Field test of a practical secure communication network with decoy-state quantum cryptography

Teng-Yun Chen¹, Hao Liang¹, Yang Liu¹, Wen-Qi Cai¹, Lei Ju¹, Wei-Yue Liu², Jian Wang¹, Hao Yin¹, Kai Chen¹, Zeng-Bing Chen¹, Cheng-Zhi Peng¹, and Jian-Wei Pan¹

¹Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
²School of Information Science and Engineering, Ningbo University, Ningbo, Zhejiang 315211, China
zbchen@ustc.edu.cn

Abstract: We present a secure network communication system that operated with decoy-state quantum cryptography in a real-world application scenario. The full key exchange and application protocols were performed in real time among three nodes, in which two adjacent nodes were connected by approximate 20 km of commercial telecom optical fiber. The generated quantum keys were immediately employed and demonstrated for communication applications, including unbreakable real-time voice telephone between any two of the three communication nodes, or a broadcast from one node to the other two nodes by using one-time pad encryption.

© 2009 Optical Society of America

OCIS codes: (270.0270) Quantum optics; (060.0060) Fiber optics and optical communications; (060.5565) Quantum communications.

References and links
1. C. H. Bennett and G. Brassard, “Quantum cryptography: public key distribution and coin tossing,” in Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing, (Bangalore, India, 1984), pp. 175–179.
2. A. Muller, T. Herzog, B. Hutten, W. Tittel, H. Zbinden, and N. Gisin, “Plug and play’ systems for quantum cryptography,” Appl. Phys. Lett. 70, 793–795 (1997).
3. T. Nishioka, H. Ishizuka, T. Hasegawa, and J. Abe, “‘Circular type’ quantum key distribution,” Photon. Technol. Lett., IEEE 14, 576–578 (2002).
4. F. Grosshans, G. V. Assche, J. Wenger, R. Brouil, N. J. Cerf, and P. Grangier, “Quantum key distribution using Gaussian-modulated coherent states,” Nature 421, 238–241 (2003).
5. C. Gobby, Z. L. Yuan, and A. J. Shields, “Quantum key distribution over 122 km of standard telecom fiber,” Appl. Phys. Lett. 84, 3762–3764 (2004).
6. C.-Z. Peng, T. Yang, X.-H. Bao, J. Zhang, X.-M. Jin, F.-Y. Feng, B. Yang, J. Yang, J. Yin, Q. Zhang, N. Li, B.-L. Tian, and J.-W. Pan, “Experimental free-space distribution of entangled photon pairs over 13 km: towards satellite-based global quantum communication,” Phys. Rev. Lett. 94, 150501 (2005).
7. T.-Y. Chen, J. Zhang, J.-C. Boileau, X.-M. Jin, B. Yang, Q. Zhang, T. Yang, R. Lallamme, and J. W. Pan, “Experimental quantum communication without a shared reference frame,” Phys. Rev. Lett. 96, 150504 (2006).
8. T. Honjo, K. Inoue, A. Sahara, E. Yamazaki, and H. Takahashi, “Quantum key distribution experiment through a PLC matrix switch,” Opt. Commun. 263, 120–123 (2006).
9. T. Takesue, S.W. Nam, Q. Zhang, R.H. Hadfield, T. Honjo, K. Tamaki, and Y. Yamamoto, “Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors”, Nat. Photonics 1, 343–348 (2007).
10. Q. Zhang, H. Takesue, T. Honjo, K. Wen, T. Hirohata, M. Suyama, Y. Takiguchi, H. Kamada, Y. Tokura, O. Tadanaga, Y. Nishida, M. Asobe, and Y. Yamamoto, “MegaBits secure key rate quantum key distribution,” eprint arxiv:quant-ph/0809.4018 (2008).
11. B. Huttner, N. Imoto, N. Gisin, and T. Mor, “Quantum cryptography with coherent states”, Phys. Rev. A 51, 1863 (1995).
12. G. Brassard, N. Lütkenhaus, T. Mor and B.C. Sanders, “Limitations on Practical Quantum Cryptography”, Phys. Rev. Lett. 85, 1330 (2000).
13. D. Gottesman, H.-K. Lo, N. Lütkenhaus, and J. Preskill, “Security of quantum key distribution with imperfect devices”, Quant. Inf. Comput. 5, 325–360 (2004).
14. H. Inamori, N. Lütkenhaus, D. Mayers, “Unconditional security of practical quantum key distribution”, Eur. Phys. J. D 41, 599-627 (2007).
15. W. Y. Hwang, “Quantum key distribution with high loss: toward global secure communication,” Phys. Rev. Lett. 91, 057901 (2003).
16. X.-B. Wang, “Beating the photon-number-splitting attack in practical quantum cryptography,” Phys. Rev. Lett. 94, 230503 (2005).
17. H.-K. Lo, X.-F. Ma, and K. Chen, “Decoy state quantum key distribution,” Phys. Rev. Lett. 94, 230504 (2005); see also H.-K. Lo, Proceedings of IEEE ISIT (International Symposium on Information Theory) 2004, p. 137 (IEEE Press, 2004).
18. Y. Zhao, B. Qi, X.-F. Ma, H.-K. Lo, and L. Qian, “Experimental quantum key distribution with decoy states,” Phys. Rev. Lett. 96, 070502 (2006).
19. Y Zhao, B Qi, X F Ma, Hoi-Kwong Lo, L Qian, “Simulation and Implementation of Decoy State Quantum Key Distribution over 60km Telecom Fiber”, Proceedings of IEEE International Symposium on Information Theory 2006, pp. 2094-2098.
20. C.-Z. Peng, J. Zhang, D. Yang, W.-B. Gao, H.-X. Ma, H. Yin, H.-P. Zeng, T. Yang, X.-B. Wang, and J.-W. Pan, “Experimental long-distance decoy-state quantum key distribution based on polarization encoding,” Phys. Rev. Lett. 98, 010505 (2007).
21. D. Rosenberg, J. W. Harrington, P. R. Rice, P. A. Hiskett, C. G. Peterson, R. J. Hughes, A. E. Lita, S. W. Nam, and J. E. Nordholt, “Long-distance decoy-state quantum key distribution in optical fiber,” Phys. Rev. Lett. 98, 010503 (2007).
22. T. Schmitt-Manderbach, H. Weier, M. Fürst, R. Ursin, F. Tiefenbacher, T. Scheidl, J. Perdigues, Z. Sodnik, C. Kurtsiefer, J. G. Rarity, A. Zeilinger, and H. Weinfurter, “Experimental demonstration of free-space decoy-state quantum key distribution over 144 km,” Phys. Rev. Lett. 98, 010504 (2007).
23. Z.L. Yuan, A.W. Sharpe, and A.J. Shields, “Unconditionally secure one-way quantum key distribution using decoy pulses”, Appl. Phys. Lett. 90, 011118 (2007).
24. S. J. D. Phoenix, S. M. Barnett, P. D. Townsend, and K. J. Blow, “Multi-user quantum cryptography on optical networks,” J. Mod. Opt. 72, 1155–1163 (1995).
25. P. D. Townsend, S.J.D. Phoenix, K. J. Blow, and S. M. Barnett, “Quantum cryptography for multi-user passive optical networks,” Electron. Lett. 30, 1875–1877 (1994).
26. P. D. Townsend, “Quantum cryptography on multi-user optical fibre networks,” Nature 385, 47–49 (1997).
27. C. Elliott, “Building the quantum network,” New J. Phys. 4, 46 (2002).
28. C. Elliott, A. Colvin, D. Pearson, O. Pikalo, J. Schlafer, and H. Yeh, “Current status of the DARPA Quantum Network,” in Quantum Information and Computation III, E. J. Donkor, A. R. Pirich, and H. E. Brandt, eds., Proc. SPIE 5815, 138–149 (2005).
29. X. Tang, L.-J. Ma, A. Mink, A. Nakassis, H. Xu, B. Hershman, J. Bienfang, D. Su, R. F. Boisvert, C. Clark, and C. Williams, “Demonstration of an active quantum key distribution network,” in Quantum Communications and Quantum Imaging IV, R. E. Meyers, Y.-H. Shih, K. S. Deacon, eds., Proc. SPIE 6305, 630506 (2006).
30. SECOQC White Paper on Quantum Key Distribution and Cryptography, http://www.secoqc.net/downloads/secoqc_crypt_wp.pdf, accessed Feb. 2009.
31. W. Chen, Z.-F. Han, T. Zhang, H. Wen, Z.-Q. Yin, F.-X. Xu, Q.-L. Wu, Y. Liu, Y. Zhang, X.-F. Mo, Y.-Z. Gui, G. Wei, and G.-C. Guo, ‘Field experimental ‘star type’ metropolitan quantum key distribution network,” eprint arxiv:quant-ph/0707.3546 (2007).
32. G.S. Vernam, “Cipher printing telegraph system for secret wire and radio telegraph communications”, J. Am. Inst. Electr. Eng. XLV, 109–115 (1926).
33. Z. L. Yuan, A. R. Dixon, J. F. Dynes, A. W. Sharpe, and A. J. Shields, “Gigahertz quantum key distribution with InGaAs avalanche photodiodes,” Appl. Phys. Lett. 92, 201104 (2008).
34. T. Thew, S. Tanzilli, L. Krainer, S.C. Zeller, A.A. Rochas, “Low jitter up-conversion detectors for telecom wavelength GHz QKD”, I. Rech, S. Cova, H. Zbinden, and N. Gisin, New J. Phys. 8, 32 (2006).
35. E. Diamanti, H. Takesue, C. Langrock, M.M. Fejer, and Y. Yamamoto, “100 km differential phase shift quantum key distribution experiment with low jitter up-conversion detectors”, Opt. Express 14, 13073 (2006).
36. D. Stucki, C. Barreiro, S. Fasel, J.-D. Gautier, O. Gay, N. Gisin, R. Thew, Y. Thoma, P. Trinkler, F. Vannel, H. Zbinden, “High speed coherent one-way quantum key distribution prototype”, eprint arxiv:quant-ph/0809.5264 (2008).
1. Introduction

Quantum cryptography can in principle offer the first provable unconditional security between communication parties, which is guaranteed by fundamental laws of quantum mechanics, rather than unproven computational assumptions. The last two decades have witnessed dramatic advances in both theoretical developments and successful experimental demonstration of quantum cryptography systems, see, e.g., [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] to name a few of them. Based on these attractive progresses, several companies (such as IdQuantique, MagiQ and SmartQuantum) have commercially developed quantum cryptography prototypes, which bring quantum cryptography into practical applications by integrating with current encryption and decryption techniques. In practice, however, the security of a specific setup is not automatically ensured due to various imperfections. Most of today’s commercially available quantum cryptography systems rely on photon sources from attenuated laser pulses, which forms a tremendous security threat for such systems. This is because weak coherent pulse sources contain two or more photons per pulse with a non-vanishing probability, leaving the systems susceptible a beam splitter attack from a formidable eavesdropper. The photon number splitting attack is in fact the main security threat of practical QKD schemes [11, 12].

Rigorous security analysis on practical quantum key distribution (QKD) system is proposed by Gottesman-Lo-Lütkenhaus-Preskill [13] and Inamori-Lütkenhaus-Mayers [14]. However, the results are not optimal, which can guarantee only a very limited key generation rates and distances for a practical quantum cryptography system.

Recent revolutionary progress has been achieved by introducing the idea of decoy state [15], and by turning the idea into systematical and rigorous theory and scheme in [16] and [17]. By using decoy state within the common setup, one can obtain much higher key generation rates and longer distances (typically from less than 30 km, to more than 100 km), in the same level compared with the case of using true single photon sources [17]. This leads to firstly successful experimental demonstrations by Lo’s group from Canada [18] for 15 km, and further for 60 km [19]. Then implementations for more than 100 km are almost simultaneously realized by research groups from China [20], America [21] and Europe [22]. Also an implementation for 25.3 km is achieved by Toshiba’s group from UK [23].

So far most research groups all over the world have put forward QKD links, however, operating in a point-to-point mode only, rather than networks with multiple users. This has greatly restricted the domain of applicability of quantum cryptography, which enjoys the extremely high security standard. Subtle design and appropriate network topology are needed to be effectively integrated into existing data networks to achieve a high key generation rate and long distance for a secure communication network.
Phoenix et al. [24] proposed the idea of passive quantum networks by using passive optical components, which can realize QKD between one user to any other user in the network. Townsend et al. [25] demonstrated that QKD is feasible between any user to any other one within a passive quantum network. However, photons are split by couplers according to their ratio which nevertheless sacrifices greatly the actual key generation rate. By using a network controller that actively controls optical switches [26], the first quantum cryptography network, DARPA (The Defense Advanced Research Projects Agency) quantum network, became operational since 2004 [27, 28]. One node contains an active 2-by-2 optical switch that can be used to actively switch between two network topologies. This network currently links the campuses of BBN Technologies, Harvard University and Boston University (BU), with distances of approximately 10 km for both BBN-Harvard span and BBN-BU span. In 2006 the NIST group also demonstrated a three-user active quantum cryptography network with one transmitter using optical switches and two receivers, each connected to transmitter by 1 km fiber links [29]. Over 1 Mbps sifted-key rate was claimed to be generated in either link. The European SECOQC (Secure Communication based on Quantum Cryptography) quantum network [30] has initiated since 2004 and currently claims to have 4 nodes in Vienna city for a fiber ring network of approximately 63 km and one additional node which is 85 km far from the ring. It is based on the trusted relay paradigm [30]. It mostly focuses on an architecture allowing integration of heterogeneous QKD-link devices. One node with decoy state device is also included in the tested network. Recently Chen et al. implemented a four-user quantum cryptography network by taking star topology based on wavelength-division multiplexing (WDM) [31]. It was built in the commercial backbone telecom fiber network in Beijing with the longest length of 42.6 km for fibers between two nodes.

The DARPA network [27, 28] realized the first quantum cryptography network with 3 node, while the European SECOQC quantum network [30] gives the first implementation of integrated heterogeneous QKD-link devices. At the mean time, the NIST network [29] gives very high sifted-key rate in a short distance network, while the quantum network in Beijing [31] gives longest length between two nodes. These progresses are quite significant and represent big steps toward a secure QKD network. However, there exist still big gaps from a practical quantum cryptography network. Without using decoy state, a prototype setup cannot achieve secure distance of more than 30 km generally [17, 14] with the standard BB84 protocol. The implemented DARPA network [28], the NIST network [29] and the network realized in [31] are all without using decoy states. Therefore, these network, in fact, either are not secure, or cannot accomplish the performance mentioned in their experiments. In addition, the distance for secure network communication are quite short, namely, less than 10 km in the case of DARPA network and only 1 km for NIST network.

In this article, we present a three-user network communication system based on decoy-state quantum cryptography in a typical application scenario. In the experiment, it is possible to create secure quantum keys on demand among USTC (University of Science and Technology of China), Binhu, and Xinglin that are located in Hefei city of China. As shown in Fig. 1 the USTC node acts as a trusted relay and constitutes a chained QKD architecture together with Binhu, and Xinglin. The telecom fiber strand is approximately 20 km for USTC-Binhu while it is also approximately 20 km for USTC-Xinglin. The produced keys were directly handed over to an application that was used to process real-time voice telephone between any two users of the three nodes. We have developed secure communication network system including both the QKD link modules and the audio application module based on quantum keys. All of optical, electronic controlling, data acquisition and processing system are integrated into one single box as a transmitter or a receiver. Successful real-time secret audio communication has been performed between any two users of the three nodes with the quantum keys through one-time
Fig. 1. Chained network architecture of our quantum cryptography network. Two sets of decoy-state QKD systems are installed for Binhu-USTC link and USTC-Xinglin link, respectively. The QKD systems have been updated in a large degree to match seamless integration with real-time audio communication by using one-time pad encryption, among the three nodes. The red dashed line indicates the fiber running out of the map.

pad encryption \[32\]. An interphone has also been accomplished when one implements a secure broadcast again by using one-time pad encryption from one node to the other two nodes, or the other way around.

Compared with prior results, we provide a complete, compact, low cost 3-node QKD network system in a real-life situation. Our motivation and results are three-fold. Firstly we focus on a practical QKD network with decoy state. The trusted-relay architecture we used is proved to be very practical and is extensively used such as in DARPA network and the SECOQC network. It has many advantages \[30\] such as feasibility with today’s technologies (not relying on unavailability of quantum repeater), allowing for longer distance compared with optical switch based network etc. \[30\]. At the mean time, decoy state method can, in a large degree, increase the key generation rate with guaranteed unconditional security. Secondly we have focused on developing a complete system, with virtues of low cost and compact, reliable and integrated components, rather than only an experimental demonstration. This would help to bring a commercial QKD network system closer. Thirdly, we focused on real-life application, such as real time two-way audio communication and one-way broadcast, by utilizing one-time pad encryption and decryption. The pseudo-random numbers are not used in our system as they are normally used in a Gigahertz QKD system \[33\], due to lack of a random number generators in the Gigahertz level. Rather we use the true random number generators in every place for the system, and has achieved practical applications with unconditional security. In addition, we use the InGaAs-type detectors with a small volume rather than upconversion \[34, 35\] or superconducting nanowire detectors \[9\]. The latter two detectors have the advantage of high
Fig. 2. Sketch of the experimental setup for one QKD-link. With a random choice of measurement basis controlled by the phase modulator at the MZ interferometer in Bob’s side, Bob has 1/2 probability to have correct basis choice. Both sides can then obtain sifted keys after comparison, which are used for further error correction, privacy amplification according to decoy state QKD mechanism. The classical communication channel is realized via a standard TCP/IP connection in our setup. Here, IM (PM): intensity (phase) modulator; BS: beam splitter; AT: controllable attenuator; SYN: synchronized signal; PC: polarization controller; PS: phase shifter; D: single-photon detector; PBS: polarizing beam splitter.

repetition rate for detection, but with a very large volume. Moreover high background count rate is accompanied with the upconversion detector, while superconducting detectors require cryogenic cooling. The InGaAs-type detector thus provides an ideal choice for our compact, low cost practical QKD network systems.

2. Experimental setup

Due to the currently lowest dispersion and attenuation for optical fiber at the telecom wavelength, we implement our setup in a real-life situation by using the running fiber network of China Netcom Group Corp Ltd. The laser sources in our quantum cryptography system are produced from distributed feedback (DFB) diodes with a center wavelength of 1550.12 nm and pulse duration of 1 ns. By a random attenuation through a fiber intensity modulator for the DFB laser, one thus creates the needed weak coherent signal, decoy pulses and vacuum for this quantum cryptography setup. In our system, there is a transmitter box in Binhu and a receiver box in Xinglin, while in USTC there are both a transmitter box and a receiver box. Every box has integrated full functions for control of QKD hardware, execution of QKD protocol module and seamless interchange with our audio communication application. This design can thus constitute two QKD links simultaneously between Binhu and USTC, and between USTC and Xinglin. A repetition rate of 4 MHz is used for the laser source. This is because true random number generators can only work at this level of rate for a commercially available product. We adopt in this experiment phase encoding method for finishing QKD tasks.

For key generation, in transmitter’s side the photon pulse is firstly sent to an time division fiber Mach-Zehnder (MZ) interferometer with the long arm through a phase modulator to generate the four primary signal states necessary for implementing the BB84 [1] protocol of a QKD system. Here we use the polarizing beam splitters and beam splitters in both Alice’s and Bob’s sides, such that photons from Alice’s short arm are directed into Bob’s long arm and vice versa [5]. This would avoid a 3dB loss for useful photons in the normal case of Mach-Zehnder (MZ) interferometers where only beam splitters are used. By using an attenuator through suitable attenuation, one can control the photon number intensity to be 0.65/pulse for signal states, and 0.08/pulse for decoy states for USTC-Xinglin link, while they are 0.60/pulse for signal states, and 0.20/pulse for decoy states for Binhu-USTC link. A synchronization laser pulse at the wavelength of 1310 nm was then combined with the signal and decoy states, through
a wavelength division multiplexing (WDM) apparatus, into the installed single-mode telecom fiber for transmission. After passing through the 20 km long dark fiber, at receiver’s side the synchronization information encoded in the fiber is firstly read out through another WDM apparatus. Finally a clock signal synchronized with transmitter is formed, which will further control correspondingly the measurement basis choice for the phase modulator located in the unbalanced fiber MZ interferometer in receiver’s side. In addition, this synchronization clock signal will also act as the gate control signal for the InGaAs-type detectors D0 and D1. The whole synchronization electronics, detection logic and signal acquisition are all integrated in a single board by using a field programmable gate array (FPGA) and running at a sampling frequency of 4 MHz. The detectors are running in gating mode while the gate width is set to be 2 ns to match our laser source. For our detectors, the “after pulse” will generally increase the error rate of the raw key. The after pulse probability for the detectors used in our setup will decrease to about 8/1000 if we set dead time be 20$\mu$s. This is in the same level of duration for dead time if compared with a recent experiment [36], in which a dead time of 30$\mu$s is used. Thus we have set dead time for all detectors be 20$\mu$s, and simultaneously match the detection events. The true dark counts rate for the detectors themselves are all about 1.0 $\times$ 10$^{-5}$/pulse. The measured value from vacuum decay state for dark counts rate $Y_0$ is about 1.0 $\times$ 10$^{-4}$/pulse due to finite extinction ratio for intensity modulator, affect of the “after pulse” for detectors, and the intrinsic dark counts. The detection efficiency for all the detectors are greater than 10%.

The telecom single mode fiber has an average attenuation of about 0.2 dB per kilometer resulting in a total attenuation of 4.5 dB including the connectors for Binhu and USTC span, and 5.6 dB for USTC and Xinglin span. To keep the identical and good coherent property for photons after propagating along the long distance fiber, a voltage-driven fiber polarization controller is used to dynamically adjust polarizations for the transmitted states according to total detection rates. This active compensation technique finally urges that photons from Alice’s short arm are directed into Bob’s long arm and vice versa. To remove system’s intrinsic phase fluctuation in the MZ interferometers at both sides, we have used a phase shifter to compensate the phase difference dynamically. This is accomplished by implementing a feedback control to stabilize the phase. Specifically we have inserted another pulsed laser (not shown in Fig. 2) with the same central wavelength of 1550.12 nm as a reference during the idle gap between two signal pulses, and making continuous active control of the MZ interferometer arm lengths.

For satisfying the necessary requirements for decoy state QKD system, we used true random number generators produced by IdQuantique (type: Quantis-OEM, which has passed the NIST and Diehard randomness tests). These random number generators are integrated in our controlling electronics: a) to process random attenuation of laser source for producing signal and decoy states; b) to load in the phase modulator in transmitter’s side for generating the needed four possible states for QKD system; and c) to load in the phase modulator in receiver’s side for forming the needed two possible measurement basis for QKD system.

3. Secure key generation and applications

In this section, we present typical characters supplied by our experimental network communication system. Besides the transmission loss in the fiber, there are also other coupling and connection losses, in particular an approximate 3.5 dB due to the inserting loss for the polarization maintaining fiber in receiver’s side. The BB84 protocol contributes an additional 3 dB loss because there are only roughly one half of received photons encoding correct information. It should be remarked that this loss can be avoided if one uses an asymmetric basis choice for Alice and Bob [37]. Our setting for the proportion of three transmitted states is 6 : 1 : 1 among the signal state, decoy state and vacuum state.

Before demonstrating our audio application among the three nodes, we have run and meas-
ured the average specifications that our system can achieve. Through a thirty-minute running, we have obtained corresponding parameters for the two QKD links, and listed all the related measurement and processing results in Table 1. The sifted key rates are archived to be more than 10.5 kbps for Binhu-USTC link and more than 9.0 kbps for USTC-Xinglin link. The quantum bit error rate (QBER) is measured to be about 1.6% for Binhu-USTC link and about 1.4% for USTC-Xinglin link. According to the systematical theory of decoy state QKD [16, 17, 38, 39], we have developed a data post-processing unit to finish both error correction and privacy amplification in real time by considering finite key length and statistical fluctuation. For the implemented algorithms themselves, we are mainly based on the result from the NIST group [40], by noting that there is no decoy state in the NIST case. Currently we realize the algorithms using software, while a FPGA implementation is more preferable in the future for high speed QKD links. Consequently we can achieve a final secure key rate of more than 1.5 kbps for both links.

| link           | Communication wavelength | QBER | Sifted-key rate | Final key rate |
|----------------|--------------------------|------|-----------------|----------------|
| Binhu-USTC     | 1550.12nm                | ~1.6%| >10.5 kbps      | >1.6 kbps      |
| USTC-Xinglin   | 1550.12nm                | ~1.4%| >9.0 kbps       | >1.5 kbps      |

We obtain the following key generation rate by using the result of [13, 17]

\[
R \geq q \{-Q_\mu f(E_\mu)H_2(E_\mu) + Q_1[1 - H_2(e_1)]\},
\]

where the subscript $\mu$ is the average photon number per signal in signal states; $Q_\mu$ and $E_\mu$ are the measured gain and the quantum bit error rate (QBER) for signal states, respectively; $q$ is an efficiency factor for the protocol. $Q_1$ and $e_1$ are the unknown gain and the error rate of the true single photon state in signal states. To achieve maximum possible key generation rate, the decoy state method can estimate the lower bound of $Q_1$ denoting as $Q_1^L$, and the upper bound of $e_1$ denoting as $e_1^U$. Thus the decoy approaches could provide an unconditional security [16, 17] for QKD systems. We follow here the method developed in [39, 19] to estimate good bounds for $Q_1$ and $e_1$, and using the stronger version for maximizing the key generation rate formula developed in [13, 17]. The $H_2(x)$ is the binary entropy function: $H_2(x) = -x \log_2(x) - (1-x) \log_2(1-x)$, while the factor $f(x)$ is for considering an efficiency of the bi-directional error correction [41].

For convenience, we denote $\nu$ the average photon number per pulse for decoy state. After experimentally measuring all the relevant parameters, we can input the following bounds for calculating final key generation rate [39, 19]

\[
Q_1 \geq Q_1^L = \frac{\mu^2 e^{-\mu} + \mu \nu}{\mu \nu - \nu^2} (Q_\nu^L e^\nu - Q_\mu e^\mu) + \frac{\nu^2 - \mu^2}{\mu^2},
\]

\[
e_1 \leq e_1^U \leq \frac{E_\mu Q_\mu - Y_0^U e^{-\mu} / 2}{Q_1^L},
\]

in which

\[
Q_\nu^L = Q_\nu(1 - \frac{10}{\sqrt{N_\nu Q_\nu}}),
\]

\[
y_0^L = Y_0(1 - \frac{10}{\sqrt{N_0 Y_0}}),
\]

\[
y_0^U = Y_0(1 + \frac{10}{\sqrt{N_0 Y_0}}),
\]
Here $N_\nu$ and $N_0$ are numbers of pulses used as decoy state and vacuum state, respectively, while $Q_\nu$ is the measured gain for the decoy states.

All the relevant parameters are listed in Table 2 for a typical running duration of 120s for USTC-Xinglin link in our experiment. From Table (2), we see a final key rate of around 4Mbps.

| Para. | Value   | Para. | Value   |
|-------|---------|-------|---------|
| $Q_\mu$ | $6.36 \times 10^{-3}$ | $E_\mu$ | $1.44 \times 10^{-2}$ |
| $Q_\nu$ | $8.61 \times 10^{-4}$ | $E_\nu$ | $7.84 \times 10^{-2}$ |
| $Q_L$ | $2.72 \times 10^{-3}$ | $e_U$ | $2.23 \times 10^{-2}$ |
| $R$ | $4.10 \times 10^{-4}$ | $q$ | 0.356 |

$4M \times R = 1.7$kbps is obtained for the typical running of our system. For achieving unconditional security, we have estimated the bounds for $Q_L$ and $e_U$ by considering the statistical fluctuations for vacuum states, gains for signal states and decoy states within 10 standard deviations. Thus the final keys rate is valid for finite key length and promises a confidence interval of about $1 - 1.5 \times 10^{-23}$. We have performed privacy amplification by utilizing the universal2 functions that are represented by Toeplitz matrices [42]. This finally improves both the efficiency and speed in a large degree for privacy amplification, compared with the case that using purely random matrices. It should be remarked that, to our knowledge, this is the first implementation for both the error correction and privacy amplification, by considering statistical fluctuation for decoy state quantum key distribution in a real-life application. There is actually a tradeoff between key generation rate and efficiency for privacy amplification. In our case we choose 120s communication time for one time of executing privacy amplification for corrected raw keys. One could certainly get faster realization for privacy amplification for shorter communication time, then one is left with bigger statistical fluctuation and thus less key generation rate.

We have accumulated a final key of about 120Mbits and performed the NIST 800-22 randomness test suite [43]. The sequence has passed all the test for a significance level of 0.8%, with the minimum pass rate for each statistical test of 95%. Also the Diehard statistical test suite [44] is performed. The reported $p$-value for the test are all between 0.009 and 0.989. Thus there is very high confidence of 98.9% that our final keys are truly random. With sufficient large data of keys, we hope to perform more extensive random test for our system in the future.

Based on these results, we have developed telephony terminal equipments through the normal analog commercial cable for telephony. The terminal has an ability to make one-time pad encryption and decryption based on our QKD links, to process common voice telephone. The audio compression ratio has arrived 0.6 kbps. In fact, our system can offer more than 1.2 kbps, which is two times the keys needed for a one-way communication. Thus our system can offer directly two-way telephony communication in real time. We have run the system for quite a few minutes, and always get clear audio signal transmission with a good quality. After one hour’s continuous running, we still found no decrease of voice quality, which shows that our setup provides a very stable and robust secure network communication system. In fact, we have tested the whole system for half a month in USTC for a telecom fiber of 20 km. There is no any problem for the secure audio communication system.

An interphone system is further developed in our experiment, which provides a broadcast of ciphered information from one user to any other two users with one-time pad encryption. Still using about a quantity of 0.6 kbps keys, we have successfully tested and finished broadcasts based on our telephony system, from any one of the Binhu, USTC and Xinglin nodes to any other two nodes. If we need feedbacks from the other two nodes, it is not temporarily possible for all the nodes due to the limited key generation rates. It is clear that it would need 1.2 x
$(N-1)$ kbps quantum keys to process this task and to make all the two-way communications simultaneously for $N$ nodes.

4. Conclusion

In summary, the experiment reported here demonstrates an operational network communication system, which allows real-time voice telephone between any two of the three communication users, or a broadcast from one user to the other two users by using one-time pad encryption. The chained network topology allows secret keys to be forwarded, in a hop-by-hop fashion, along QKD links. Therefore unconditional authentication and encryption for information transmission by using one-time pad will become possible. The middle node acts as trusted relays and increases the key generation rate in a large degree, compared with the case of direct connection between the nodes with an exponential decreasing. Our setup can be easily expanded to many-node network, and enjoys an advantage of slowly increasing for key’s need. Near future work would cover improving the key generation rates, by employing high performance detectors and high-speed true random number generators etc. We expect that it would be possible to finish two-way audio communications in real time for QKD network with a few nodes. In the case that the key rates is not enough for video conference with one-time pad encryption, we expect to use classical symmetrical encryption algorithm such as AES (Advanced Encryption Standard) with a high refreshing rate of keys, and maintain a desired security level.

Acknowledgments

We acknowledge the financial support from the CAS, the National Fundamental Research Program of China under Grant No.2006CB921900, and the NNSFC. T.Y.C. also gratefully acknowledges the support of China Postdoctoral Science Foundation funded project and the K.C. Wong Education Foundation, Hong Kong of China. The authors are grateful for very valuable discussions and communications with Xiang-Bin Wang, Hoi-Kwong Lo, Bing Qi, Xiong-Feng Ma and Yi Zhao.