^{Z}$  | $1.63 \times 10^{-3}$ | $1.97 \times 10^{-3}$ | $1.86 \times 10^{-4}$ |
| $e_1^{X}$  | 14.00%      | 20.28%      | 16.72%            |
| $Q_{ss}^{Z}$| $2.24 \times 10^{-4}$ | $3.05 \times 10^{-5}$ | $3.10 \times 10^{-5}$ |
| $E_{ss}^{Z}$| 0.91%       | 2.50%       | 0.91%             |
| $R$        | 343         | 0.11        | 25.50             |
| Ratio      | 1           | 3118        | 13.5              |
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