We employ quantum state and process tomography with time-bin qubits to benchmark a city-wide metropolitan quantum communication system. Over this network, we implement real-time feedback control systems for stabilizing the phase of the time-bin qubits, and obtain a 99.3% quantum process fidelity to the ideal channel, indicating the high quality of the whole quantum communication system. This allows us to implement field trial of high-rate quantum key distribution using coherent one way protocol with averaged quantum bit error rate and visibility of 0.25% and 99.2% during 12 hours over 61 km. Our results pave the way for the high-performance quantum network with metropolitan fibers.

Keywords: Quantum process tomography, Quantum networks, Quantum communication, Quantum key distribution.
collected by FPGA with 156 ps resolutions. The system is synchronized via co-propagating multiplexed pulses in different wavelength (1548.51 nm) and polarization with respect to the quantum signals at a rate of 1 MHz. To optimize the visibility, we develop a real-time proportional-integral-derivative (PID) feedback system, where a thermal phase shifter is used to compensate the phase drifts of the interferometer per 0.47 seconds with the error count rate in monitor line as the feedback.

To characterize the performance of the quantum system, we perform single-qubit quantum state tomography (QST) on the quantum states transmitted over the 61.1 km looped back fiber. We create photons in, and project them onto, well-defined time-bin states, such as $|0\rangle$, $|1\rangle$, $|+\rangle=\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)$, and $|-\rangle=\frac{1}{\sqrt{2}}(|0\rangle-|1\rangle)$, where $|0\rangle$ ($|1\rangle$) stands for the quantum state of photon being early (late) temporal mode. The density matrices of the six final output states reconstructed by QST are shown in Fig. 2(a) in green bar, which are very close to ideal state (black line).

Figure 2(b) shows the state fidelities, which is defined as the overlap between the ideal states and the final output states. The fidelities for the six states are estimated to be $0.997429\pm0.000006$, $0.998614\pm0.000004$, $0.9944\pm0.0007$, $0.9962\pm0.0006$, $0.9957\pm0.0006$ and $0.9940\pm0.0007$, respectively. The process of transmitting qubits over this quantum channel is quantified by QPT. We choose $|0\rangle$, $|1\rangle$, $|+\rangle$ and $|L\rangle$ as the input states and their corresponding output states $\rho_{out}$ to determine the process matrix $\chi$. The output states are related to the input states through the process density matrix, i.e. $\rho_{out} = \sum_{k=0}^{3} \chi_{ik} \sigma_{i} \rho_{in} \sigma_{k}$, where $\sigma_{i}$ are the Pauli matrices with $\sigma_{0}$ being the identity operator. The real and imaginary parts of $\chi$ are shown in Fig. 2(c) and (d). The process fidelity is defined as $F_{proc} = Tr(\chi_{ideal}\chi)$, where $\chi_{ideal}$ is the ideal process matrix. In our experiment, we calculate the process fidelity to be $99.3\%\pm0.7\%$. The X, Y, and Z components of the matrix $\chi$ represent the probabilities of a bit-flip or phase-flip error in the channel. A single-qubit quantum process can be represented graphically by the deformation of the Bloch sphere subjected to the quantum process [15].

In Fig. 2(e), we plot the ideal states as a wire grid of the Bloch sphere. After the long-fiber transmission from Alice and Bob, the receiving quantum states are, although very close to, not the same as the original states. Therefore, the ideal Bloch sphere is deformed into a slightly anisotropic ellipsoid as shown in the solid blue color.

Having established this high-quality quantum system, we proceed to perform QKD by employing COW protocol [19, 24-30]. The coherent pulses chopped by Alice are either empty or have a mean photon number $\mu=0.29$. Each logical bit of information is defined by the position of non-empty pulse in neighboring bins, for example $\mu=0$ for a logical "0" or $0\mu$ for a logical "1". Decoy sequences $\mu=\mu$ are sent to prevent photon-number-splitting attacks[24]. To obtain the key, Bob measures the arrival time of the photons on his data line, detector Ds in Bob1 of Fig. 1. In order to avoid Raman noise generated by synchronized signals, along with them we send empty sequences which is not used for coding. Attenuated laser pulses with 1.5 ns width are modulated to signal, decoy and empty sequences with probabilities of 90%, 7% and 3%, respectively. To ensure
the security, Bob randomly measures the coherence between successive non-empty pulses, such as bit sequences “1-0” or decoy sequences, with the unbalanced interferometer and detectors D1 and D2. Ideally, due to the coherence between pulses, we have all detections on D1 and no detection on D2. A loss of coherence, hence reduced visibility, indicates the presence of disturbance, in which case the key is simply discarded. Coherence can be quantified by the visibility of the interference

\[ V = \frac{c(D1) - c(D2)}{c(D1) + c(D2)}. \]  

where \(c(D1)\) and \(c(D2)\) are respectively the detector counts of D1 and D2. Fig. 3 shows the quantum bit error rate (QBER) and the interference visibility over a 61.1 km (28.02 dB loss) looped back field trials for 12 hours. The averaged QBER and visibility of the system are 0.250% ± 0.006% and 0.992 ± 0.002, respectively, indicating the high performance of our system. This result matches state fidelities well, which proves the reliability and accuracy of our QPT method. The figure also illustrates the system’s long-time continuous operation capability. Moreover, from the interference visibility, a phase error rate of about 0.004 can be expected during the key exchange scenario, which is low even compared with other indoor QKD protocols at similar attenuations [30-33]. Fig. 4 shows the secure key rate (SKR) per pulse as a function of channel attenuation. The error correction efficiency is set to 1.16. The SKRs of 30.5 km (5.78*10^-4 bit/pulse for 12.95 dB loss) and 61.1 km (1.82*10^-5 bit/pulse for 28.02 dB loss), marked as red and green pentagrams respectively, are estimated using the above system parameters with the measured QBER and visibilities. According to the security proof by Branciard et al. [24], it has been shown to be an upper bound under the assumption of collective attacks (i.e., Eve interacts with each individual state using the same strategy). We calculate the key rate in the infinite key scenario. As the channel attenuation increases, the number of counts decreases and the dark count rates (DCRs) of the SSPDs (about 10^-7/ns) becomes a major component of QBER, thus the secure key rate decreases exponentially. With the high visibility and negligible DCRs, our system can tolerate more channel loss, which means a wider area networks.
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