# 量子信息导论
# PHYS5251P

中国科学技术大学
物理学院/合肥微尺度物质科学国家研究中心

陈凯

2024.4

# 第四章 量子通信

徐飞虎：量子通信方案，量子密钥分发QKD；非理想条件下量子保密通信方案和实验，数据处理方法；QKD安全性分析等

陈凯：量子隐形传态理论和实验，纠缠交换，量子网络等

# 第四章 量子通信

1. 保密通信
2. QKD基本原理
3. BB84协议过程
4. QKD安全性
5. 诱骗态(Decoy-state QKD)
   ① Decoy QKD原理
   ② 实用Decoy QKD
   ③ Decoy QKD实验
6. QKD的现实安全性
   ① 探测端的安全性 **à** MDI-QKD
   ② 设备无关的 **à** DI-QKD
7. 量子隐形传态(Quantum Teleportation) [原理、实验]
8. 量子纠缠交换(Entanglement Swapping)
9. 量子通信网络
10. 量子通信商用公司
11. 量子通信发展与实用化QKD之路

# Requirements for unconditional security

1. Eve cannot intrude into Alice′s and Bob′s devices to access either the emerging key or their choices of settings.

2. Alice and Bob must trust the random number generators that select the state to be sent or the measurement to be performed.

3. The classical channel is authenticated with unconditionally secure protocols, which exist.(Carter and Wegman, 1979; Wegman and Carter, 1981; Stinson, 1995)

4. Eve is limited by the laws of physics. This requirement can be sharpened: in particular, one can ask whether security can be based on a restricted set of laws. In this review, as in the whole field of practical QKD, we assume that Eve has to obey the whole of quantum physics.

# Several techniques for security proofs

1. The very first proofs by Mayers were somehow based on the uncertainty principle Mayers, 1996, 2001. This approach has been revived recently by Koashi 2006a, 2007.

2. Most of the subsequent security proofs have been based on the correspondence between entanglement distillation and classical post processing, generalizing the techniques of Shor and Preskill 2000. For instance, the most developed security proofs for imperfect devices follow this pattern Gottesman, Lo, Lütkenhaus, and Preskill, 2004.

3. The most recent techniques use instead information theoretical notions Ben-Or, 2002; Kraus, Gisin, and Renner, 2005; Renner, 2005; Renner, Gisin, and Kraus, 2005.

# BOUNDS ON THE BIT ERROR RATE FOR BB84 AND THE SIX-STATE SCHEME

TABLE I

BOUNDS ON THE BIT ERROR RATE FOR BB84 AND THE SIX-STATE SCHEME USING ONE-WAY AND TWO-WAY CLASSICAL POST-PROCESSING. THE LOWER BOUNDS FOR TWO-WAY POST-PROCESSING, 18.9% FOR BB84 AND 26.4% FOR THE SIX-STATE SCHEME, COME FROM THE CURRENT WORK

**BB84**

| | one-way | two-way |
|---|---|---|
| Upper bound | 14.6% | 1/4 |
| Lower bound | 11.0% | 18.9% |

**Six-state Scheme**

| | one-way | two-way |
|---|---|---|
| Upper bound | 1/6 | 1/3 |
| Lower bound | 12.7% | 26.4% |

Daniel Gottesman and Hoi-Kwong Lo, Proof of Security of Quantum Key Distribution With Two-Way Classical Communications, IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. 49, 457-475 (2003)

# Decoy-state quantum key distribution with two-way classical postprocessing

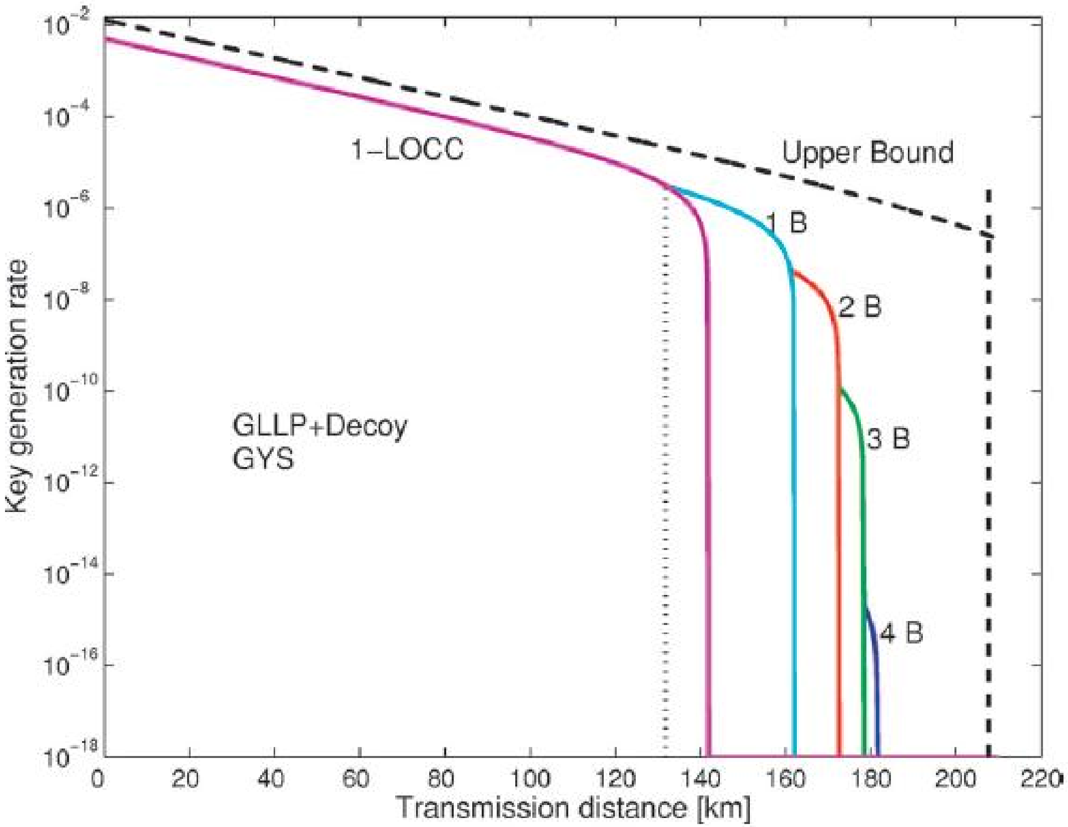


FIG. 3. (Color online) Plot of the key generation rate as a function of the transmission distance with the data postprocessing scheme of GLLP+decoy+B steps method. The parameters used are from the GYS experiment [19] listed in Table I. The GLLP +decoy+B steps scheme surpasses the scheme with 1-LOCC at a distance of 132 km. The maximal secure distance using four B steps is 181 km, which is not far from the upper bound of 208 km.

X.-F. Ma, C,-H. Fred Fung,† F. Dupuis, K. Chen, K. Tamaki,and H.-K. Lo, Phys. Rev. A 74, 032330 (2006)

# Decoy-state quantum key distribution with both source errors and statistical fluctuations

Xiang-Bin Wang, C.-Z. Peng, J. Zhang, L. Yang, Jian-Wei Pan
General theory of decoy-state quantum cryptography with source errors
Phys. Rev. A 77, 042311 (2008)

Xiang-Bin Wang, Lin Yang, Cheng-Zhi Peng, Jian-Wei Pan, Decoy-state quantum key distribution with both source errors and statistical fluctuations, New. J. Phys., 11, 075006 (2009)

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# QUANTUM TELEPORTATION

Teleportation of unknown quantum state encompasses the complete transfer of information from one particle to another

Unknown quantum state

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

EPR source

$$|EPR-pair\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

Total state

$$|\psi\rangle|EPR-pair\rangle = \frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle\right)$$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) \qquad |\Phi^-\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right) \qquad |\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

# QUANTUM TELEPORTATION

The joint state of three particles

$$|\psi\rangle|EPR-pair\rangle = \frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle\right)$$

can be rephrased as follows:

$$|\psi\rangle|EPR-pair\rangle = |\Phi^+\rangle\frac{1}{2}\left(\alpha|0\rangle + \beta|1\rangle\right) + |\Psi^+\rangle\frac{1}{2}\left(\beta|0\rangle + \alpha|1\rangle\right)$$

$$+|\Phi^-\rangle\frac{1}{2}\left(\alpha|0\rangle - \beta|1\rangle\right) + |\Psi^-\rangle\frac{1}{2}\left(-\beta|0\rangle + \alpha|1\rangle\right)$$

Therefore Bell measurements on the first two particles would project the state of Bob's particle into a variant of $|\psi_1\rangle$ of the state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where

$|\psi_1\rangle$ = either $|\psi\rangle$ or $\sigma_x|\psi\rangle$ or $\sigma_z|\psi\rangle$ or $\sigma_x\sigma_z|\psi\rangle$

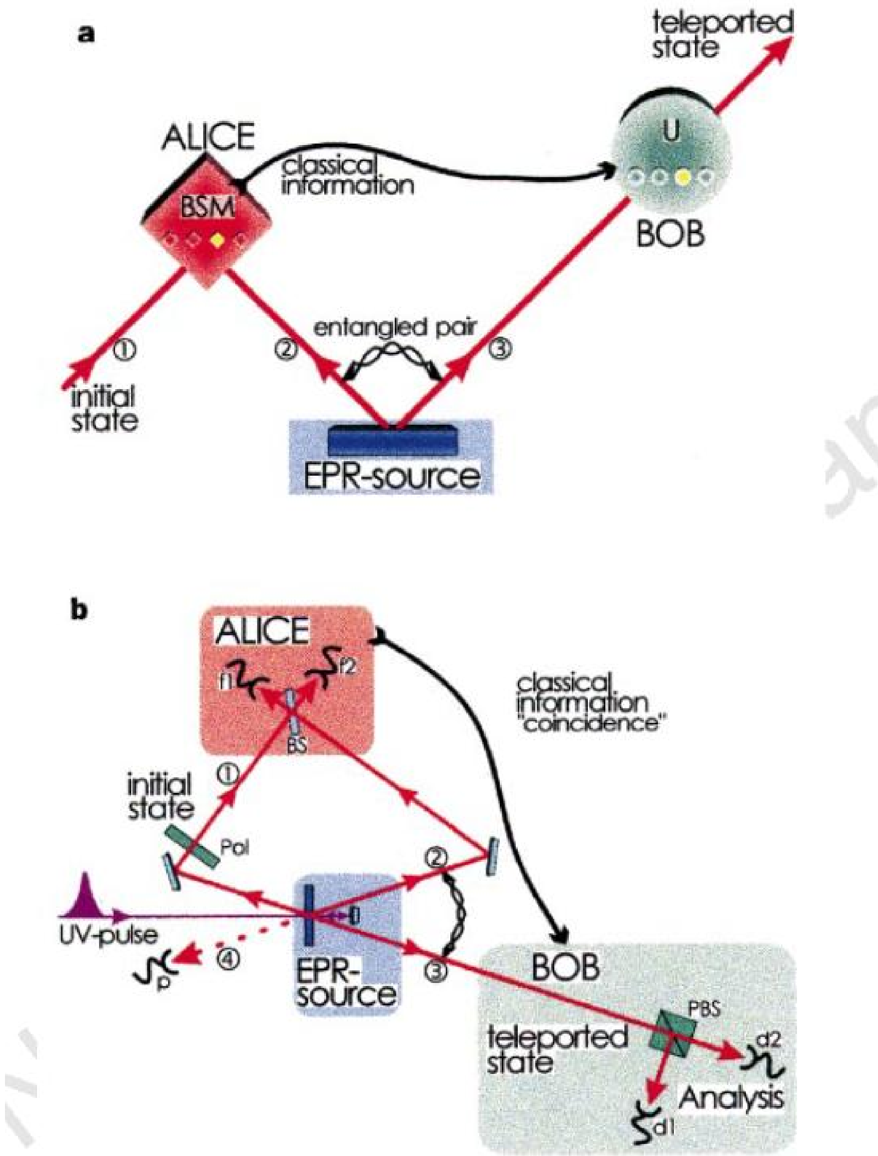
The unknown state $|\psi\rangle$ can therefore be obtained from $|\psi_1\rangle$ by applying one of the four operations

$$I, \sigma_x, \sigma_y, \sigma_z,$$

and the result of the Bell measurement provides two bits specifying which of the above four operations should be applied.

Alice can send to Bob these two bits of classical information using a classical channel (by phone, email for example).

# Quantum Teleportation



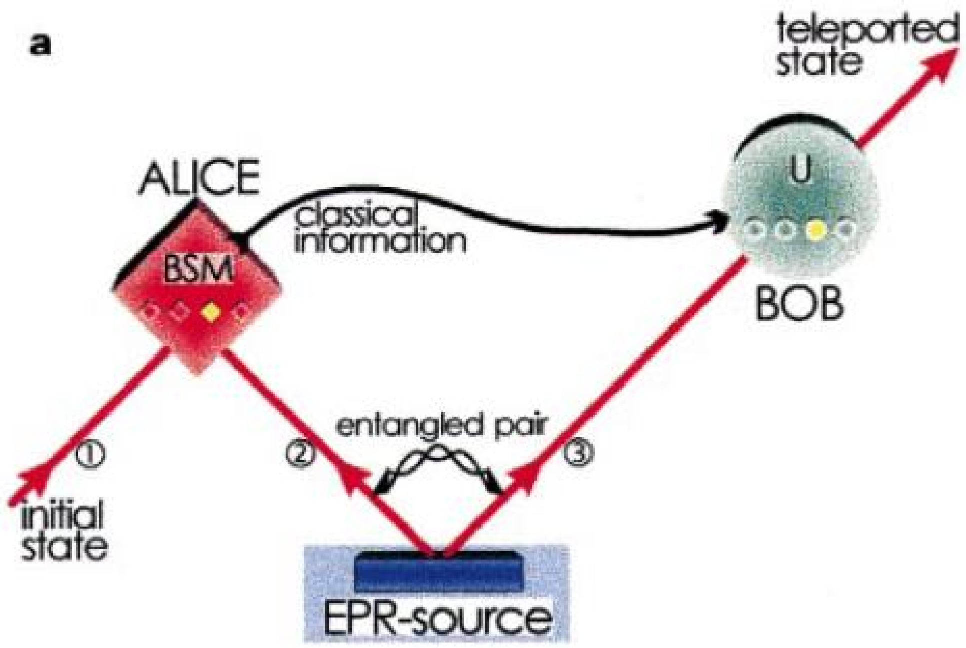

Scheme showing principles involved in quantum teleportation (a) and the experimental set-up (b).



- EPR correlations used as a source
- Teleporting an unknown quantum state not the particle
- Entanglement between photon 2 and 3
- Bell-state measurement plus classical communication and recovery operation lead to successful teleportation

D. Bouwmeester *et al.,* Experimental quantum teleportation, *Nature 390*, 575-579 (1997);
M. Zukowski, A. Zeilinger, & H. Weinfurter, Entangling photons radiated by independent pulsed sources. Ann. NY Acad. Sci. 755, 91–102 (1995).

# Quantum Teleportation

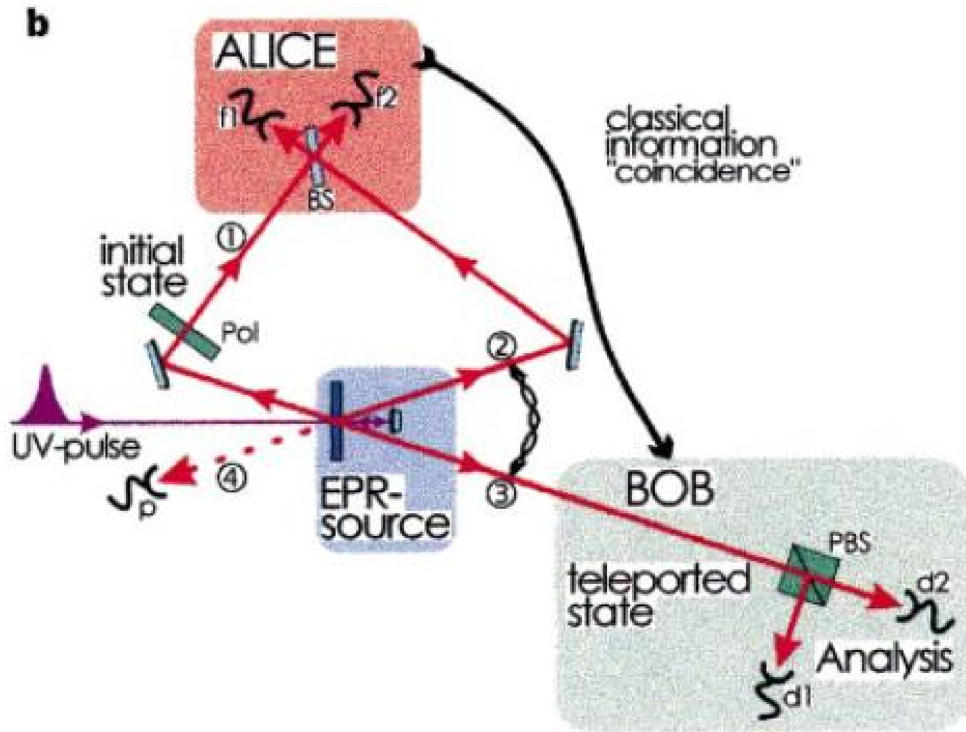



Alice has a quantum system, particle 1, in an initial state which she wants to teleport to Bob. Alice and Bob also share an ancillary entangled pair of particles 2 and 3 emitted by an Einstein–Podolsky–Rosen (EPR) source. Alice then performs a joint Bell-state measurement (BSM) on the initial particle and one of the ancillaries, projecting them also onto an entangled state. After she has sent the result of her measurement as classical information to Bob, he can perform a unitary transformation (U) on the other ancillary particle resulting in it being in the state of the original particle.

D. Bouwmeester *et al., Nature 390*, 575-579 (1997)

# Quantum Teleportation

A pulse of ultraviolet radiation passing through a nonlinear crystal creates the ancillary pair of photons 2 and 3. After retroflection during its second passage through the crystal the ultraviolet pulse creates another pair of photons, one of which will be prepared in the initial state of photon 1 to be teleported, the other one serving as a trigger indicating that a photon to be teleported is under way.




Alice then looks for coincidences after a beam splitter BS where the initial photon and one of the ancillaries are superposed. Bob, after receiving the classical information that Alice obtained a coincidence count in detectors f1 and f2 identifying the $|\psi^-\rangle_{12}$ Bell state, knows that his photon 3 is in the initial state of photon 1 which he then can check using polarization analysis with the polarizing beam splitter PBS and the detectors d1 and d2. The detector p provides the information that photon 1 is under way.

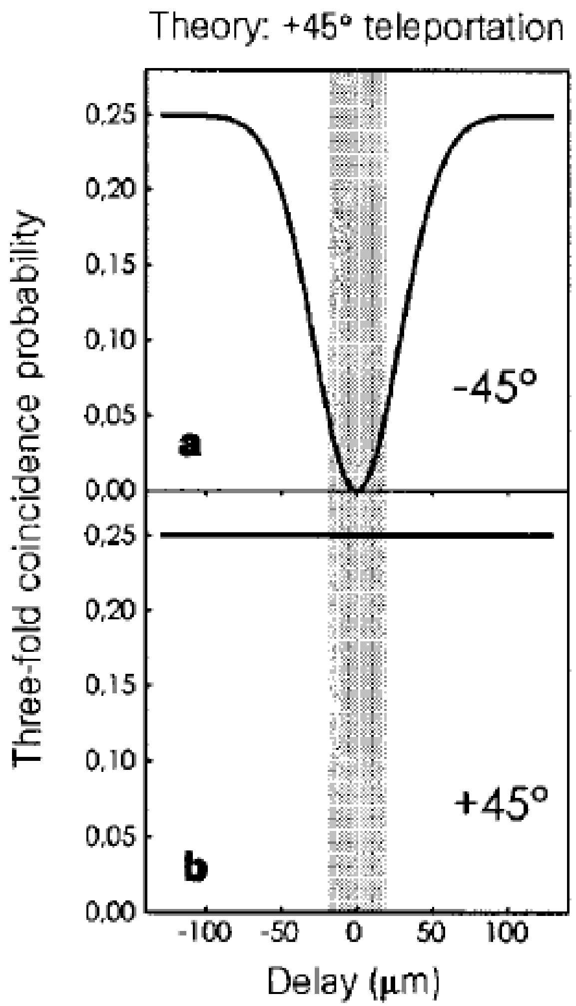
D. Bouwmeester *et al., Nature 390*, 575-579 (1997)

# Quantum Teleportation

**Results**

In the first experiment photon 1 is polarized at 45°. Teleportation should work as soon as photon 1 and 2 are detected in the $|\psi^-\rangle_{12}$ state, which occurs in 25% of all possible cases. The $|\psi^-\rangle_{12}$ state is identified by recording a coincidence between two detectors, f1 and f2, placed behind the beam splitter (Fig. 1b).

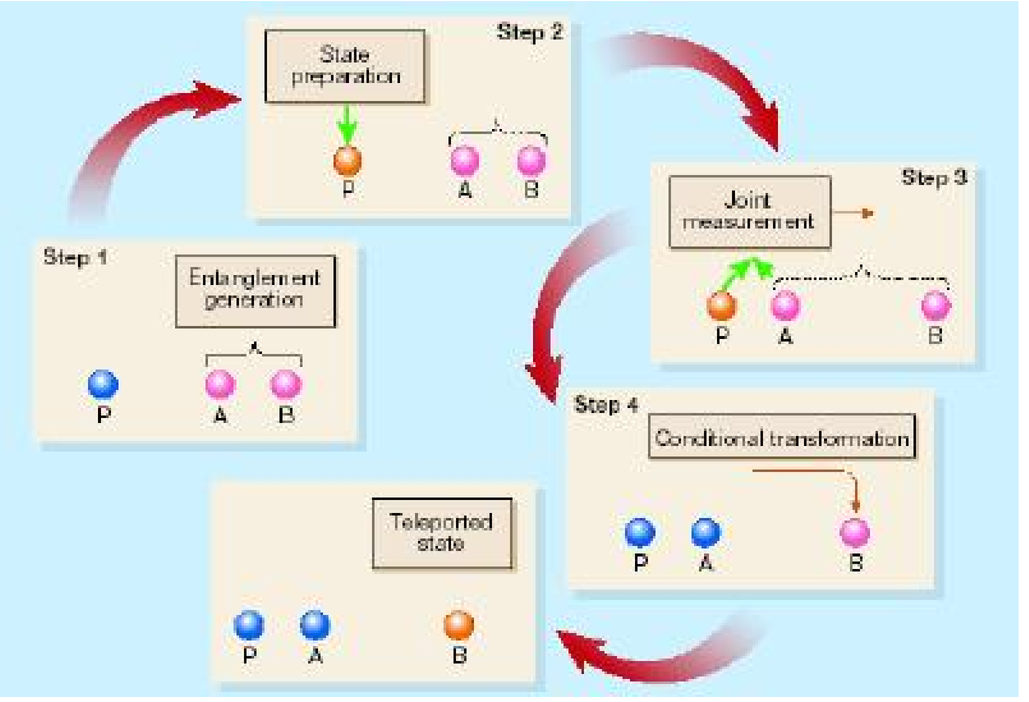
If we detect a f1f2 coincidence (between detectors f1 and f2), then photon 3 should also be polarized at 45°. The polarization of photon 3 is analysed by passing it through a polarizing beam splitter selecting +45° and –45° polarization. To demonstrate teleportation, only detector d2 at the +45° output of the polarizing beam splitter should click (that is, register a detection) once detectors f1 and f2 click. Detector d1 at the –45° output of the polarizing beam splitter should not detect a photon. Therefore, recording a three-fold coincidence d2f1f2 (+45° analysis) together with the absence of a three-fold coincidence d1f1f2 (–45° analysis) is a proof that the polarization of photon 1 has been teleported to photon 3.




D. Bouwmeester *et al., Nature 390*, 575-579 (1997)

# Teleportation of Massive Particles

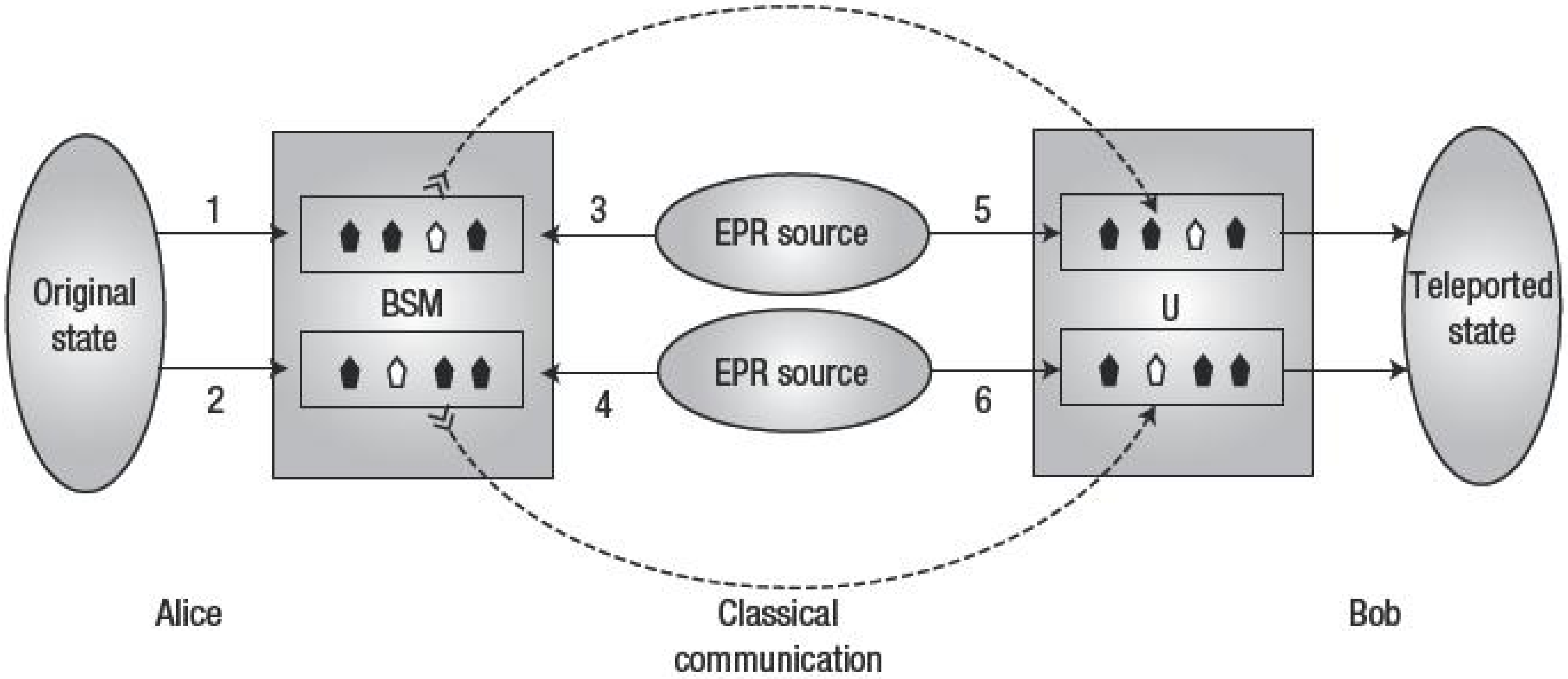
David Wineland and colleagues from the National Institute of Standards and Technology (NIST) in Colorado began by creating a superposition of spin up and spin down states in a single trapped beryllium ion (*Nature* **429** 737 [2004]). Using laser beams, they teleported these quantum states to a second ion with the help of a third, auxiliary ion (see figure). The NIST technique relied on being able to move the ions within the trap.




Meanwhile, Rainer Blatt and co-workers at the University of Innsbruck performed a similar experiment using trapped calcium ions (*Nature* **429** 734 [2004]). However, rather than moving the ions, they "hide" them in a different internal state.

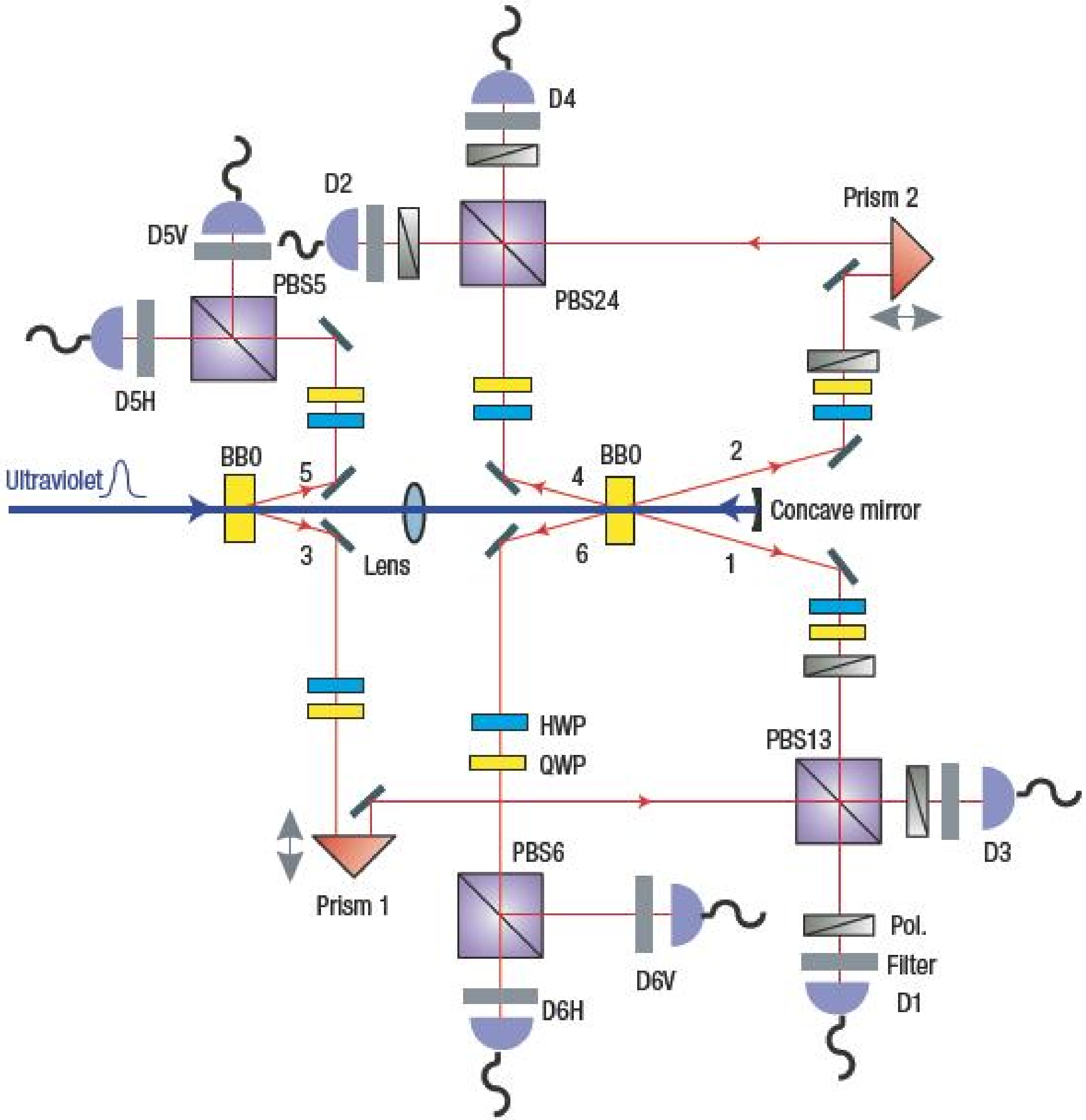
http://physicsworld.com/cws/article/news/19690

# Experimental quantum teleportation of a two-qubit composite system




Qiang Zhang *et al.*, *Nature Physics* 2, 678-682 (2006)

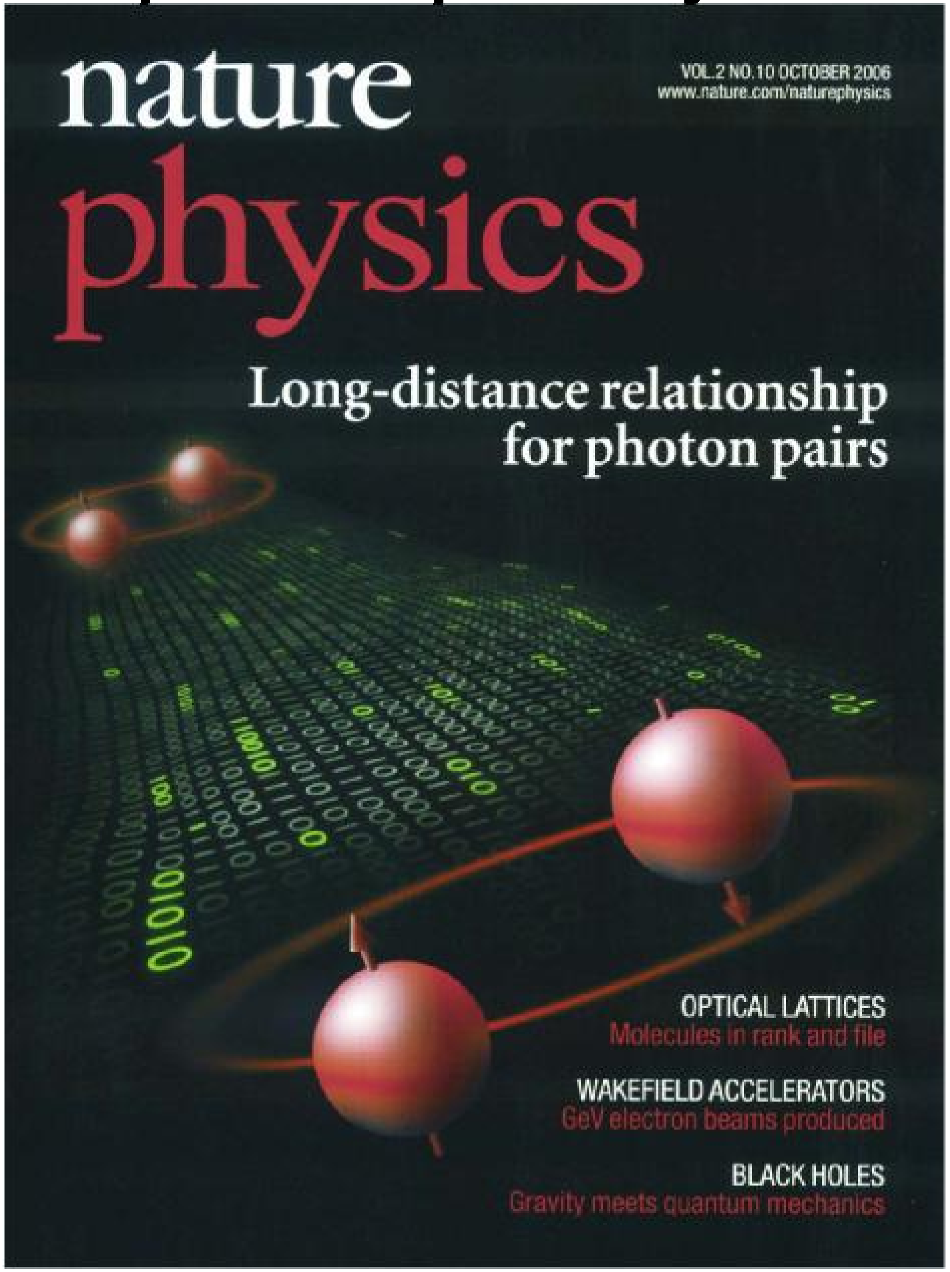
# Experimental quantum teleportation of a two-qubit composite system






Qiang Zhang *et al.*, *Nature Physics* 2, 678-682 (2006)

# Experimental quantum teleportation of a two-qubit composite system






Qiang Zhang *et al.*, *Nature Physics* 2, 678-682 (2006)

# Memory-built-in quantum teleportation with photonic and atomic qubits

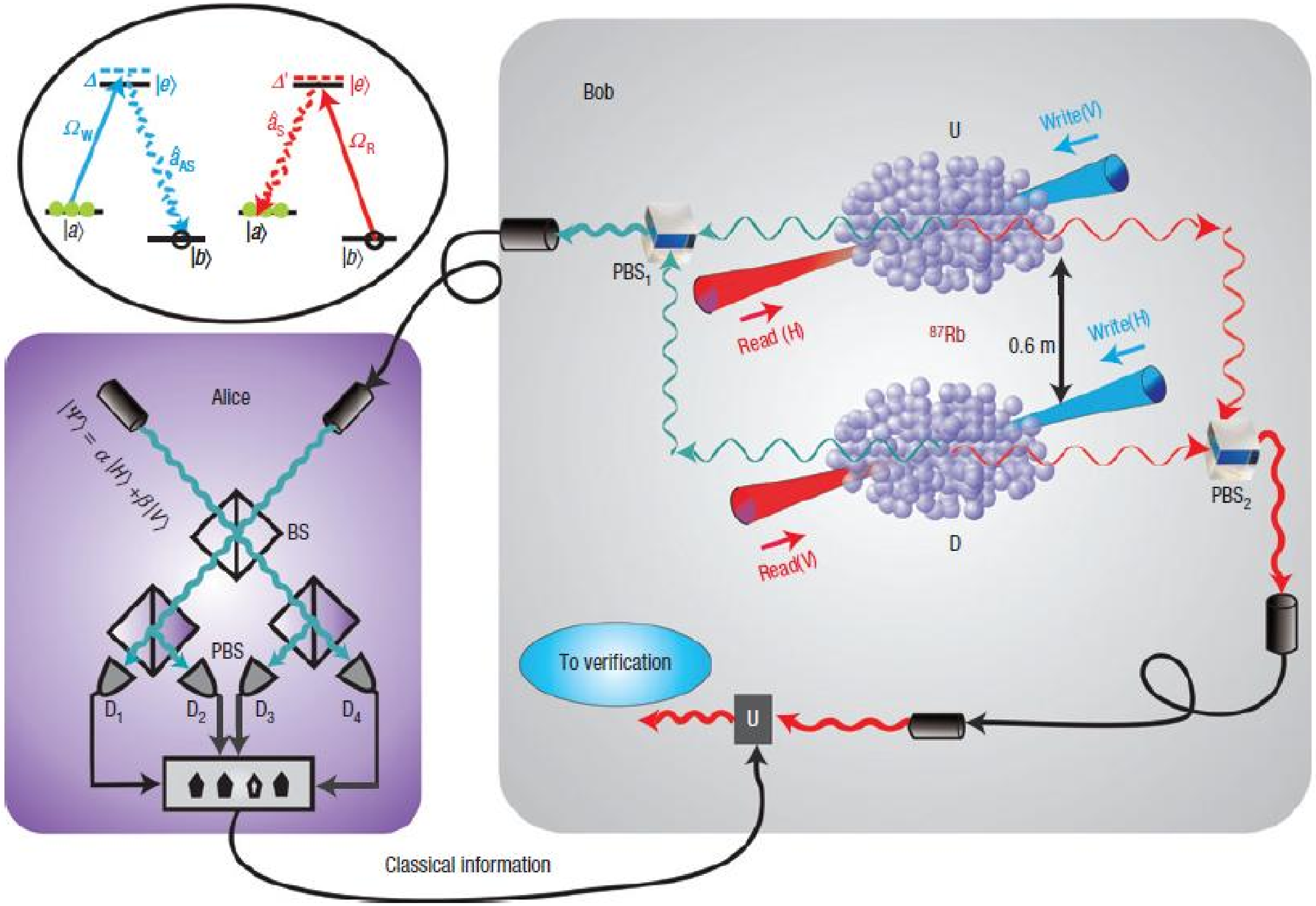



**Figure 1 Experimental set-up for teleportation between photonic and atomic qubits.** The top-left diagram shows the structure and the initial populations of atomic levels for the two ensembles. At Bob's site, the anti-Stokes fields emitted from U and D are collected and combined at $PBS_1$, selecting perpendicular polarizations. Then the photon travels 7 m through the fibres to Alice's site to overlap with the initial unknown photon on a beam splitter (BS) to carry out the BSM. The results of the BSM are sent to Bob through a classical channel. Bob then carries out the verification of the teleported state in the U and D ensembles by converting the atomic excitation to a photonic state. If the state $|\Psi^+\rangle$ is registered, Bob directly carries out a polarization analysis on the converted photon to measure the teleportation fidelity. On the other hand, if the state $|\Psi^-\rangle$ is detected, the converted photon is sent through a half-wave plate via the first-order diffraction of an AOM (not shown). The half-wave plate is set at 0° serving as the unitary transformation of $\hat{\sigma}_z$. Then the photon is sent through the polarization analyser to obtain the teleportation fidelity.

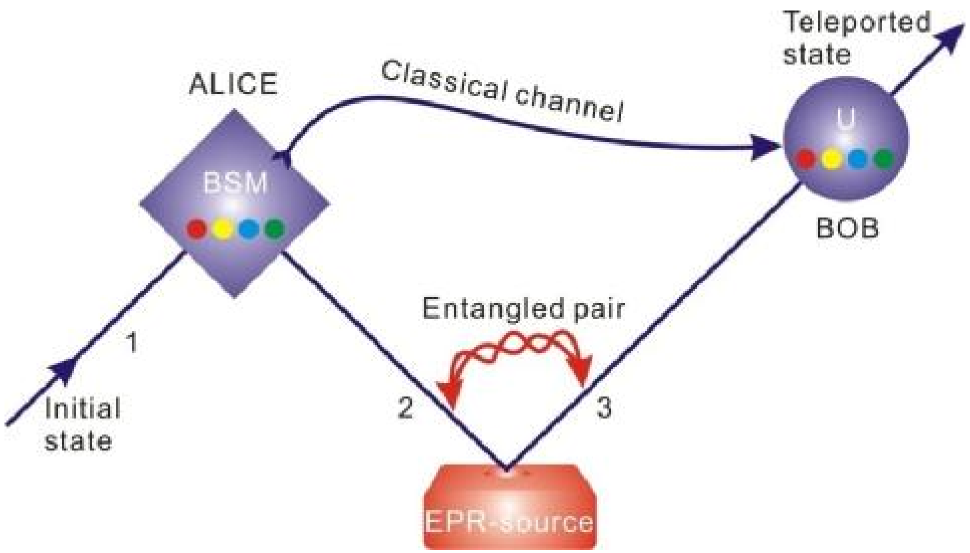


Yu-Ao Chen *et al., Nature Physics 4*, 103-107 (2008)

# Motivation: longer and not only longer

- Fundamental interest: faithfully transfer of quantum state between two distant locations without physically transmitting carrier itself:

- Long-distance quantum communication network: quantum relay, quantum repeater.



# Quantum Teleportation Progress

- First proof-of-principle verification

Bouwmeester, D. et al. Nature, 390, 575( 1997).

Boschi, D. et al. Phys. Rev. Lett., 80,1121(1998).

Furusawa, A. et al. Science 282, 706–709 (1998).

Sherson, J. F. et al. Nature 443, 557–560 (2006).

- Fiber-based long-distance teleportation :

55m：Marcikic, I. et al. Nature 421, 509-513 (2003)

600m：  Ursin, R. et al. Nature 430, 849 (2004)

- Optical free-space link is highly desirable for extending the transfer distance

Effective aerosphere thickness: ~equivalent to 5-10 km ground atmosphere
How to **exceed this?**

# Polarization Entanglement Source

Bell states – maximally entangled states:

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2\right)$$

$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2\right)$$

Singlet:

$$|\Psi^{-}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$$

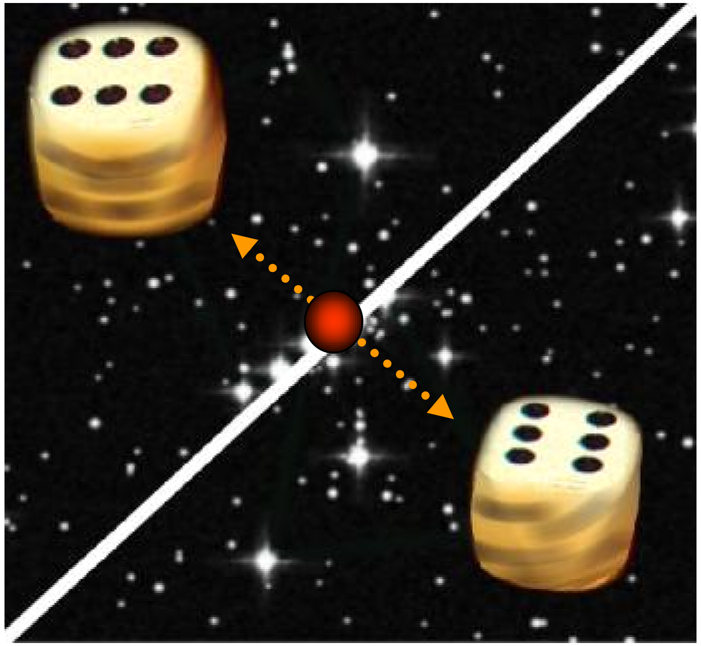
$$= \frac{1}{\sqrt{2}}(|H'\rangle_1|V'\rangle_2 - |V'\rangle_1|H'\rangle_2)$$

where

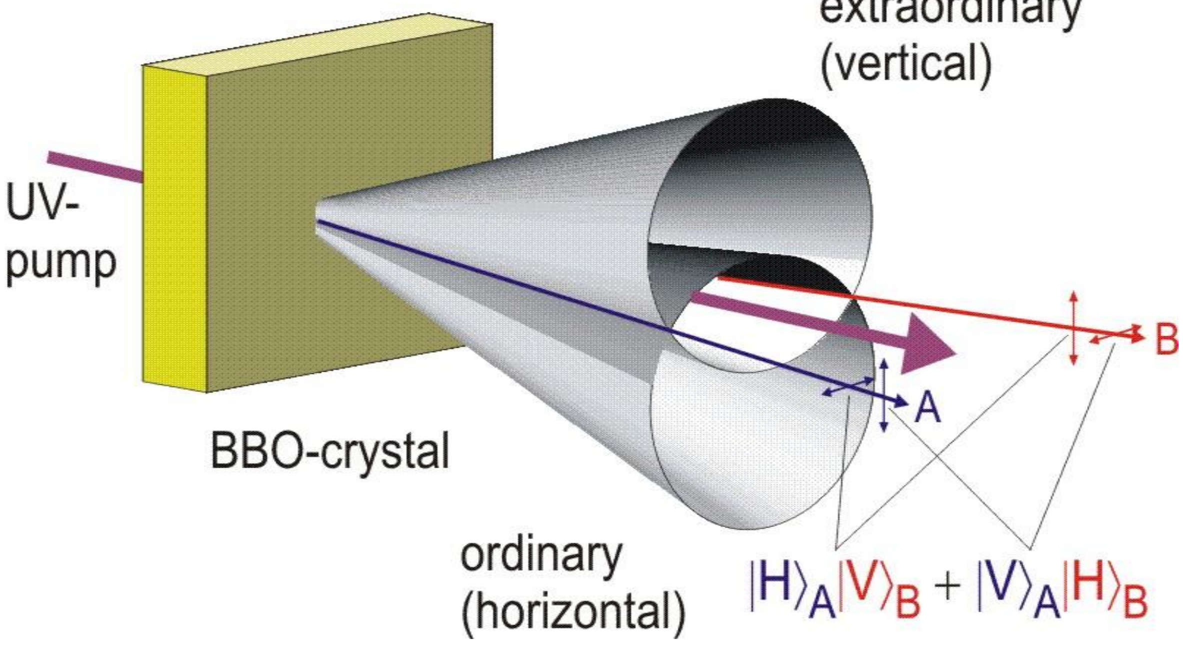
$$|H'\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$$

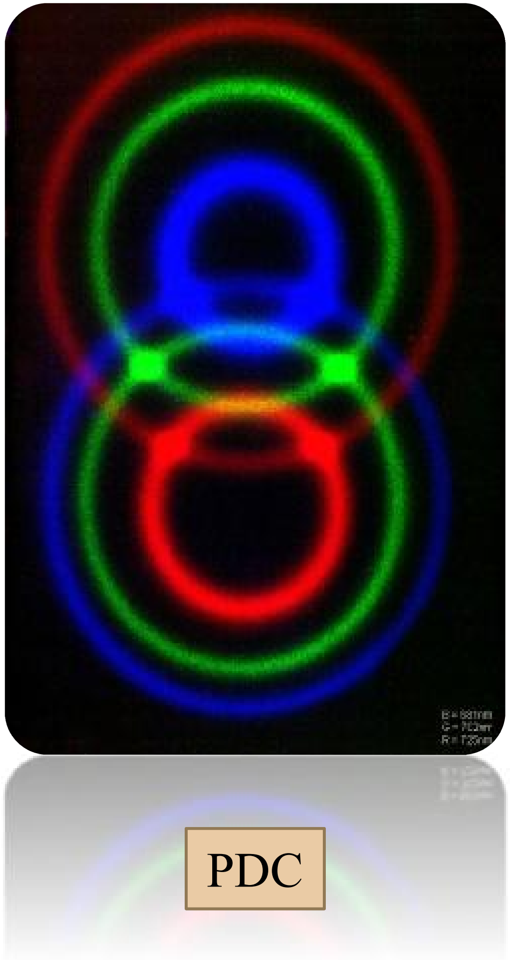
$$|V'\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$$

45-degree polarization



# Polarization Entanglement Source



PDC

$$|\Phi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1 |H\rangle_2 \pm |V\rangle_1 |V\rangle_2)$$

$$|\Psi^{\pm}\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1 |V\rangle_2 \pm |V\rangle_1 |H\rangle_2)$$

- P. G. Kwiat et al., Phys. Rev. Lett. 75, 4337 (1995)

# Modified Rome quantum teleportation scheme

$$\left|\Psi^{-}\right\rangle_{1w2p}=\left|V\right\rangle_{1p}\otimes\frac{1}{\sqrt{2}}\left(\left|R\right\rangle_{1w}\left|V\right\rangle_{2p}-\left|L\right\rangle_{1w}\left|H\right\rangle_{2p}\right)$$

- Initial state: $\left|\Psi\right\rangle_{1p}=\alpha\left|H\right\rangle_{1p}+\beta\left|V\right\rangle_{1p}$

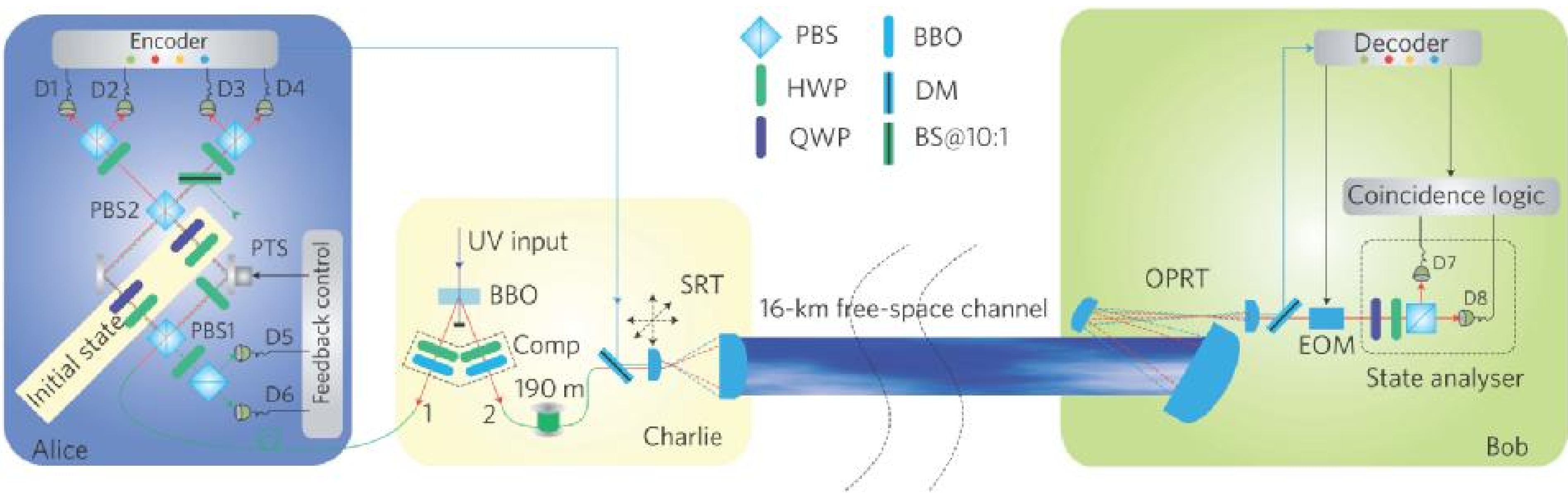
- Bell state:

$$\left|\Psi^{\pm}\right\rangle_{1w1p}=\left(\left|R\right\rangle_{1w}\left|V\right\rangle_{1p}\pm\left|L\right\rangle_{1w}\left|H\right\rangle_{1p}\right)/\sqrt{2}$$

$$\left|\Phi^{\pm}\right\rangle_{1w1p}=\left(\left|R\right\rangle_{1w}\left|H\right\rangle_{1p}\pm\left|L\right\rangle_{1w}\left|V\right\rangle_{1p}\right)/\sqrt{2}$$

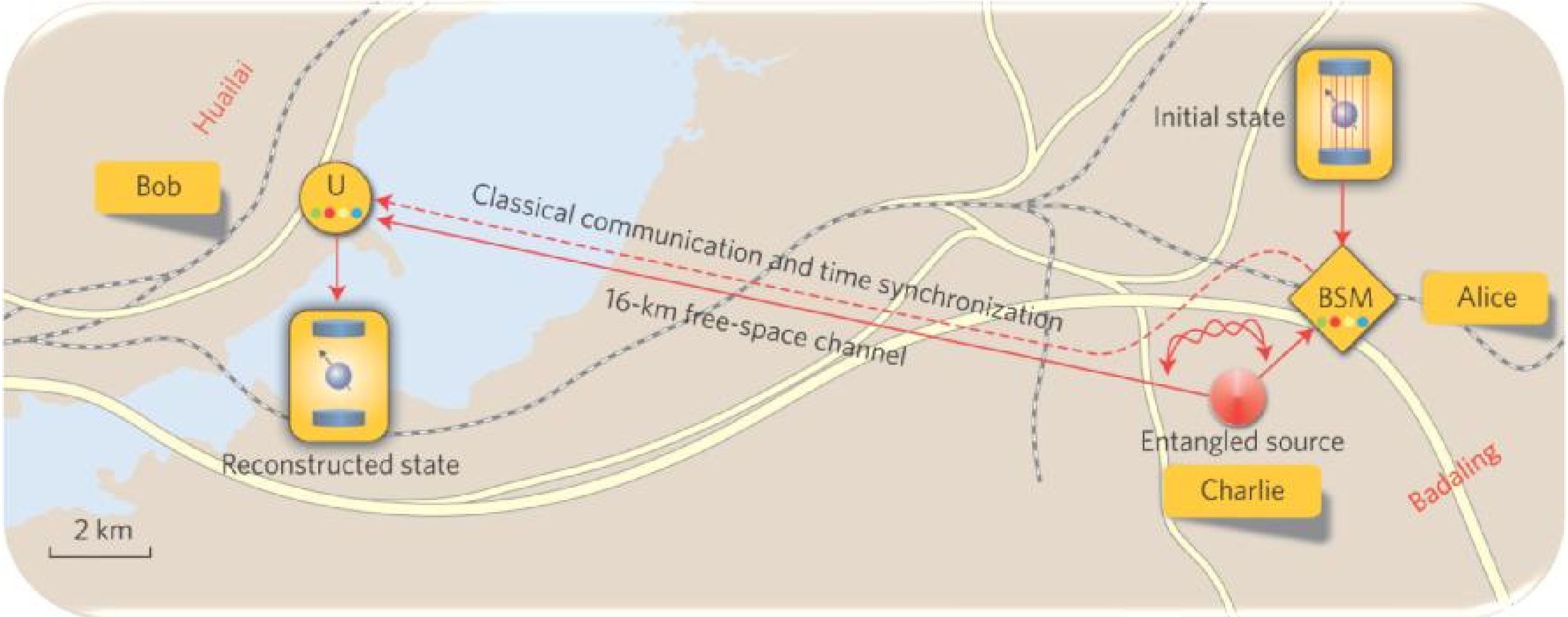
$$\left|\Psi\right\rangle_{1p1w2p}=\left|\Psi\right\rangle_{1p}\otimes\left|\Psi^{-}\right\rangle_{1w2p}$$

$$=\frac{1}{2}\left(\left|\Psi^{-}\right\rangle_{1p1w}+\left|\Phi^{-}\right\rangle_{1p1w}\hat{\sigma}_x-\left|\Phi^{+}\right\rangle_{1p1w}i\hat{\sigma}_y-\left|\Psi^{+}\right\rangle_{1p1w}\hat{\sigma}_z\right)\left|\Psi\right\rangle_{2p}$$



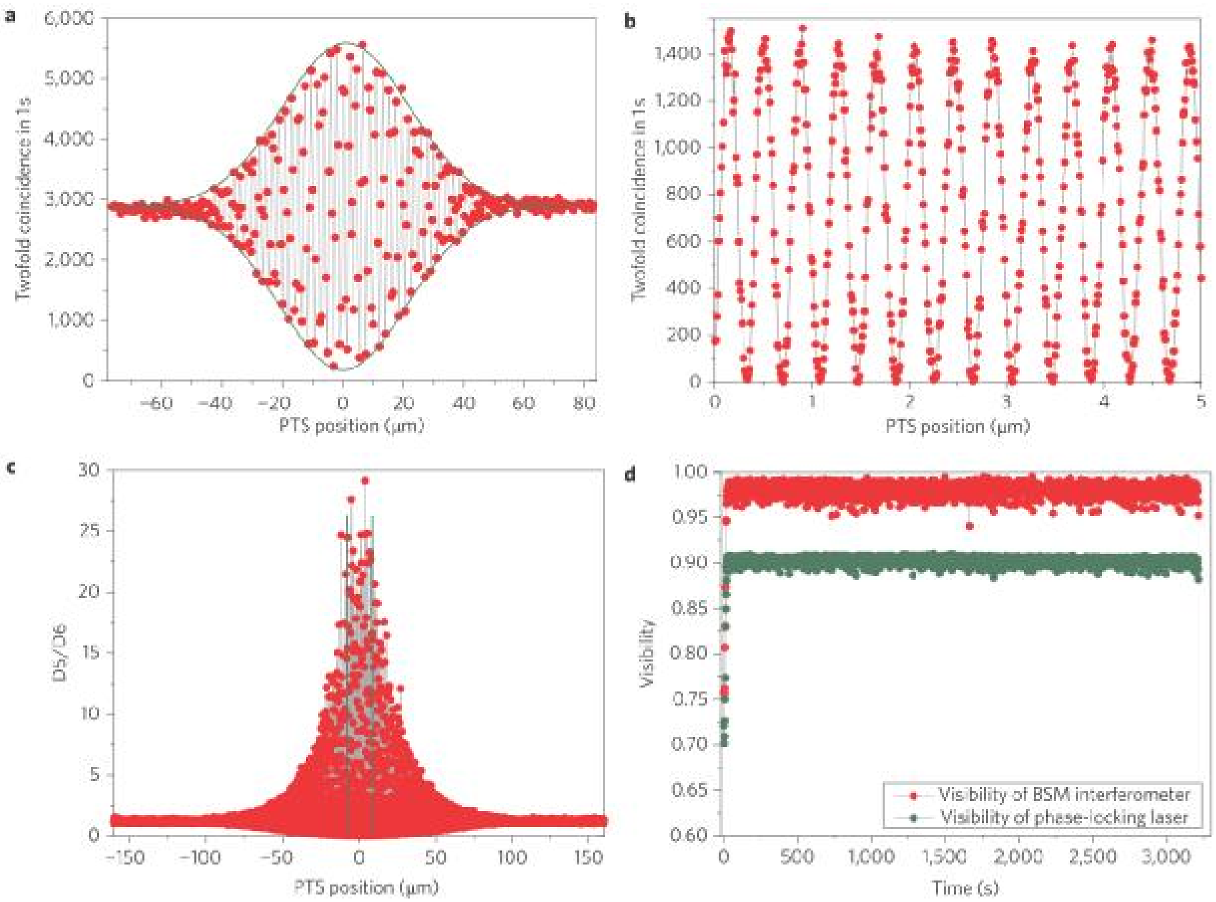
# Free-space channel + Stable BSM + Active Feedforward

- Split-type refracting telescope(SRT): f=2.372, d=0.2m, 0.42μrad per step, 0.4~1m(point)
- Off-axis parabolic reflecting telescope (OPRT):d=0.4m, 1000kg, stability 0.3μrad/hour
- Optical link efficiency between SRT and OPRT:-14 dB ~ -31 dB.






# Free-space channel + Stable BSM + Active Feedforward




l Perfect overlap :spatial, temporal, spectral.
Visibility of BSM:~99.2%

l Active lock BSM interferometer: reverse propagating direction, 633nm
The instability can be suppressed within λ/52

# Teleportation Fidelities

$$F = Tr(\hat{\rho}\left|\Psi\right\rangle_{1p\ 1p}\left\langle\Psi\right|) = Tr(\hat{\rho}(\left|\alpha\right|^2\left(\hat{\mathrm{I}}+\hat{\sigma}_z\right)+\alpha\beta^*\left(\hat{\sigma}_x+i\hat{\sigma}_y\right)+\beta\alpha^*\left(\hat{\sigma}_x-i\hat{\sigma}_y\right)+\left|\beta\right|^2\left(\hat{\mathrm{I}}-\hat{\sigma}_z\right)))/2$$

$$F_{|H\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}+\hat{\sigma}_z))/2$$

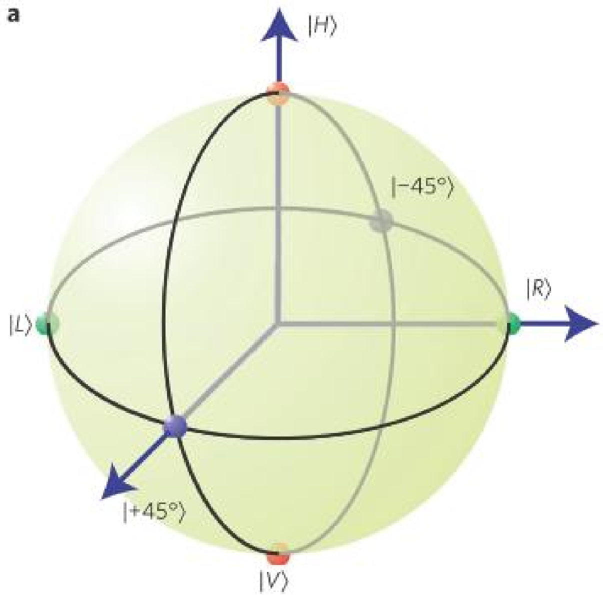
$$F_{|V\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}-\hat{\sigma}_z))/2$$

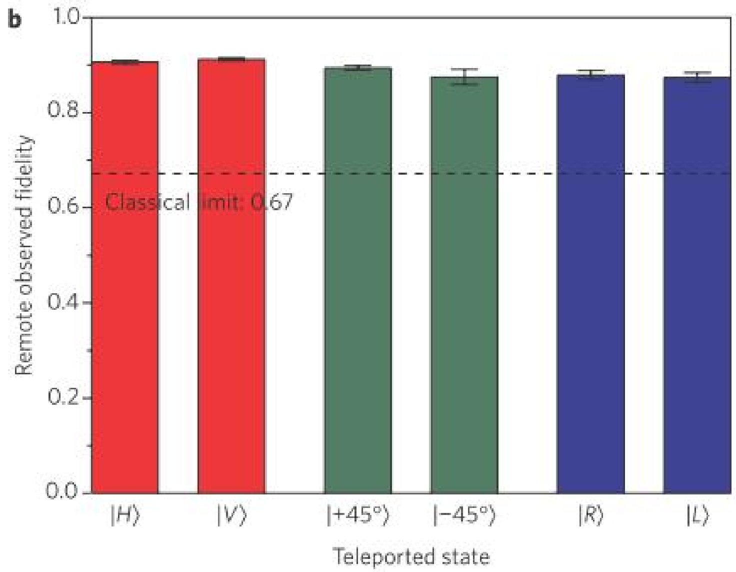
$$F_{|+45^\circ\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}+\hat{\sigma}_x))/2$$

$$F_{|-45^\circ\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}-\hat{\sigma}_x))/2$$

$$F_{|R\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}+\hat{\sigma}_y))/2$$

$$F_{|L\rangle} = Tr(\hat{\rho}(\hat{\mathrm{I}}-\hat{\sigma}_y))/2$$

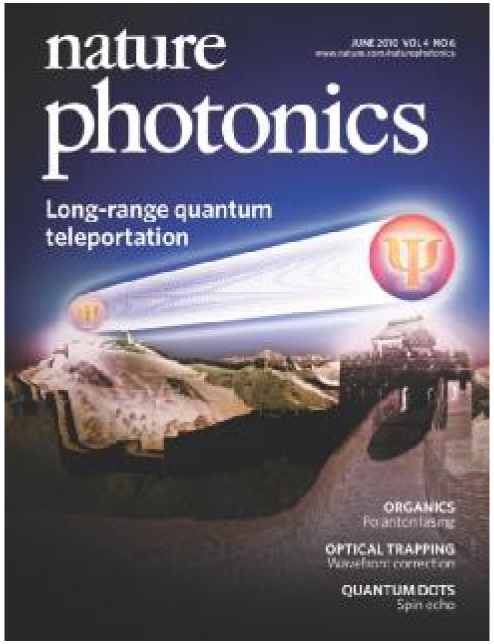



- Swap projection: Eliminate the biased effect caused by different detection efficiencies of D7 and D8
- The real teleportation fidelity: $F = 1\big/\left(1+\sqrt{C_7' C_8 / C_7 C_8'}\right)$

**Table 1 | Experimental measurement for teleportation fidelities.**

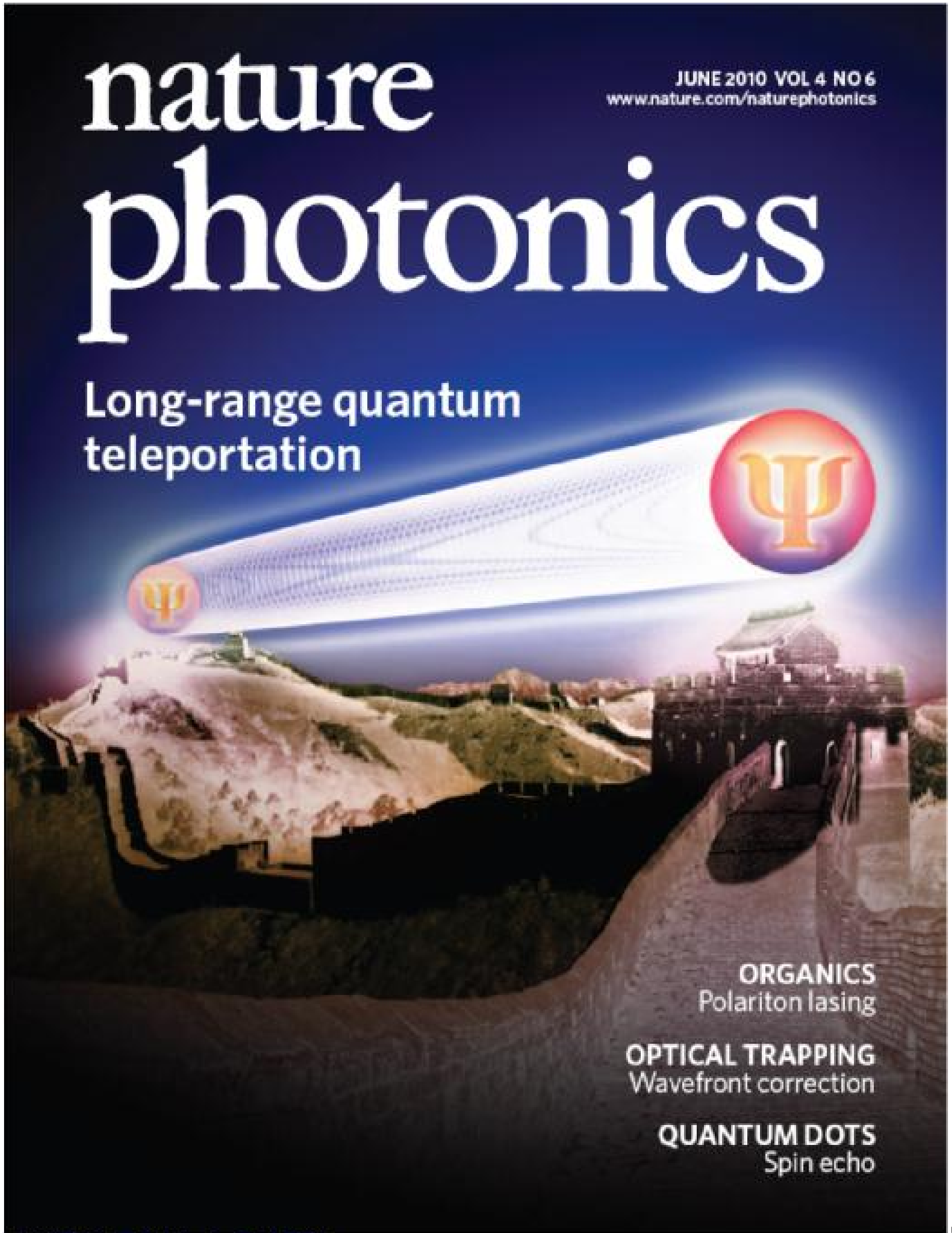
| Initial states | $\lvert H\rangle$ | $\lvert V\rangle$ | $\lvert +45^\circ\rangle$ | $\lvert -45^\circ\rangle$ | $\lvert R\rangle$ | $\lvert L\rangle$ |
|---|---|---|---|---|---|---|
| $\lvert\Psi\rangle_{1p}$ (D7) | 2,936 | 4,939 | 2,027 | 213 | 591 | 631 |
| $\lvert\Psi\rangle_{1p}^{\perp}$ (D8) | 225 | 391 | 276 | 30 | 83 | 103 |
| $\lvert\Psi\rangle_{1p}$ (D8) | 3,232 | 5,125 | 1,279 | 152 | 553 | 300 |
| $\lvert\Psi\rangle_{1p}^{\perp}$ (D7) | 458 | 605 | 131 | 22 | 74 | 38 |
| Fidelities | 0.906(4) | 0.912(3) | 0.894(5) | 0.875(16) | 0.879(9) | 0.874(11) |




Xian-Min Jin *et al.*, Experimental Free-Space Quantum Teleportation, **Nature Photonics 4, 376-381** (2010).

- *Developed techniques:*
- *Real-time feedback control for high stability interferometer for single photon Bell state measurement*
- *Active feed-forward manipulation on single photon state for reconstruction of the initial teleported qubit*
- *Novel design of telescopes tailored for teleportation experiment*
- *Achieve quantum teleportation in free-space at a distance 16 km, 20 times longer than the previous implementation*
- *confirms the feasibility of space-based experiments, and presents an important step towards quantum communication applications on a global scale.*

# Nature Photonics 4, 376-381 (2010)封面文章




**Beam Us Up** Teleportation doesn't work for humans — yet — but it works over long distances, a new study reports. *Time Magazine*

**隐形传态过程虽然不能够传送人类， 然而一个最新的研究显示，它的确可以远距离地传送信息。 美国《时代杂志》**

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**Research Highlights**

**Subject Category:** Physics

Published online: 2 June 2010 | doi:10.1038/nchina.2010.65

**Quantum physics: Teleportation goes long distance**

Felix Cheung

**Researchers in China have achieved quantum teleportation in free space over a distance of 16 km**

Original article citation
Jin, X. M. *et al.* Experimental free-space quantum teleportation. *Nature Photon.* doi:10.1038/nphoton.2010.87 (2010).

Full text article available for download

Quantum communication promises the world a completely secure way of transferring information, and quantum teleportation is an information transfer protocol that will one day make quantum communication over long distance possible. Previous studies have demonstrated quantum teleportation using an optical fibre, but photon losses due to decoherence in the fibre are large and the transmission distance is limited to 600 metres. Jianwei Pan at the University of Science and Technology of China in Hefei, Chengzhi Peng at Tsinghua University in Beijing and co-workers[1] have now achieved quantum teleportation in an optical free-space channel over a distance of 16 kilometres.

© (2010) istockphoto.com/Andrey Volodin

The researchers generated an entangled photon pair at Badaling in Beijing using a semiconductor, a blue laser beam and a beta-barium borate crystal. They sent one photon in the pair to 'Alice', situated at Badaling, for measurement. They then sent the other photon in the pair and the results of Alice's measurement to 'Bob' at Huailai in Hebei province — 16 kilometres away — through the free-space channel.

The researchers used specially designed telescopes to optimize the transmission efficiency and improve the stability of the free-space channel. They found that Bob could recover the results of Alice's measurements using the photon it received, thus demonstrating quantum teleportation. The study confirms the feasibility of quantum teleportation in free space and represents an important step towards quantum communication on a global scale.

# 自然・中国

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« DARPA's New Sniper Rifle Offers a Perfect Shot Across 12 Football Fields
To Cope With the Chaos of Swarming, Locusts Enlarge Their Brains »

## Physicists Achieve Quantum Teleportation Across a Distance of 10 Miles

Stumble! 9 submit to digg


How far can you beam information instantaneously? Try 10 miles, according to a study in *Nature Photonics* that pushes the limits of quantum teleportation to its greatest distance yet. At that distance, the scientists say, one can begin to consider the possibility of someday using quantum teleportation to communicate between the ground and a satellite in orbit.

As stories about quantum teleportation usually note, this isn't the Starship Enterprise's transporter: The weird quantum phenomenon makes it possible to send information, not matter, across a distance.

> It works by entangling two objects, like photons or ions. The first teleportation experiments involved beams of light. Once the objects are entangled, they're connected by an invisible wave, like a thread or umbilical cord. That means when something is done to one object, it immediately happens to the other object, too. Einstein called this "spooky action at a distance." [Popular Science]

# Discover Magazine

中国科学技术大学 陈凯

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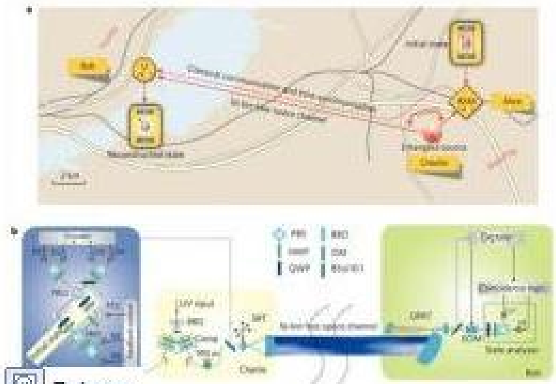
## Quantum teleportation achieved over 16 km

May 20, 2010 by Lin Edwards



Enlarge

a, A birds-eye view of the 16-km free-space quantum teleportation experiment. Charlie sends photon 1 to Alice for BSM. Classical information, including the results of the BSM and the signal for time synchronization, is sent through the free-space channel with photon 2, to Bob, before decoding and triggering of the corresponding unitary transformation. b, Sketch of the experimental system. See the original paper for more details. Image copyright: Nature Photonics, doi:10.1038/nphoton.2010.87

**(PhysOrg.com) -- Scientists in China have succeeded in teleporting information between photons further than ever before. They transported quantum information over a free space distance of 16 km (10 miles), much further than the few hundred meters previously achieved, which brings us closer to transmitting information over long distances without the need for a traditional signal.**

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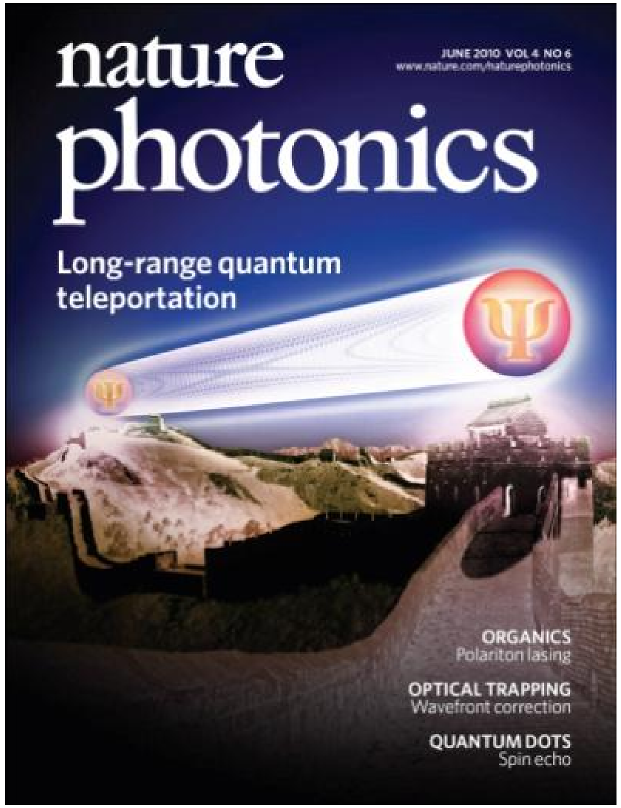
## Quantum teleportation through open air

By Physics Today on May 17, 2010 10:17 AM | No Comments | No TrackBacks

A central tenet of quantum information processing asserts that an unknown qubit cannot be cloned (see *Physics Today*, February 2009, page 76). But the unknown state of one qubit can be transferred to another qubit in a process termed quantum teleportation. The first experimental demonstrations succeeded in teleporting a qubit state a meter or so (see *Physics Today*, February 1998, page 18). Subsequent experiments with photons, whose polarizations form a convenient basis for quantum information, have used fiber optics to achieve teleportation over hundreds of meters. But practical quantum communication will require teleportation over much greater distances. Jian-Wei Pan, Cheng-Zhi Peng, and coworkers at the University of Science and Technology of China and Tsinghua University have now transferred a qubit state through free space over a distance of 16 km, from "Alice" in the Beijing suburb of Badaling, across towns and roads, to "Bob" in Huailai, on the other side of Guanting Reservoir. The experiment employed a standard teleportation protocol: Alice and Bob each receive one of a pair of entangled photons; Alice measures hers in combination with an unknown qubit and sends the result, by classical means, to Bob; armed with that result, Bob projects his photon onto the state of the unknown qubit. The new work, though, adds many refinements, including novel telescope designs for open-air transmission, active feedback control for increased stability, and synchronized real-time information transfer. The resulting teleportation fidelity was nearly 90%. Such high-fidelity transmission, say the researchers, could help enable quantum teleportation to orbiting satellites. (X.-M. Jin et al., *Nat. Photon.*, in press, doi:10.1038/nphoton.2010.87.)—Richard J. Fitzgerald

# 自由空间量子通信

- **国际上距离最远的(16公里)自由空间量子隐形传态** [Nature Photonics 4, 376] (2010)




两院院士评为
“中国十大科技进展新闻

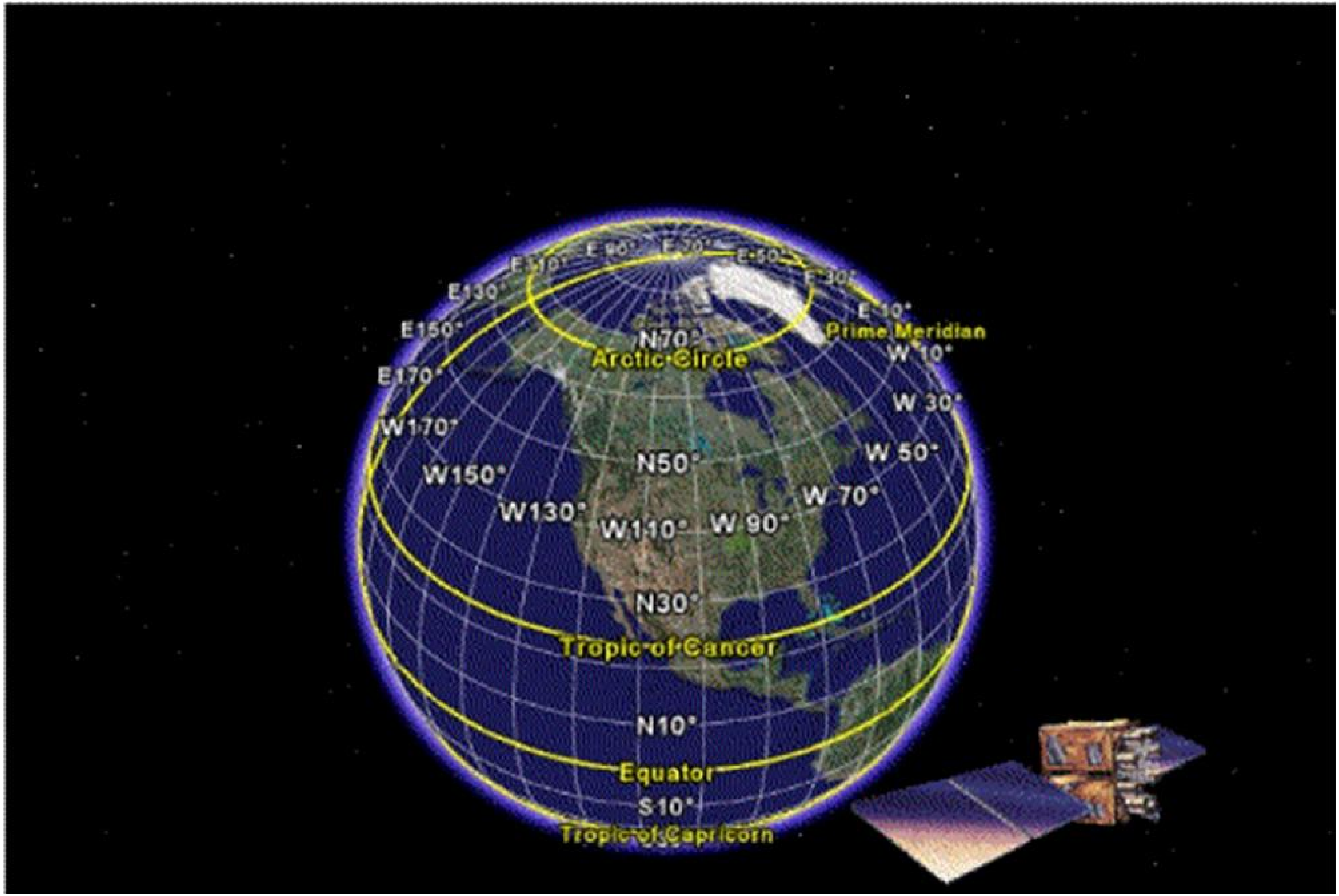
科技部评为
“中国科学十大进展”


美国物理学家组织的报道


《自然·中国》的报道


美国《今日物理》的报道

# Global Quantum Communication Network



# About Quantum Teleportation

- In a quantum teleportation an unknown quantum state can be disambled into, and later reconstructed from, two classical bit-states and an maximally entangled pure quantum state.

- Using quantum teleportation an unknown quantum state can be *teleported* from one place to another by a sender who does not need to know - for teleportation itself - neither the state to be teleported nor the location of the intended receiver.

- The teleportation procedure can not be used to transmit information faster than light

but

- it can be argued that quantum information presented in unknown state is transmitted instanteneously (except two random bits to be transmitted at the speed of light at most).

- EPR channel is irreversibly destroyed during the teleportation process.

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# Entanglement Swapping: Entangling Photons That Never Interacted

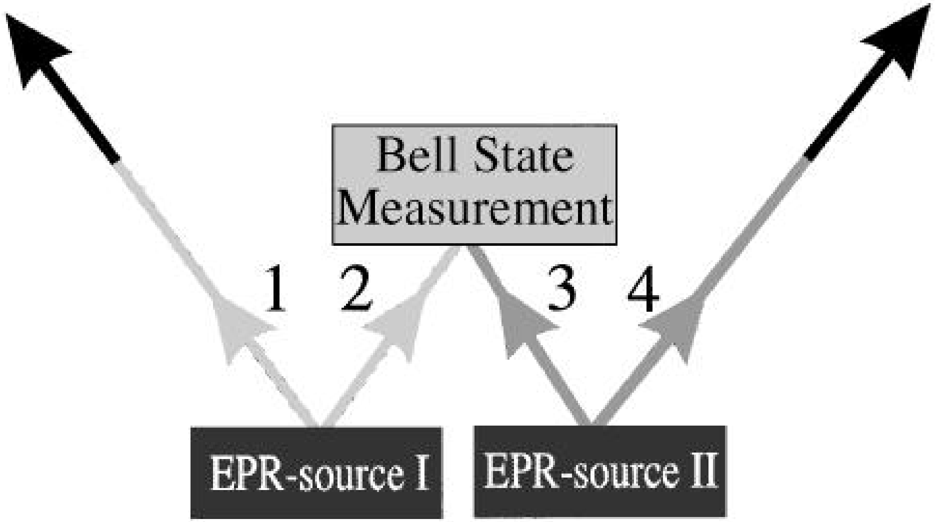


FIG. 1. Principle of entanglement swapping. Two EPR sources produce two pairs of entangled photons, pair 1-2 and pair 3-4. One photon from each pair (photons 2 and 3) is subjected to a Bell-state measurement. This results in projecting the other two outgoing photons 1 and 4 onto an entangled state. Change of the shading of the lines indicates the change in the set of possible predictions that can be made.

Jian-Wei Pan *et al.*, Phys. Rev. Lett. 80, 3891-3894 (1998)

# Entanglement Swapping: Entangling Photons That Never Interacted

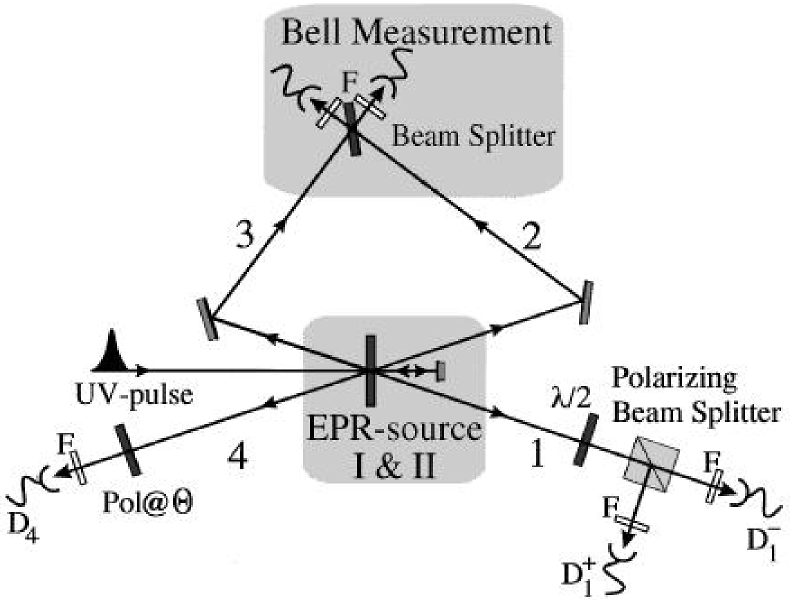


FIG. 2. Experimental setup. A UV pulse passing through a nonlinear crystal creates pair 1-2 of entangled photons. Photon 2 is directed to the beam splitter. After reflection, during its second passage through the crystal the UV pulse creates a second pair 3-4 of entangled photons. Photon 3 will also be directed to the beam splitter. When photons 2 and 3 yield a coincidence click at the two detectors behind the beam splitter, they are projected into the $|\Psi^-\rangle_{23}$ state. As a consequence of this Bell-state measurement the two remaining photons 1 and 4 will also be projected into an entangled state. To analyze their entanglement we look at coincidences between detectors $D_1^+$ and $D_4$, and between detectors $D_1^-$ and $D_4$, for different polarization angles $\Theta$. By rotating the $\lambda/2$ plate in front of the two-channel polarizer we can analyze photon 1 in any linear polarization basis. Note that, since the detection of coincidences between detectors $D_1^+$ and $D_4$, and $D_1^-$ and $D_4$ are conditioned on the detection of the $\Psi^-$ state, we are looking at fourfold coincidences. Narrow bandwidth filters (F) are positioned in front of each detector.

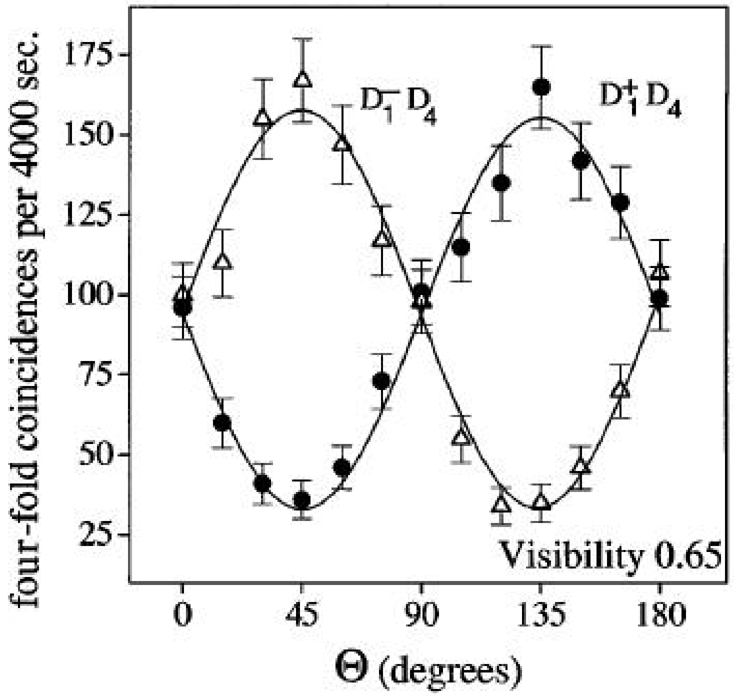


FIG. 3. Entanglement verification. Fourfold coincidences, resulting from twofold coincidence $D1^+D4$ and $D1^-D4$ conditioned on the twofold coincidences of the Bell-state measurement, when varying the polarizer angle $\Theta$. The two complementary sine curves with a visibility of $0.65 \pm 0.02$ demonstrate that photons 1 and 4 are polarization entangled.

Jian-Wei Pan *et al.*, Phys. Rev. Lett. 80, 3891-3894 (1998)

# Multistage Entanglement Swapping

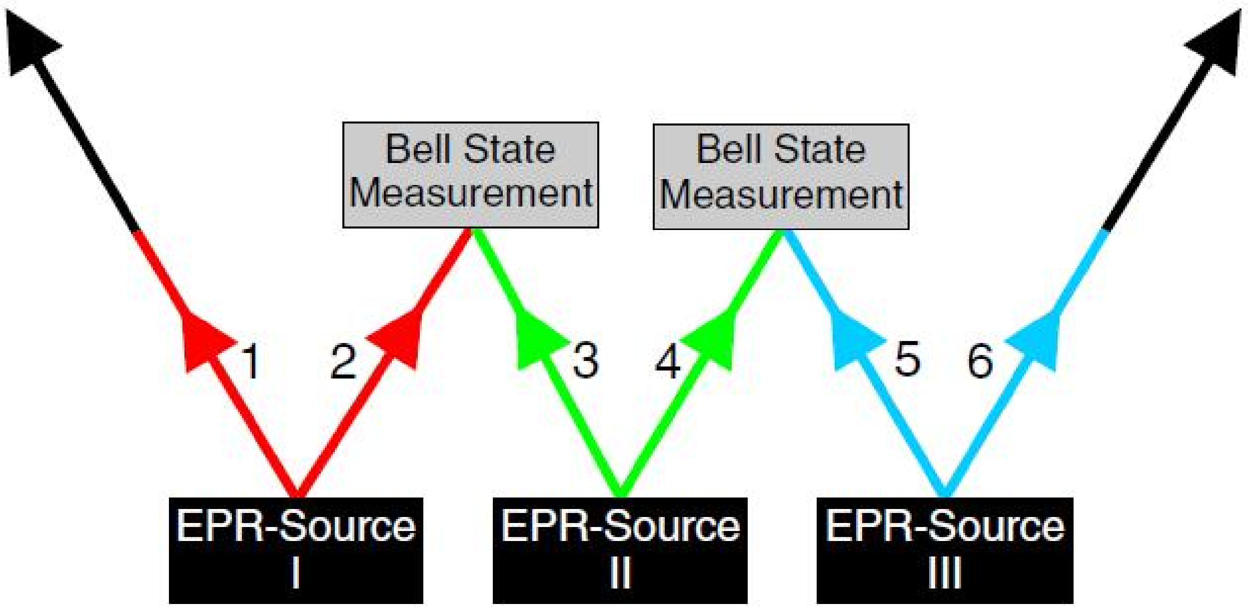


FIG. 1 (color online). Principle of multistage entanglement swapping: three EPR sources produce pairs of entangled photons 1–2, 3–4, and 5–6. Photon 2 from the initial state and photon 3 from the first ancillary pair are subjected to a joint BSM, and so are photon 4 from the first ancillary and photon 5 from the second acillary pair. The two BSMs project outgoing photons 1 and 6 onto an entangled state. Thus the entanglement of the initial pair is swapped to an entanglement between photons 1 and 6.

Alexander M. Goebel *et al.*, Phys. Rev. Lett. 101, 080403 (2008)

# Multistage Entanglement Swapping

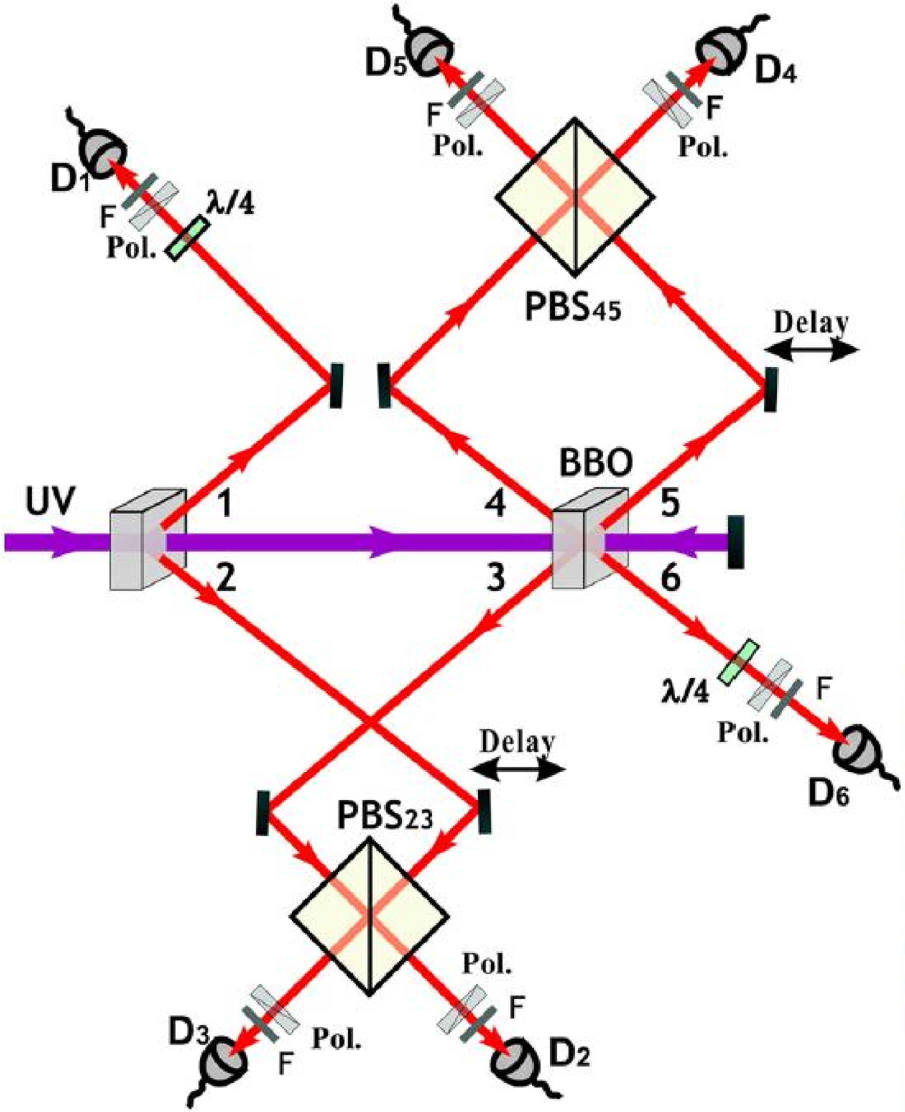


FIG. 2 (color online). The focused ultraviolet laser beam passes the first BBO generating photon pair 1–2. Refocused, it passes the second BBO generating the ancillary pair 5–6 and again retroreflected through the second BBO generating pair 3–4. In order to achieve indistinguishability at the interference PBS23 and PBS45 the spatial and temporal overlap are maximized by adjusting the delays and observing "Shih-Alley-Hong-Ou-Mandel-type" interference fringes [19] behind the PBS23 (PBS45) in the ± basis [20]. With the help of polarizers and half or quarter wave plates, we are able to analyze the polarization of photons in arms 1 and 6. All photons are spectrally filtered by narrow band filters with $\Delta\lambda_{FWHM} \approx 2.8$ nm and are monitored by silicon avalanche single-photon detectors [21]. Coincidences are counted by a laser clocked field-programmable gate array based coincidence unit.

Alexander M. Goebel *et al.*, Phys. Rev. Lett. 101, 080403 (2008)

# Experimental Multiparticle Entanglement Swapping for Quantum Networking

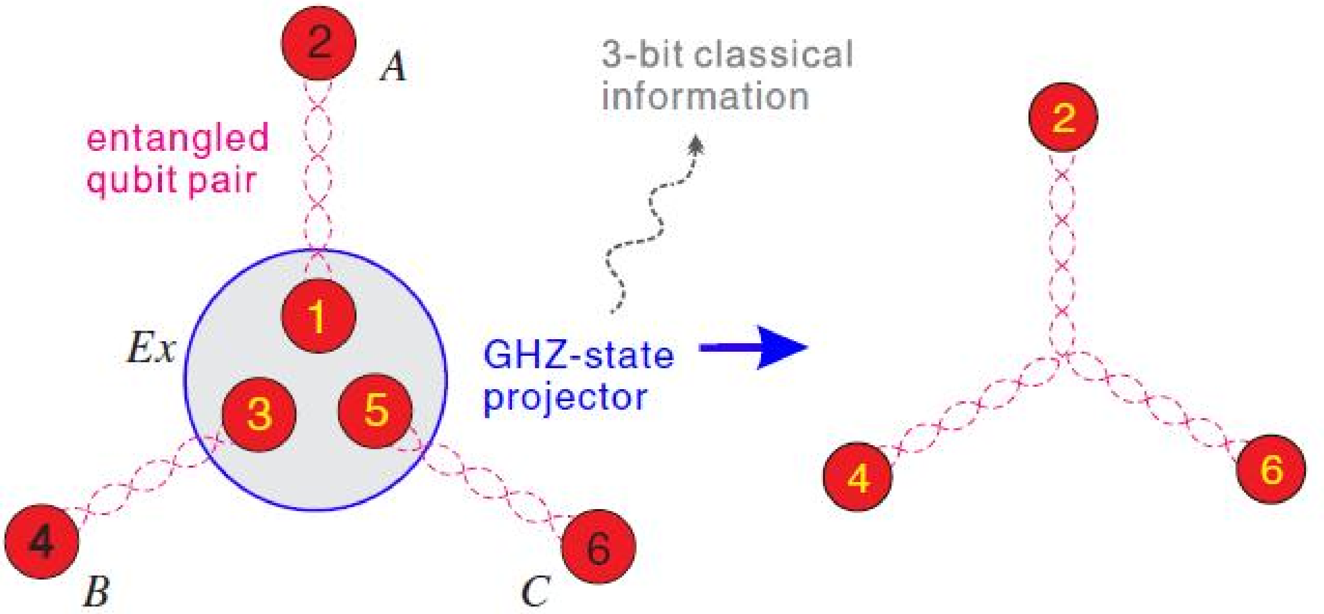


FIG. 1 (color online). Configuration of a multiparty quantum network and GHZ entanglement swapping. Initially, users *A*, *B*, and *C* share entangled qubit pairs with the central exchange Ex. If Ex projects the three particles, 1, 3, and 5, into a GHZ state, the other three particles, 2, 4, and 6 belonging to *A*, *B*, and *C* respectively, will be entangled into a GHZ state by entanglement swapping.


Chao-Yang Lu, Tao Yang, and Jian-Wei Pan, Phys. Rev. Lett. 103, 020501 (2009)

# Experimental Multiparticle Entanglement Swapping for Quantum Networking

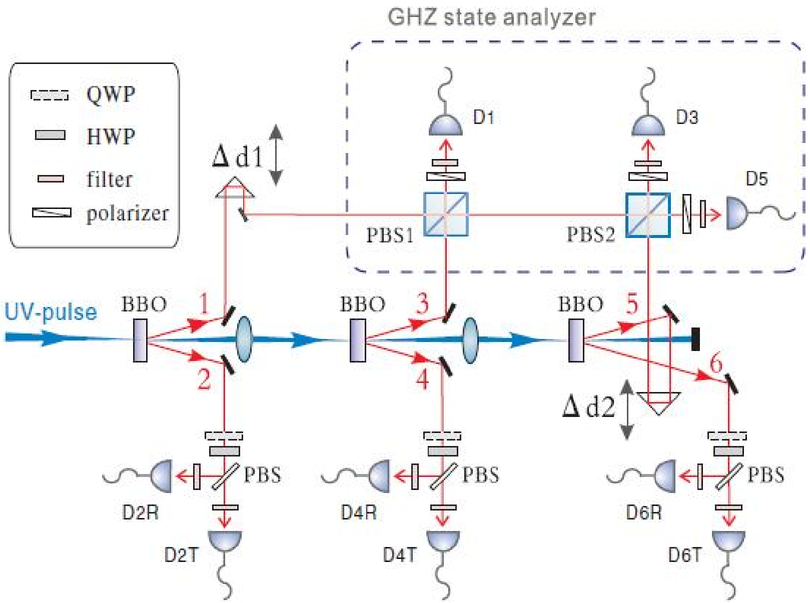


FIG. 2 (color online). Experimental setup for entanglement swapping of a three-photon GHZ state. Ultraviolet laser pulses (with a central wavelength of ~394 nm, a pulse duration of ~120 fs, and a repetition rate of ~76 MHz) are focused on three BBO crystals, producing entangled photon pairs emitted into spatial modes 1–2, 3–4, and 5–6. Photons 1, 3, and 5 are projected into a GHZ state (dashed box, see text and Ref. [18]), and the photons 2, 4, and 6 are analyzed by a combination of a quarter-wave plate (QWP), a half-wave plate (HWP) and a PBS. The photons are spectrally filtered by narrow-band filters ($\Delta\lambda_{FWHM} = 3.2$ nm) and monitored by fiber-coupled silicon avalanche single-photon detectors (D1, D2T, $\cdots$, D6R). The multiphoton events are registered by a laser clocked multichannel coincidence unit.

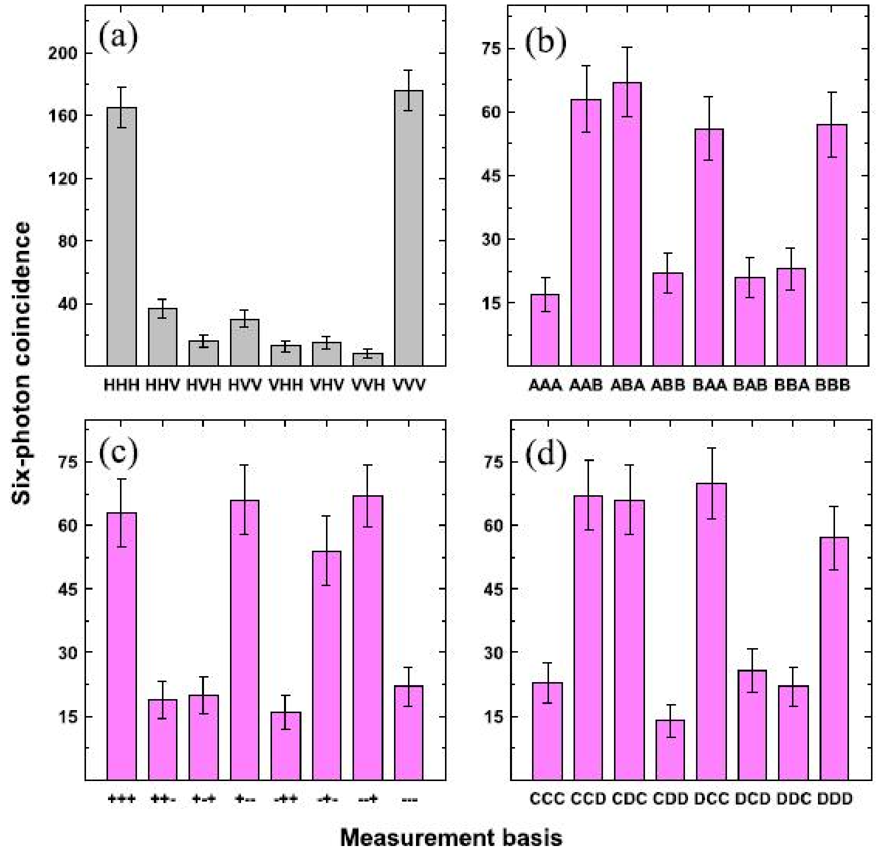


FIG. 4 (color online). Sixfold coincidence in the measurement basis of: (a) $H/V$, (b) $A/B$, (c) $+/-$, and (d) $C/D$ for witnessing the genuine entanglement of the three emerging photons 2, 4, and 6. The accumulation time for each data set is 24 h in (a) and 18 h in (b),(c), and (d). The error bars represent 1 standard deviation deduced from Poissonian counting statistics of the raw detection events.



Chao-Yang Lu, Tao Yang, and Jian-Wei Pan, Phys. Rev. Lett. 103, 020501 (2009)

# 课后作业

## Entanglement Swapping的原理推导

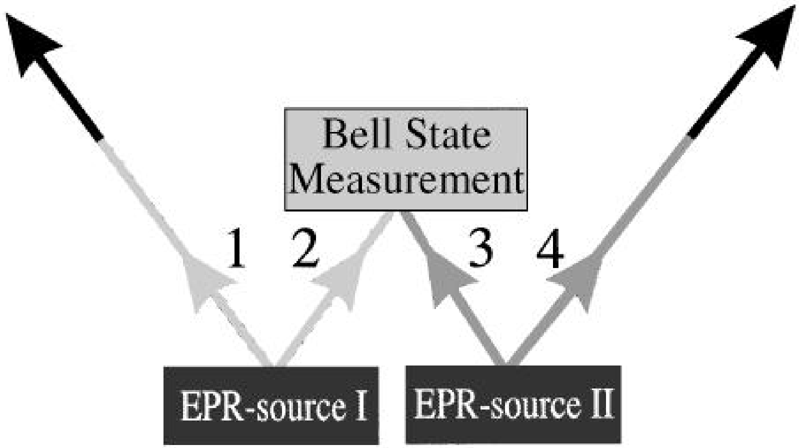


FIG. 1. Principle of entanglement swapping. Two EPR sources produce two pairs of entangled photons, pair 1-2 and pair 3-4. One photon from each pair (photons 2 and 3) is subjected to a Bell-state measurement. This results in projecting the other two outgoing photons 1 and 4 onto an entangled state. Change of the shading of the lines indicates the change in the set of possible predictions that can be made.

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# 量子通信网络进展

**US**

- **DARPA** 网络, 连接波士顿市区的哈佛大学、波士顿大学和**BBN**公司 **10km** 链接。其**3**个节点之后增加到了**10**个。
- **NIST 3**节点网络 **1km** 链接。

**EU**

- 欧盟从**2006**年起，成立了 "基于密码的安全通信（**SECOQC**）" 网络, 囊括了来自英国、法国、德国、意大利、奥地利和西班牙等**12**个国家的**41**个相关领域的机构和组织 。典型的网络 **6**个节点，**8**个链接。 **2008**年**10**月在维也纳演示。采用混合类型的协议和可信中继架构。光纤的环形网络**63 km**, 一个额外节点**85 km**。

**Japan**

- 日本国家情报通信研究机构（**NICT**） 主导联合项目'**Seamless QKD in Metropolitan- and Backbone- Networks**'. **NEC & Mitsubishi**的互联于**2006**年演示。**2010**年**10**月，**NICT**主导，联合日本电信电话株式会社(**NTT**)、**NEC**和三菱电机，并邀请东芝欧洲有限公司，瑞士**ID Quantique**公司和奥地利的**All Vienna**共同协作在东京建成和演示了**6**节点城域量子通信网络" **Tokyo QKD Network**"。最远通信距离为**90**公里，**45**公里距离上点对点通信速率可达**60kbps**（使用超导探测器）

# 量子通信网络进展

**China**

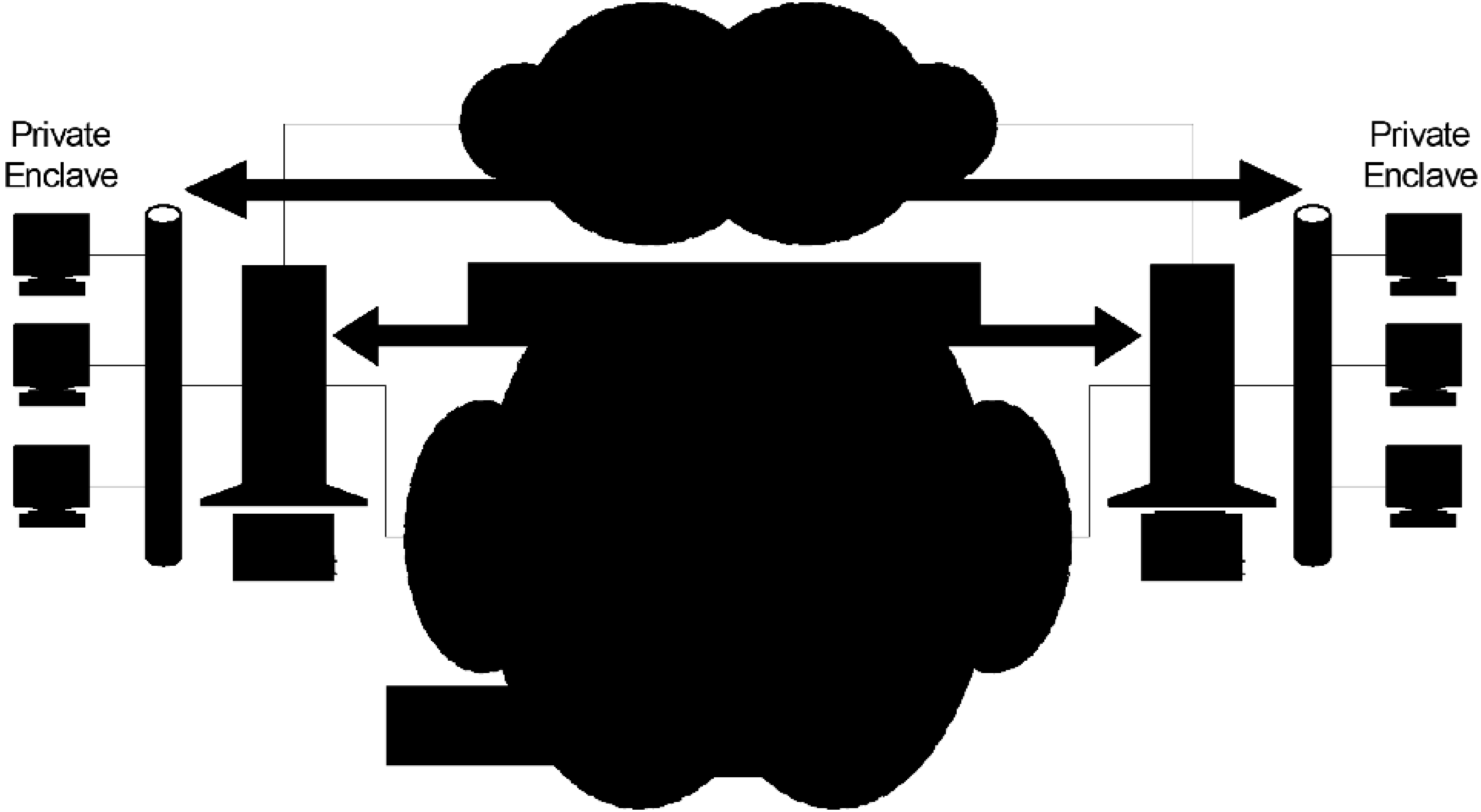
- **USTC 潘建伟教授团队 5节点大于16km链接。最远链接60km（延伸至130km）。所有节点互联互通。**
- **USTC 郭光灿教授团队7个节点最远10km链接。4节点互通5.6km。**

商用量子通信产品公司

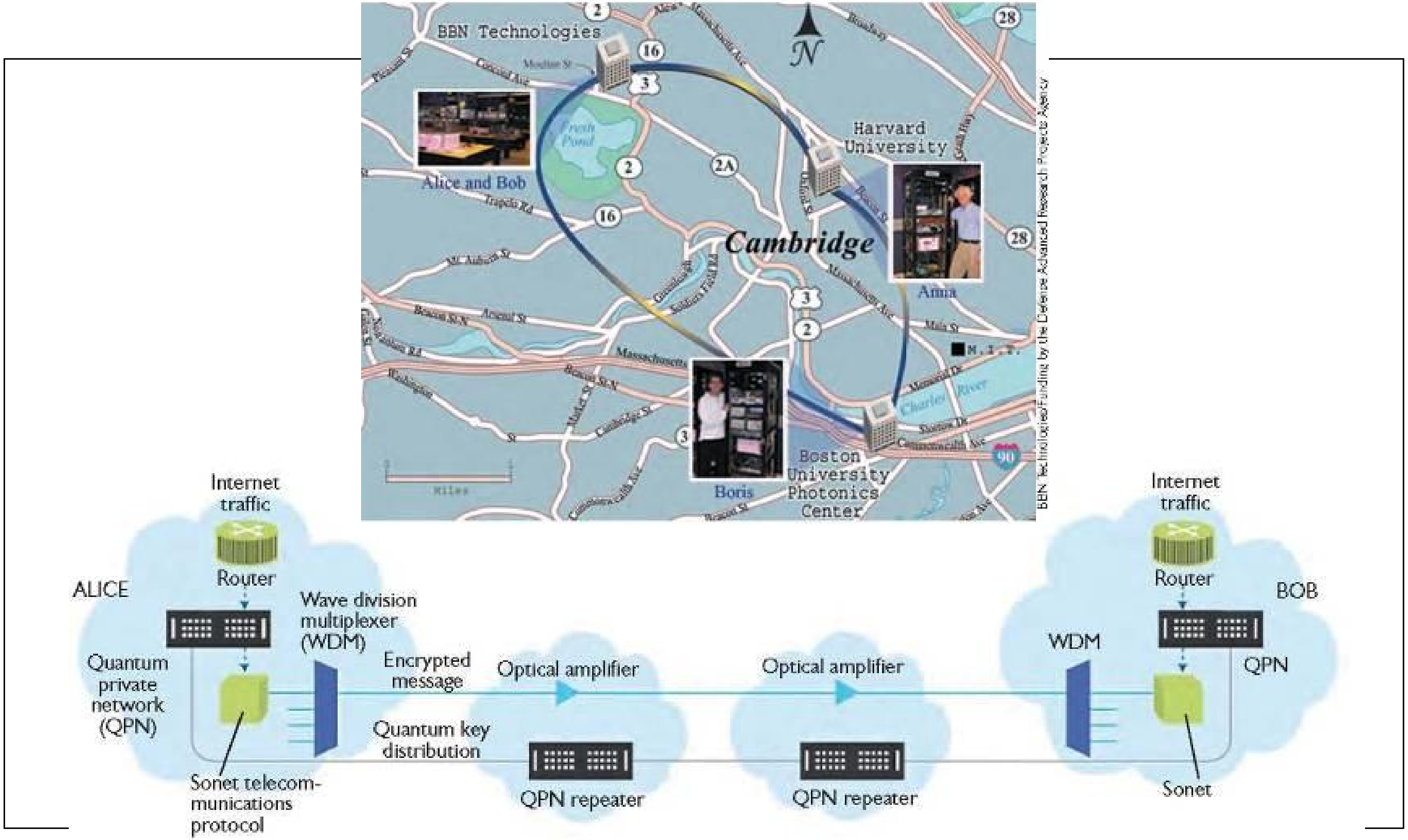
- **id Quantique: Geneva, Switzerland**
- **MagiQ Technologies: US, New York**
- **SmartQuantum，France，Lannion （破产）**
- **QuintessenceLabs, Australia, Canberra**

**etc.**

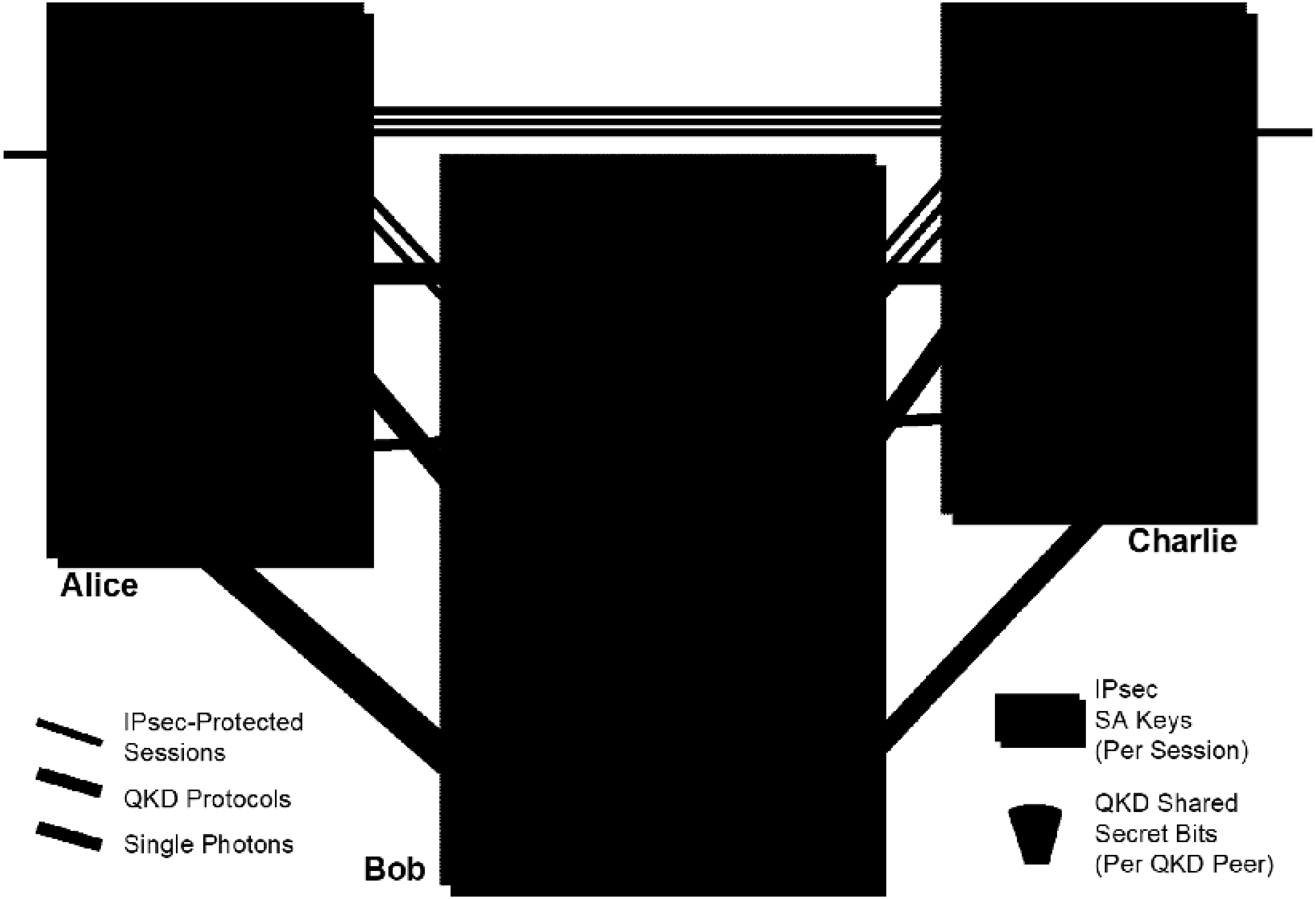
# The DARPA Quantum Network



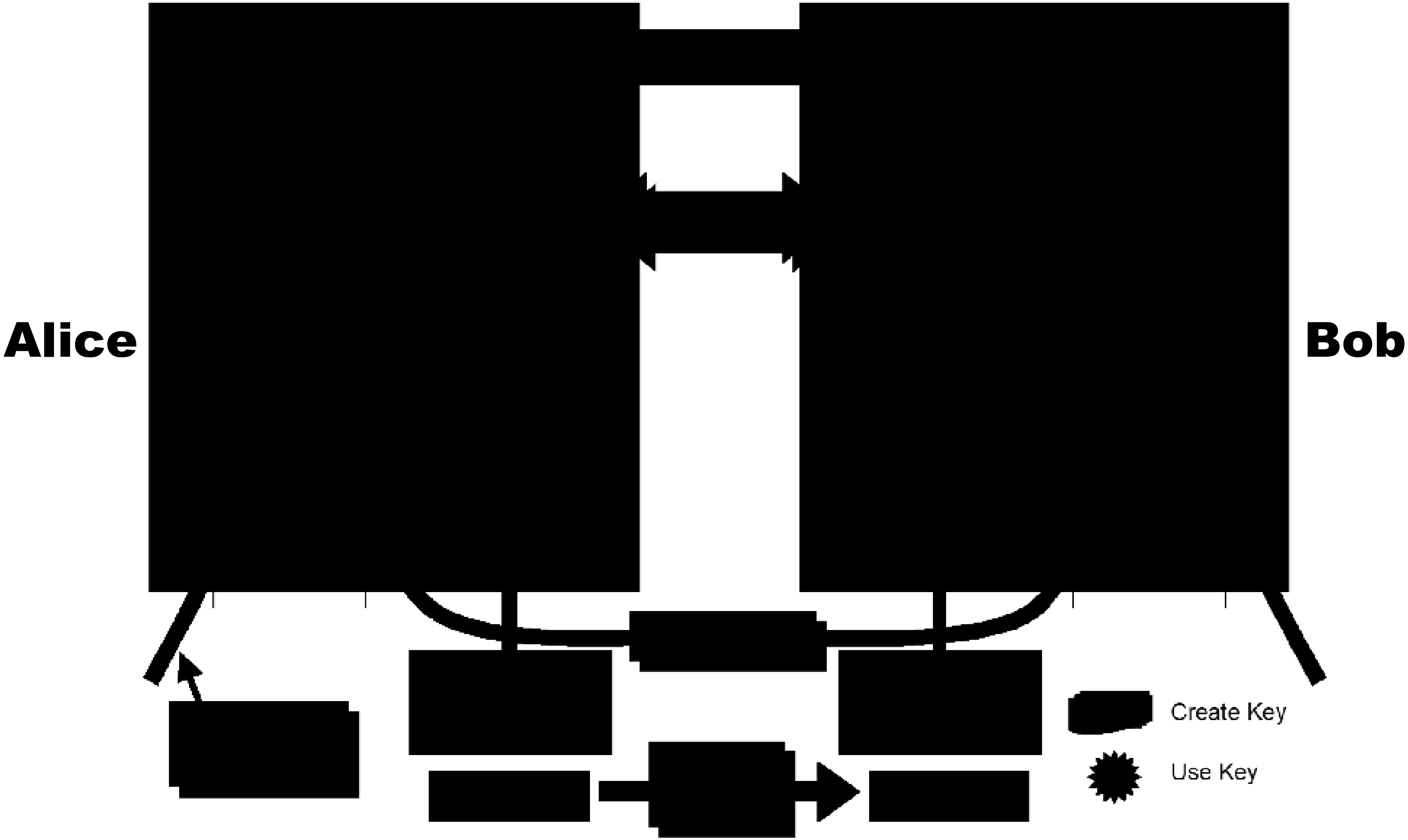
# The DARPA Quantum Network



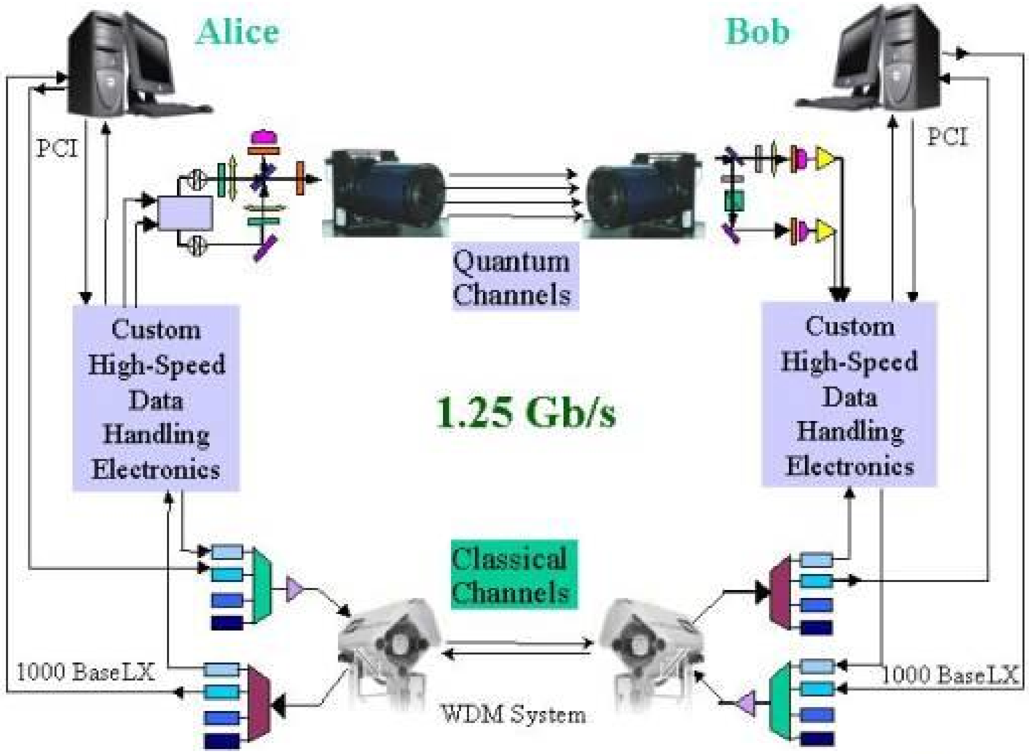
# The DARPA Quantum Network架构



# The DARPA Quantum Network架构



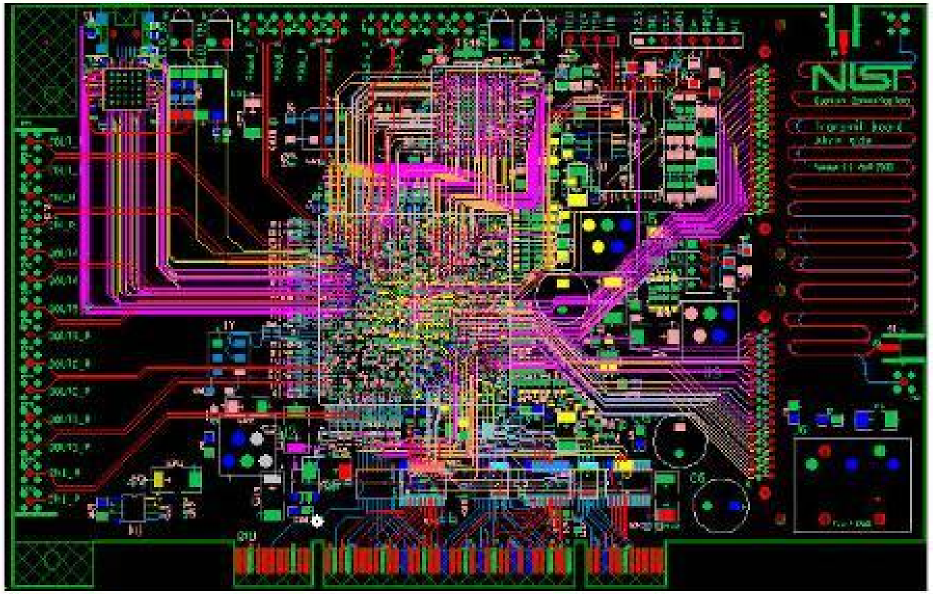
# NIST Quantum Communication Testbed



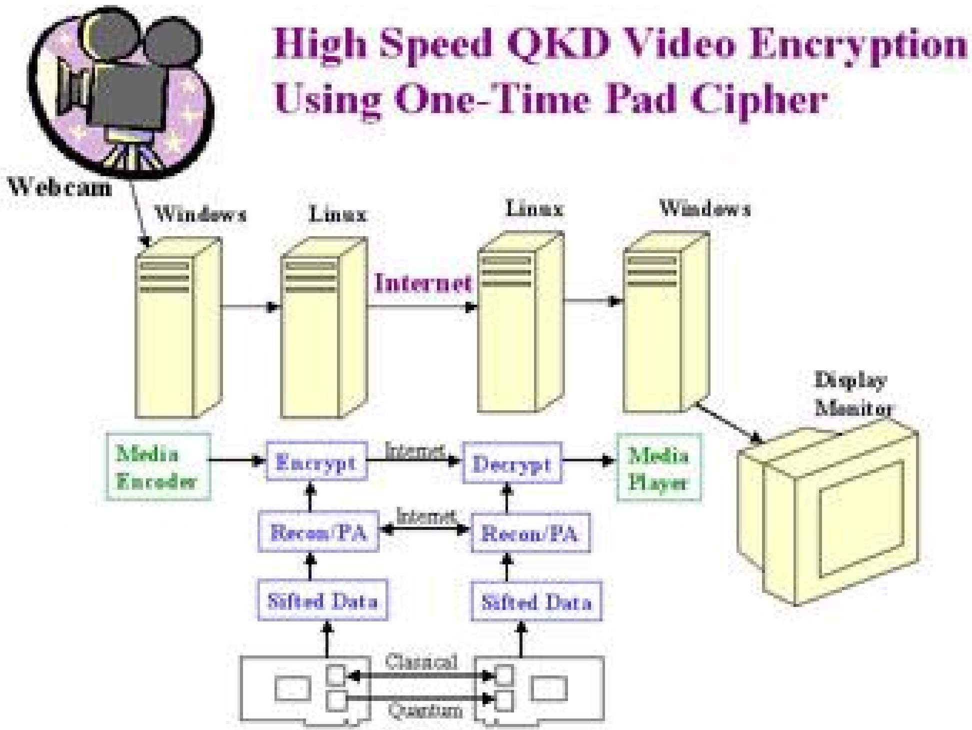

PCI interface high-speed electronics boards for Alice (left) and Bob (right).

1 Mbit/s over 4km (2006年)

# NIST 量子网络

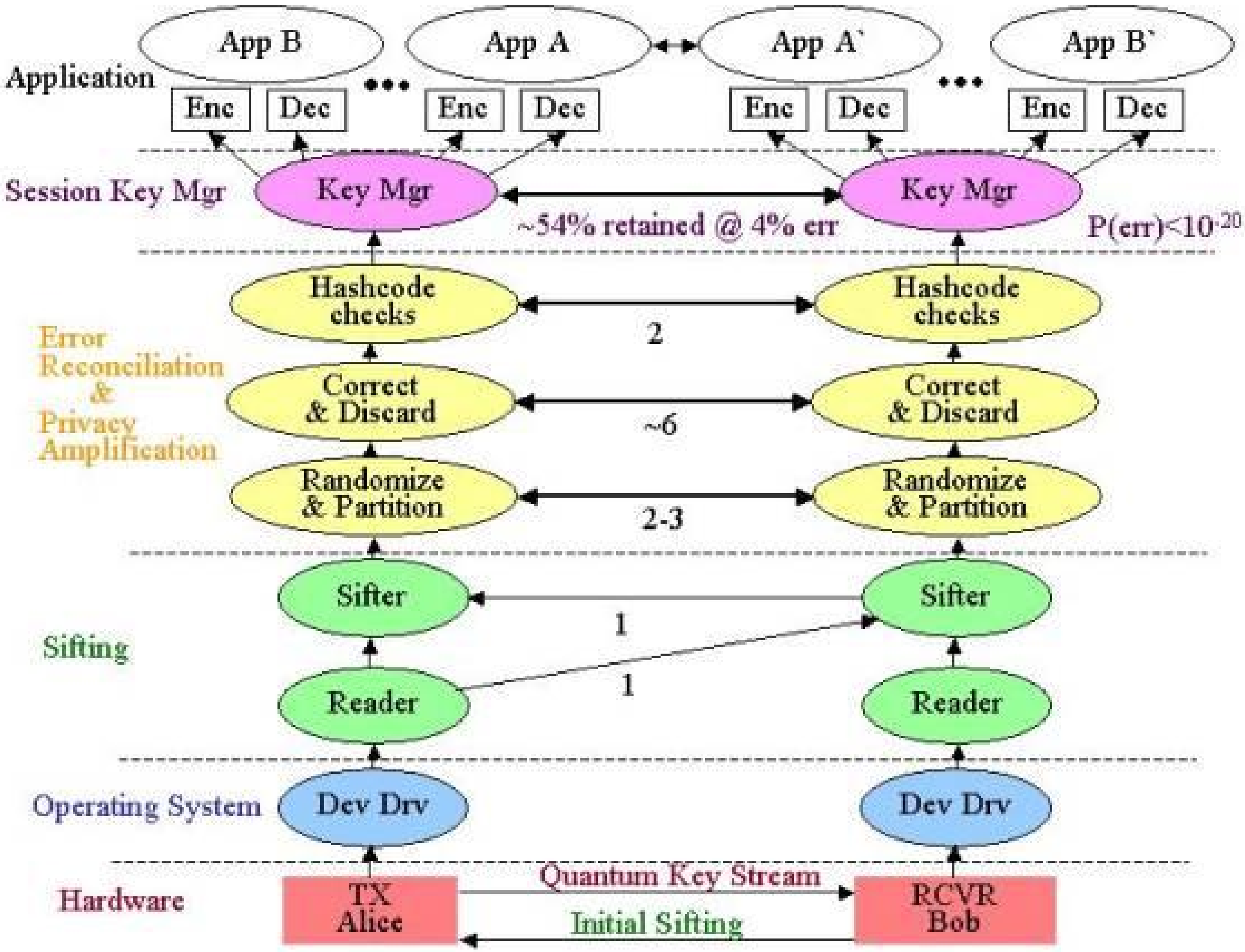


集成的高速电路板




视频会议演示

# NIST QKD Protocol Stack (2006)



# SECOQC QKD网络拓扑和分布

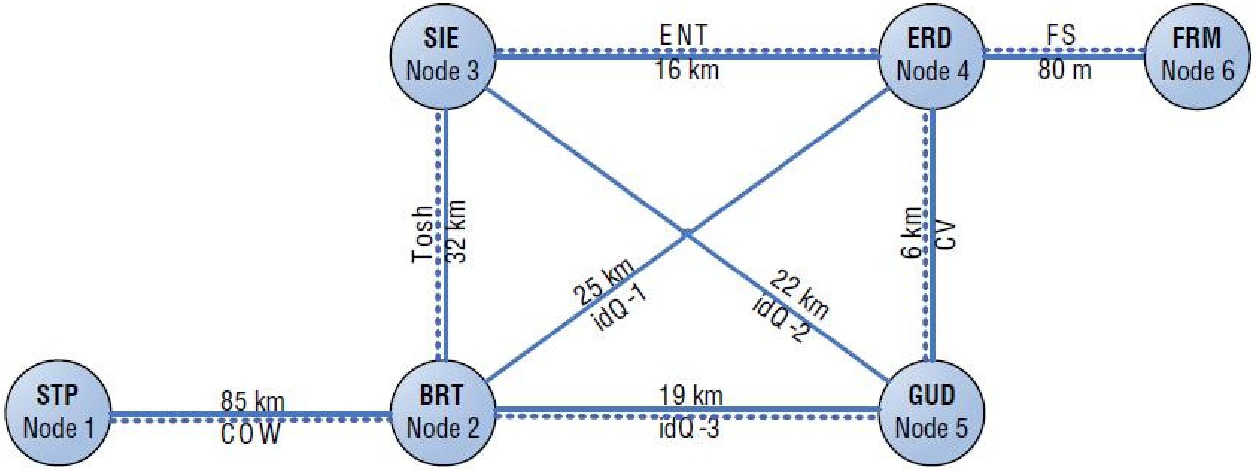




**Figure 3.** Satellite map with the locations of the nodes of the prototype.

# SECOQC QKD-链接协议和设备

- Attenuated Laser Pulses (Id Quantique)
- Coherent-One-Way (University of Geneva)
- One-way, decoy states (Toshiba UK)
- Entangled photons (University of Vienna)
- Continuous Variables (Prof. Grangier)
- Access Free Space Link (LMU of Munich)

  The “last mile“ (80 m, >10kbit/s)

# SECOQC QKD节点组成

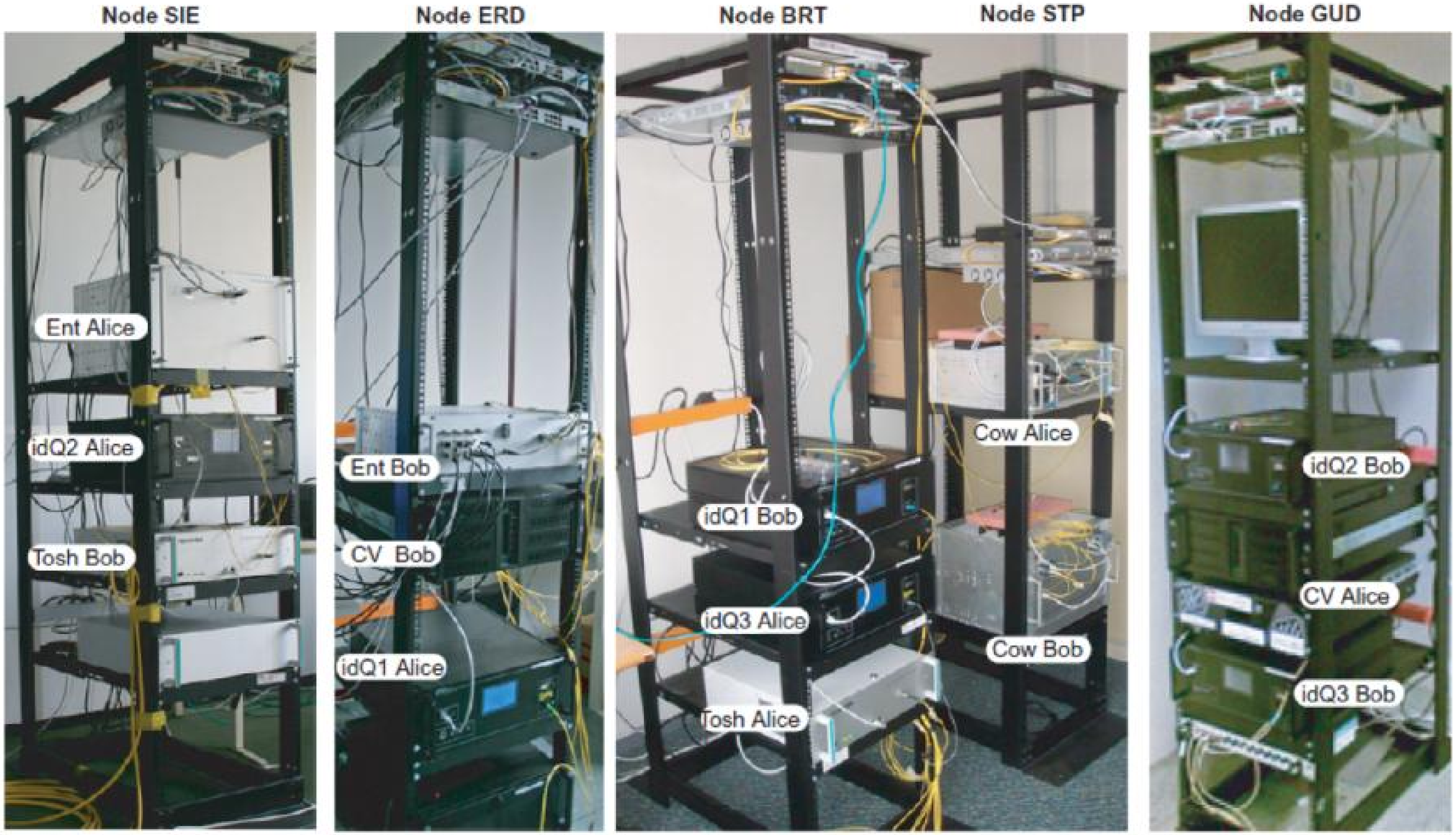
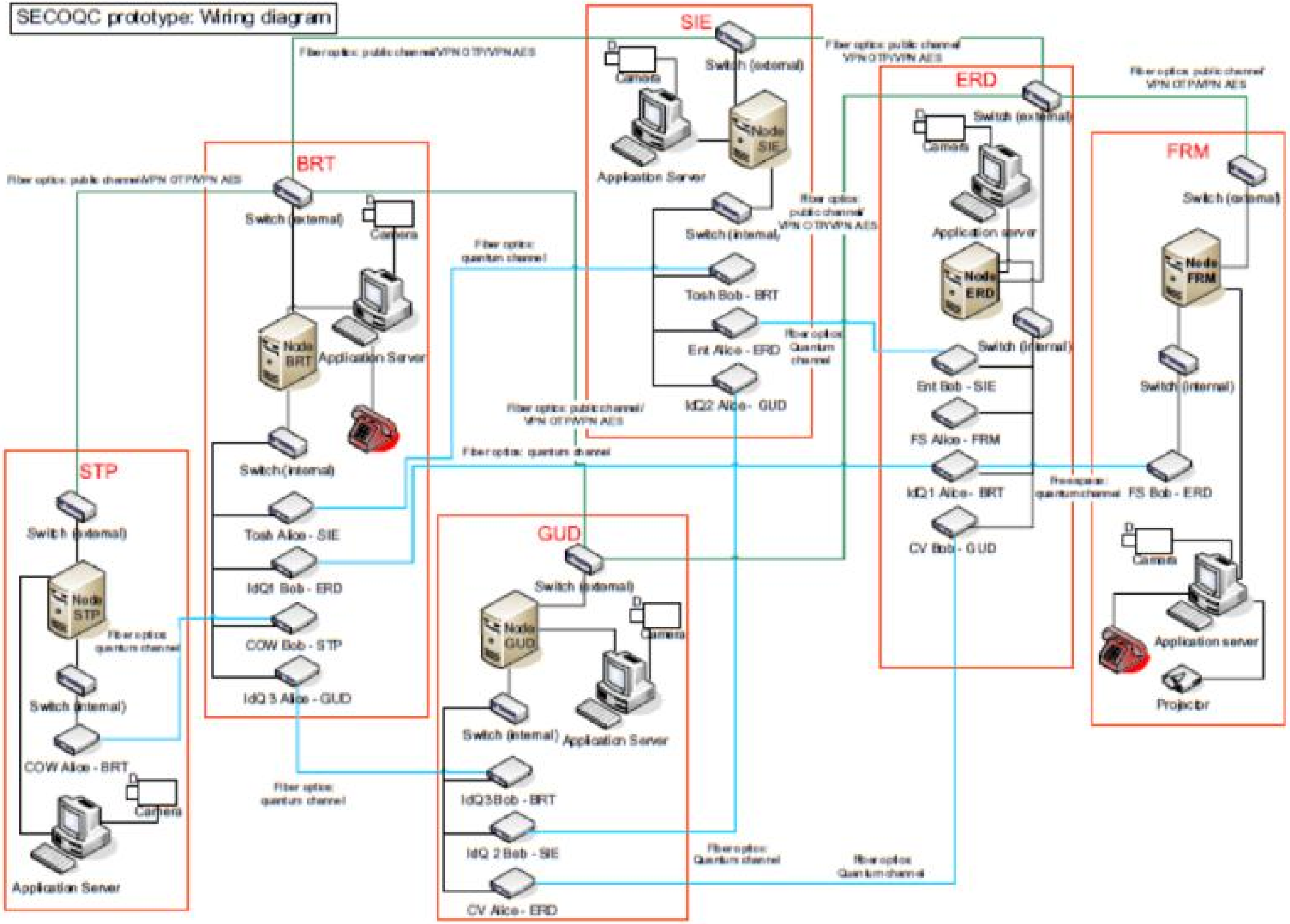



**Figure 5.** Photographs of the SECOQC network node racks.

成码率：0.6～10kbps

# SECOQC QKD链接方式




中国科学技术大学 陈凯

# SECOQC QKD节点模块

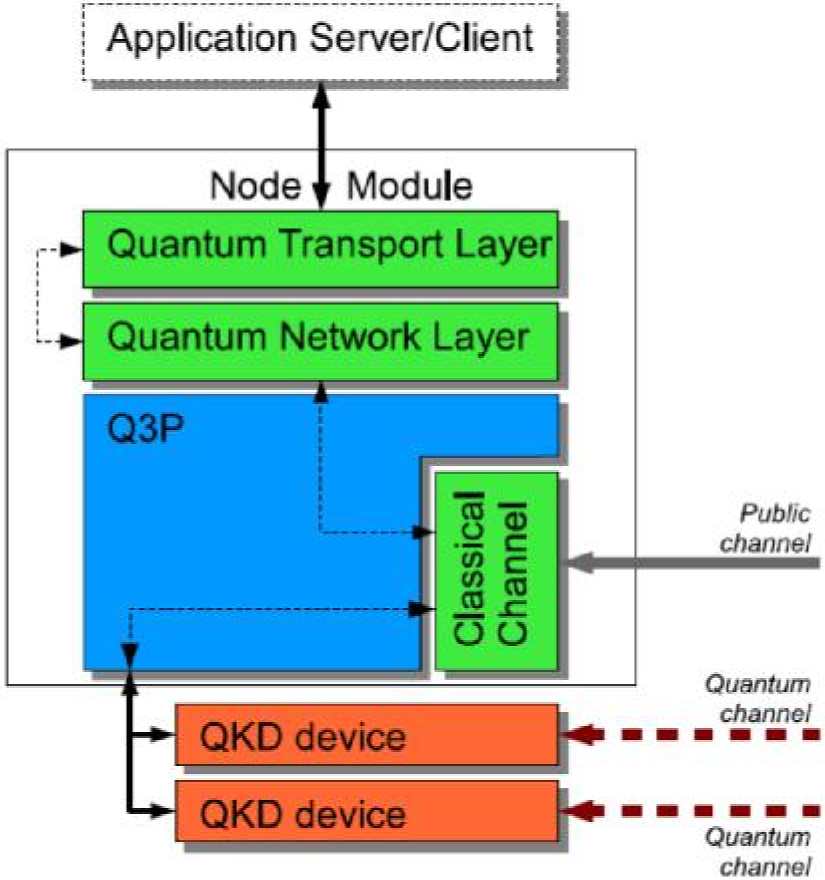
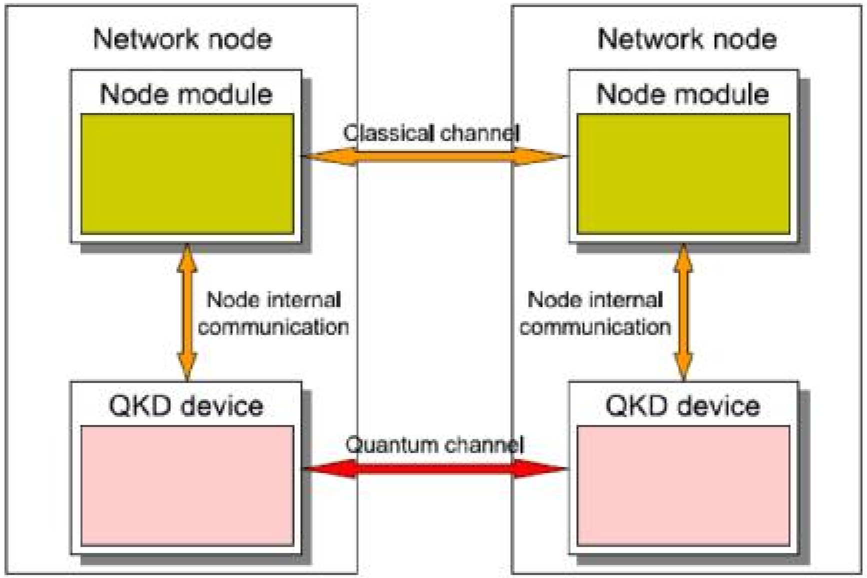
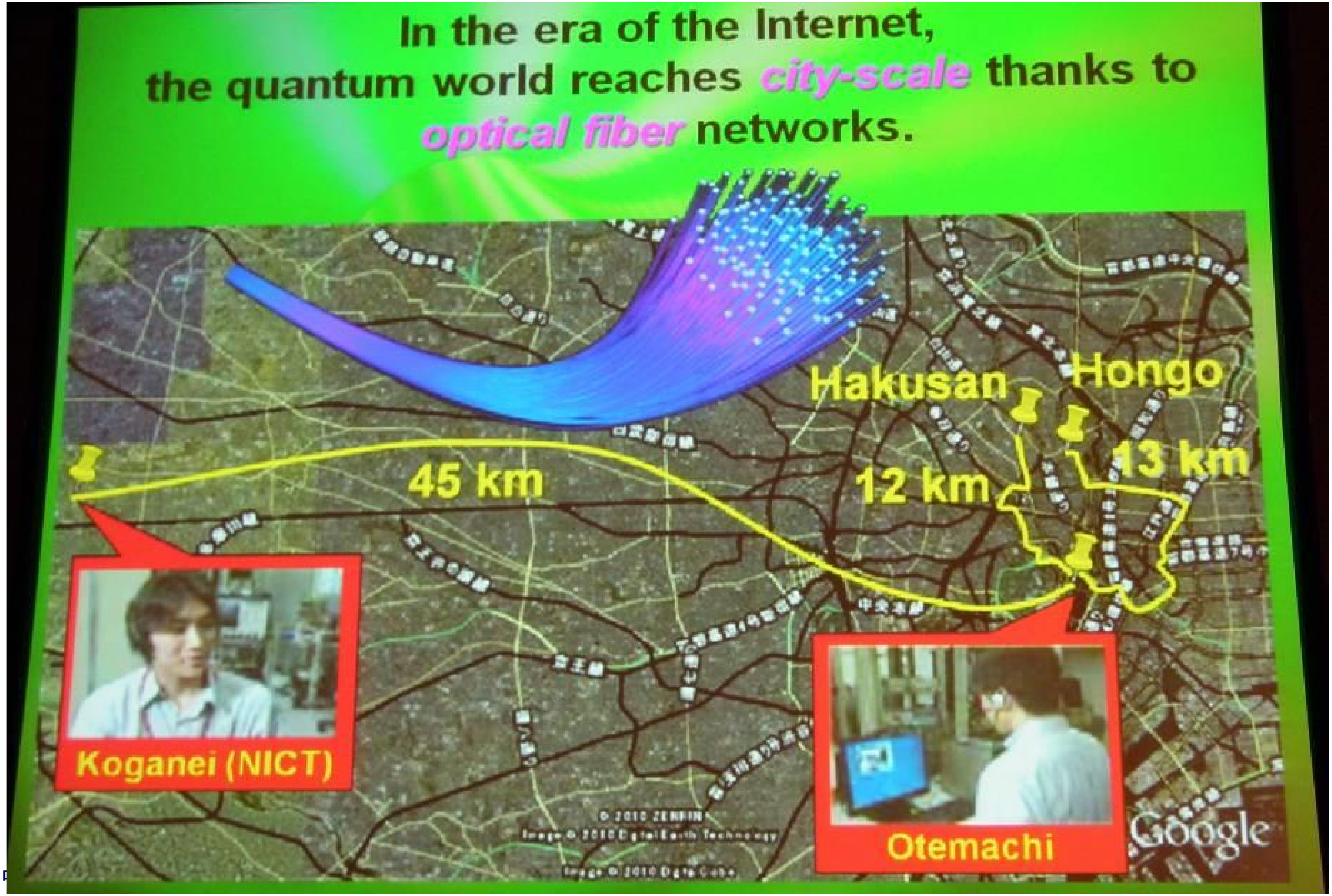
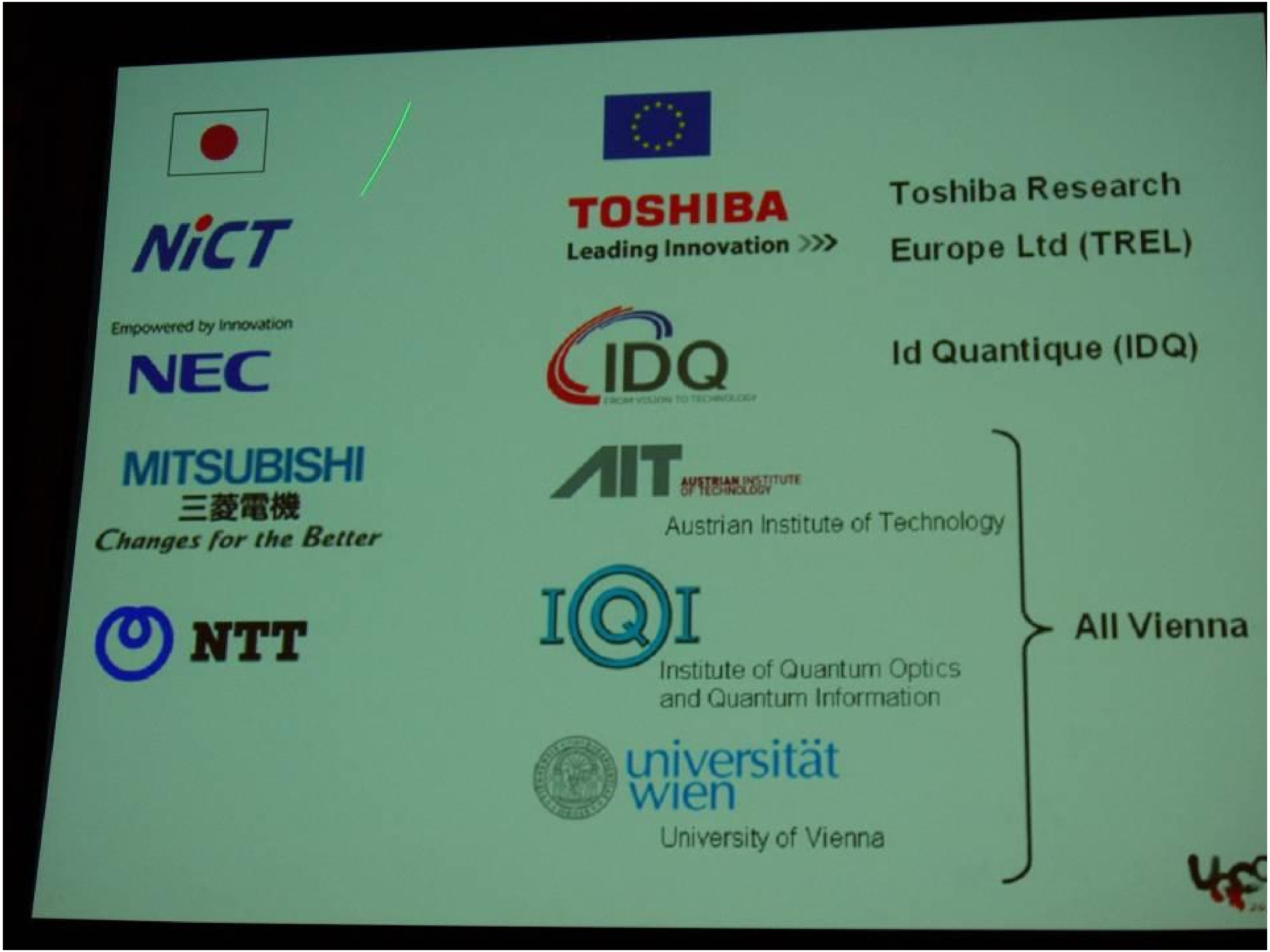



**Figure 18.** Design of the node module.



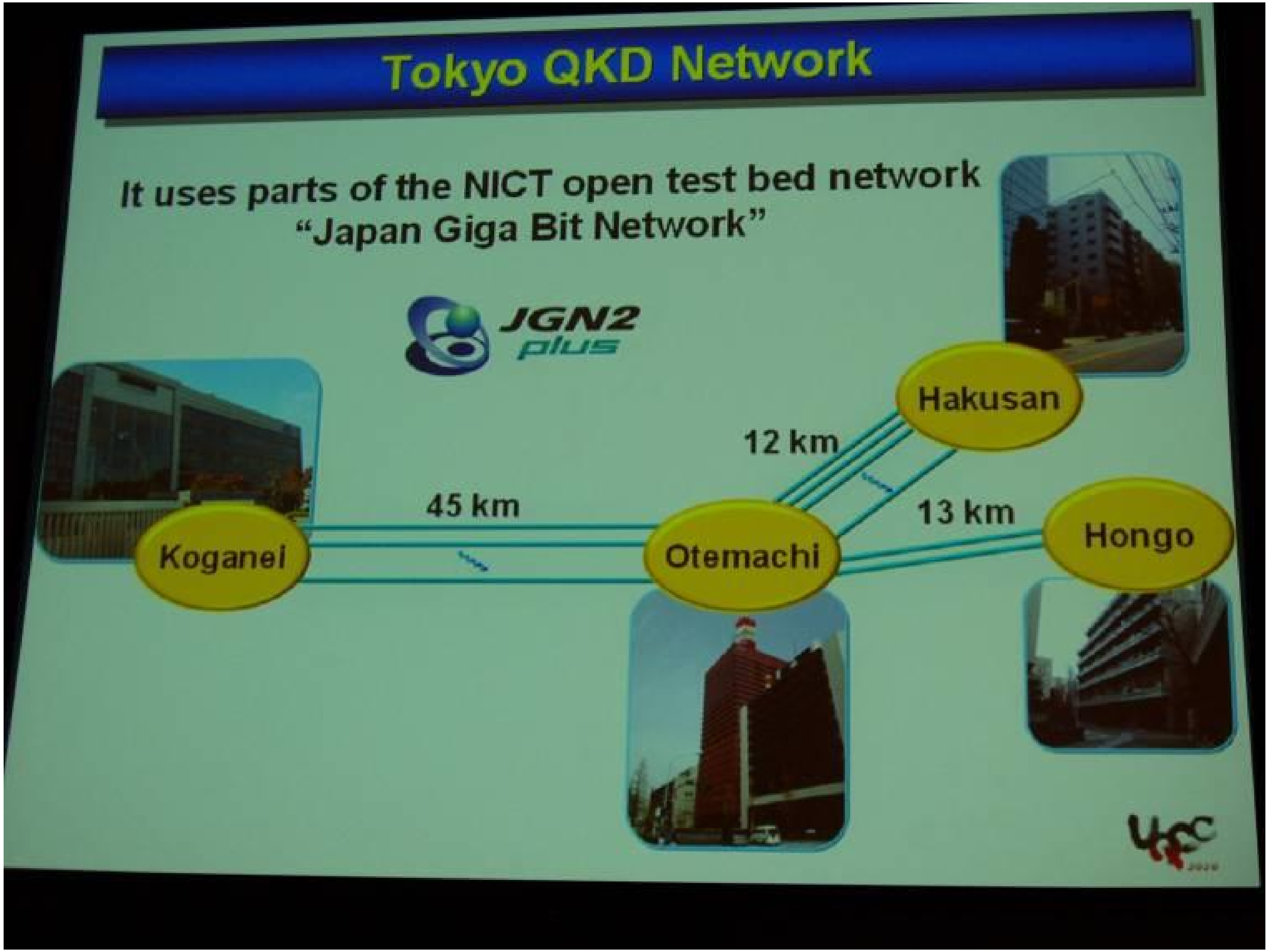
# Tokyo QKD network





NiCT
Empowered by Innovation
NEC
MITSUBISHI
三菱電機
Changes for the Better
NTT
TOSHIBA
Leading Innovation >>>
Toshiba Research
Europe Ltd (TREL)
IDQ
Id Quantique (IDQ)
AIT
Austrian Institute of Technology
IQI
Institute of Quantum Optics
and Quantum Information
universität
wien
University of Vienna
All Vienna

# 连接点




东京网络基于日本的一个光纤实验床，有6个节点，3个在Koganei，2个在Otemachi，1个在Hongo

# Tokyo QKD Network网络拓扑、距离和损耗

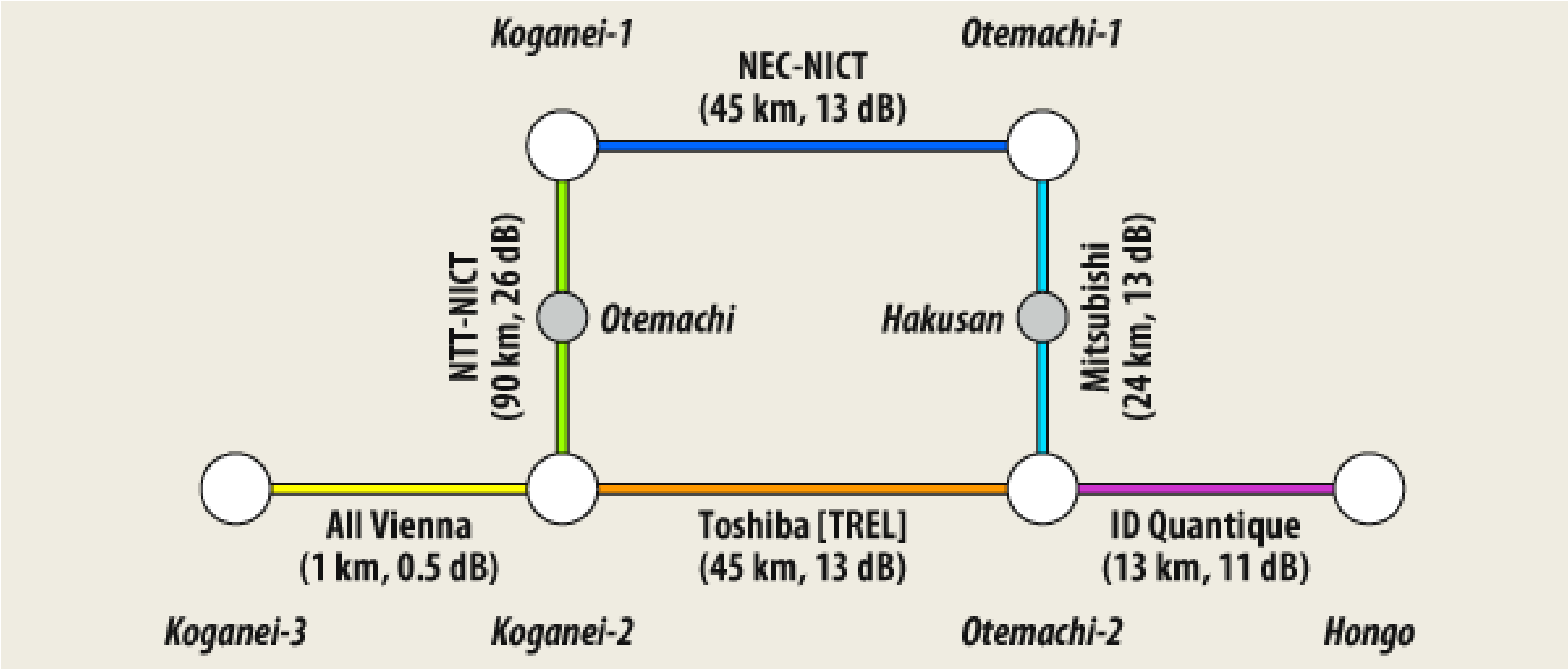



Fig. 3 Topological Map of the Tokyo QKD Network

**NEC, Mitsubishi Electric, NTT, NICT, Toshiba Research Europe Ltd. (UK)**
**ID Quantique (Switzerland) All Vienna (Austria)**

# 网络架构

- 基于JGN2plus（Japan's Gigabit Network ）
- 星形结构

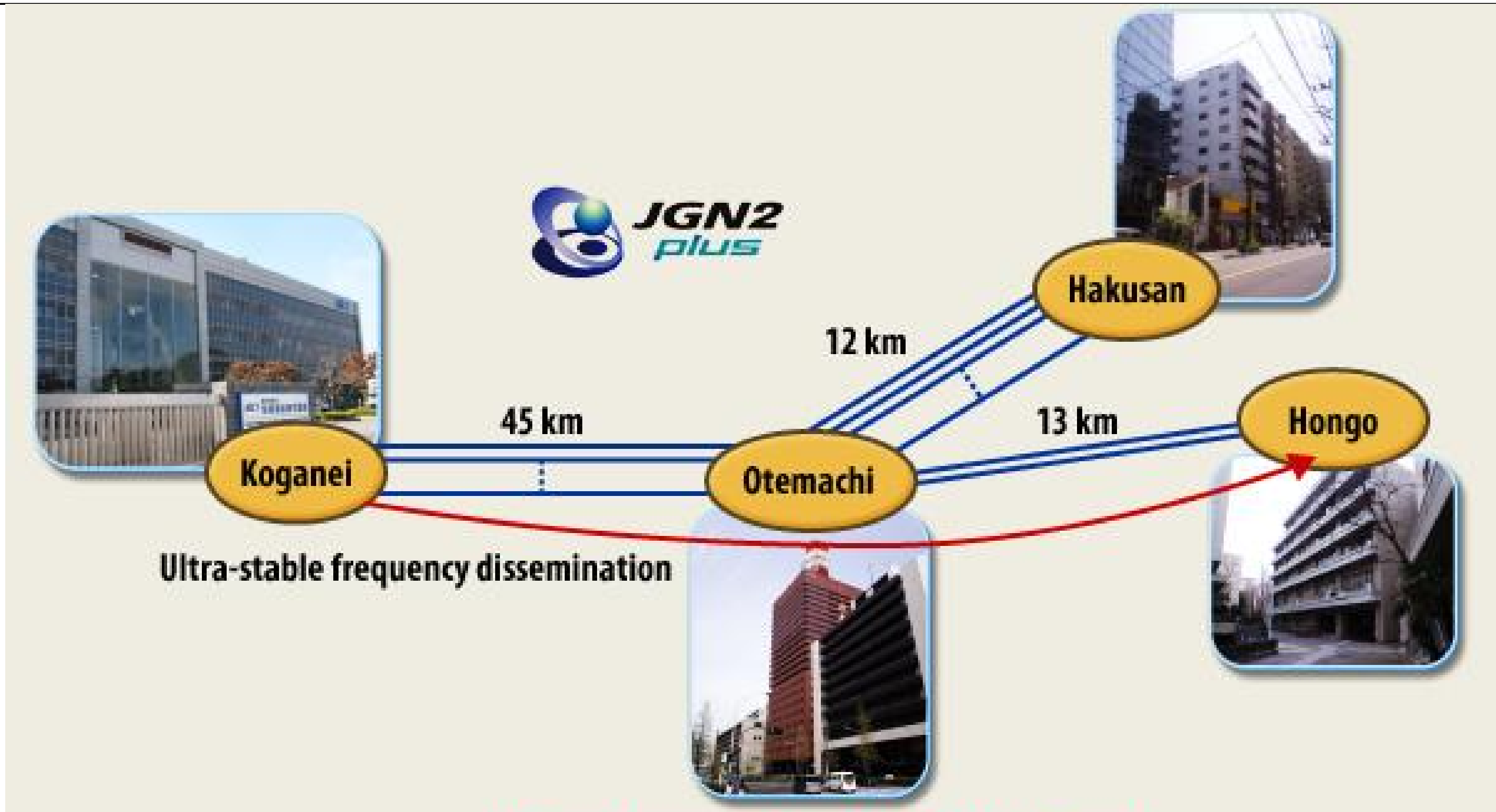



Fig. 1 Network Layout of the Tokyo QKD Network

# Network Layer结构

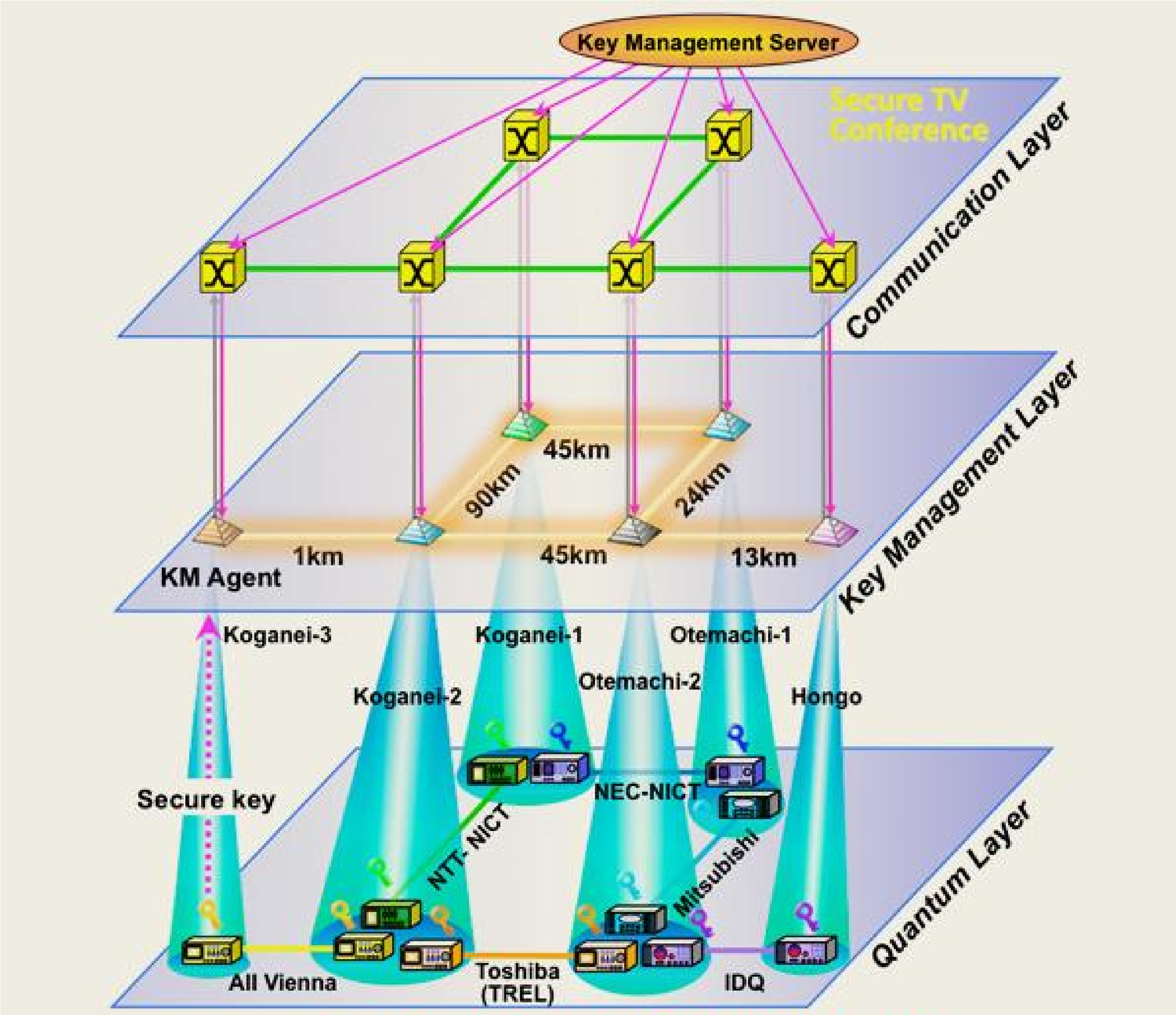
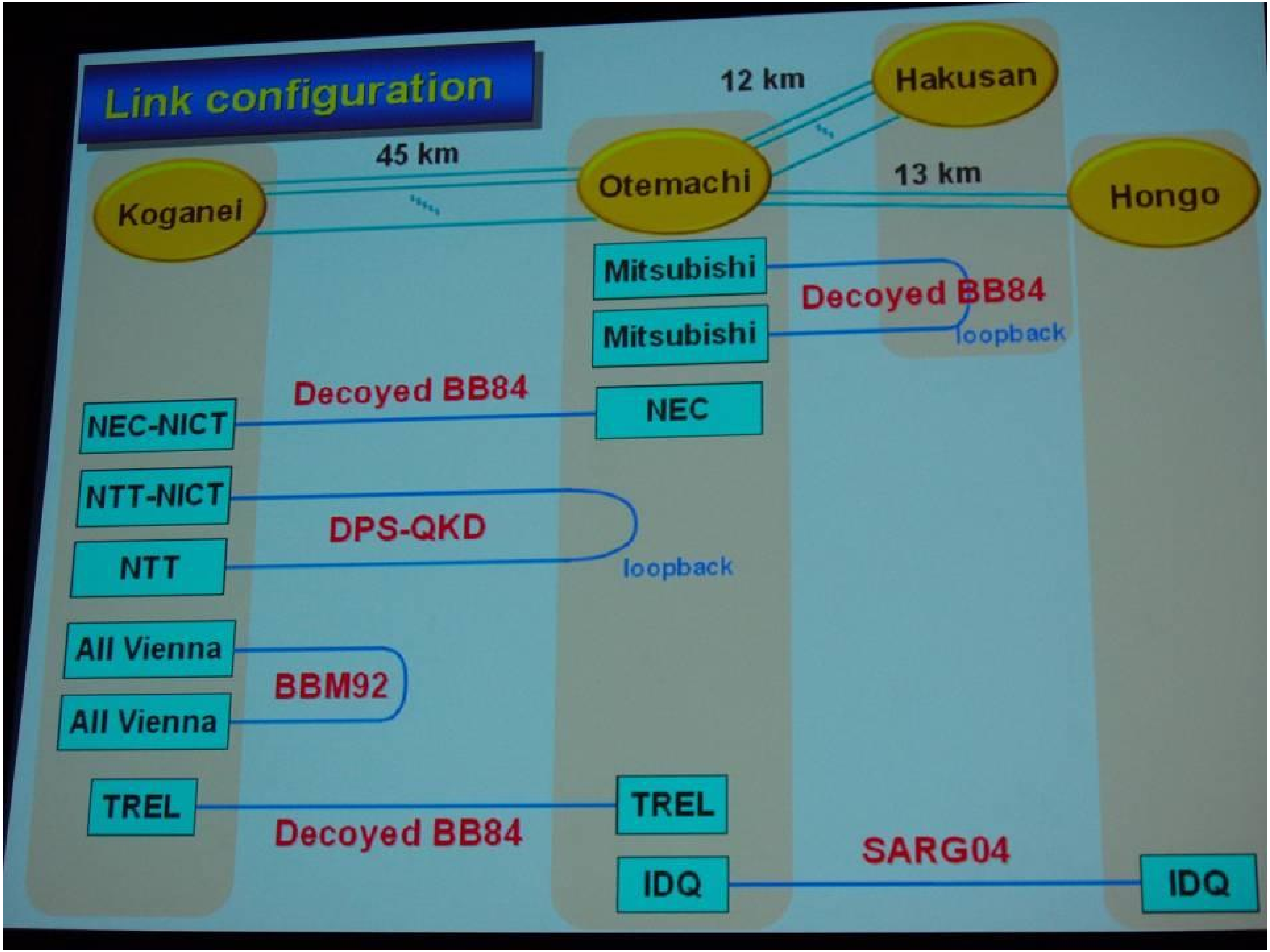
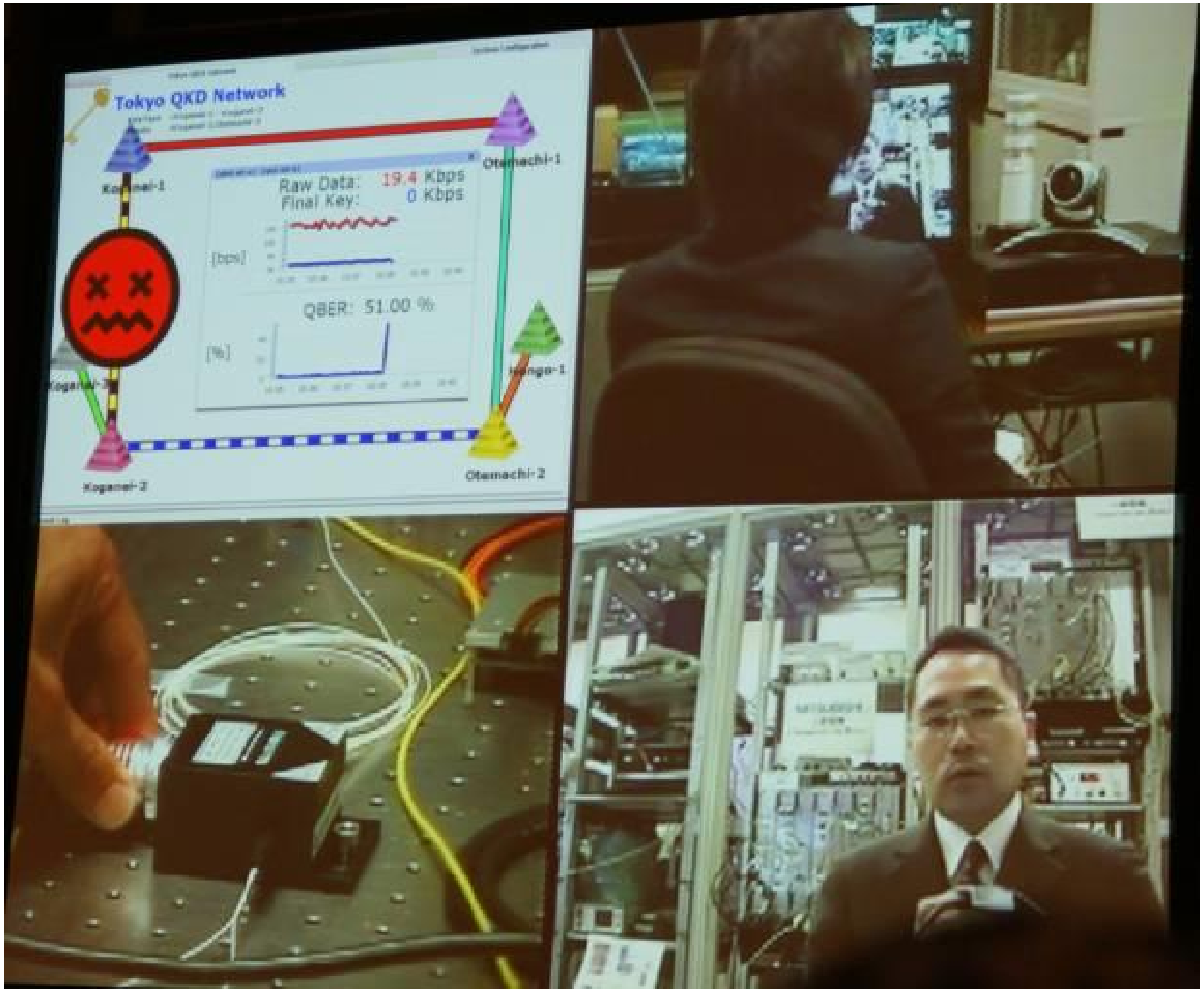



Fig. 2 Network Layer Structure of the Tokyo QKD Network


Link configuration
12 km
Hakusan
45 km
Otemachi
13 km
Koganei
Hongo
Mitsubishi
Mitsubishi
Decoyed BB84
loopback
Decoyed BB84
NEC-NICT
NEC
NTT-NICT
DPS-QKD
NTT
loopback
All Vienna
BBM92
All Vienna
TREL
TREL
Decoyed BB84
SARG04
IDQ
IDQ

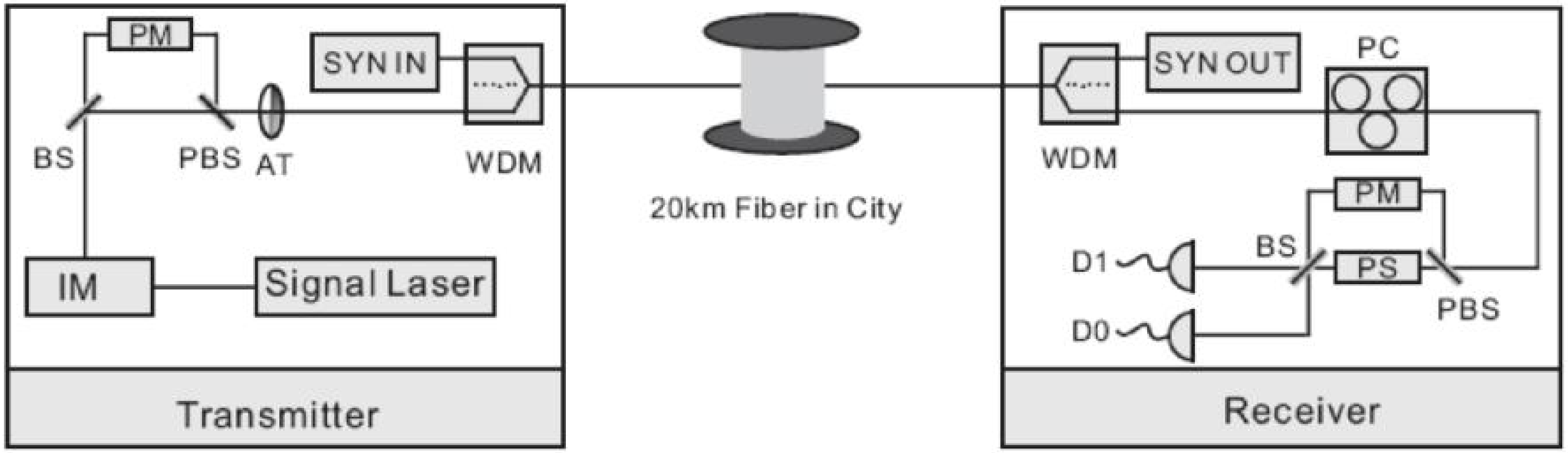
# Tokyo QKD Network视频会议演示



# 3节点光量子电话网络

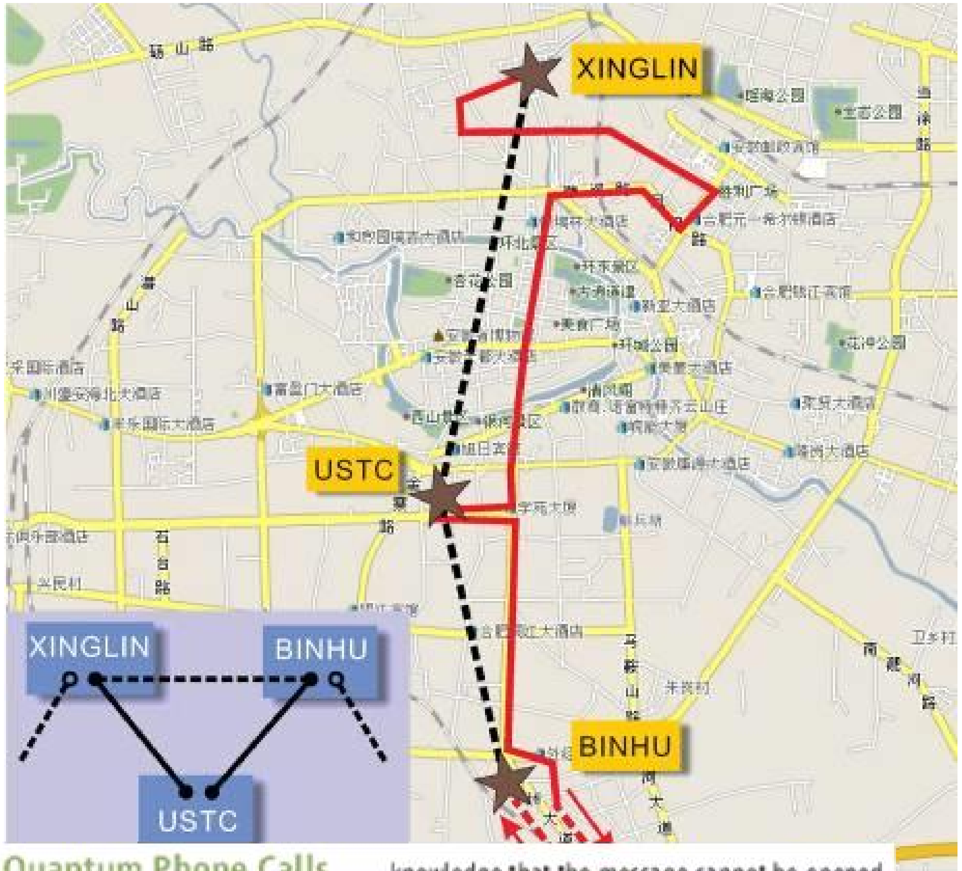
- 极化编码
- **4 MHz**
- **Decoy BB84**
- 可信中继架构
- 任意两节点通信距离**≥20 km**
- 信号和诱骗态脉冲: **1550nm;** 同步脉冲:**1310 nm** 使用**WDM**

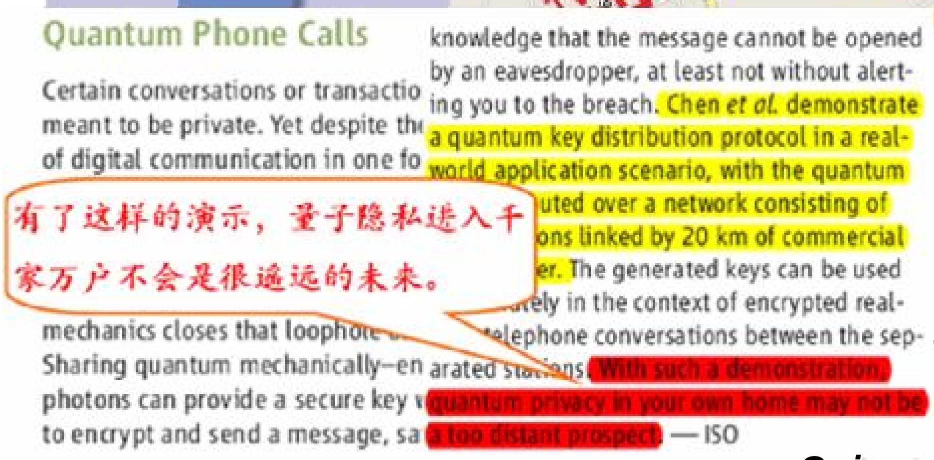
- 相位涨落的实时稳相
- 最终成码率**≥1.5kbps**
- 无条件安全，考虑了有限长度的密钥统计涨落。




T.-Y. Chen *et al.*, *Optics Express* Vol. 17, Iss. 8, pp. 6540–6549 (2009).

# 3节点光量子电话网络



Quantum Phone Calls

Certain conversations or transactio
meant to be private. Yet despite th
of digital communication in one fo
mechanics closes that loophole
Sharing quantum mechanically—en
photons can provide a secure key
to encrypt and send a message, sa

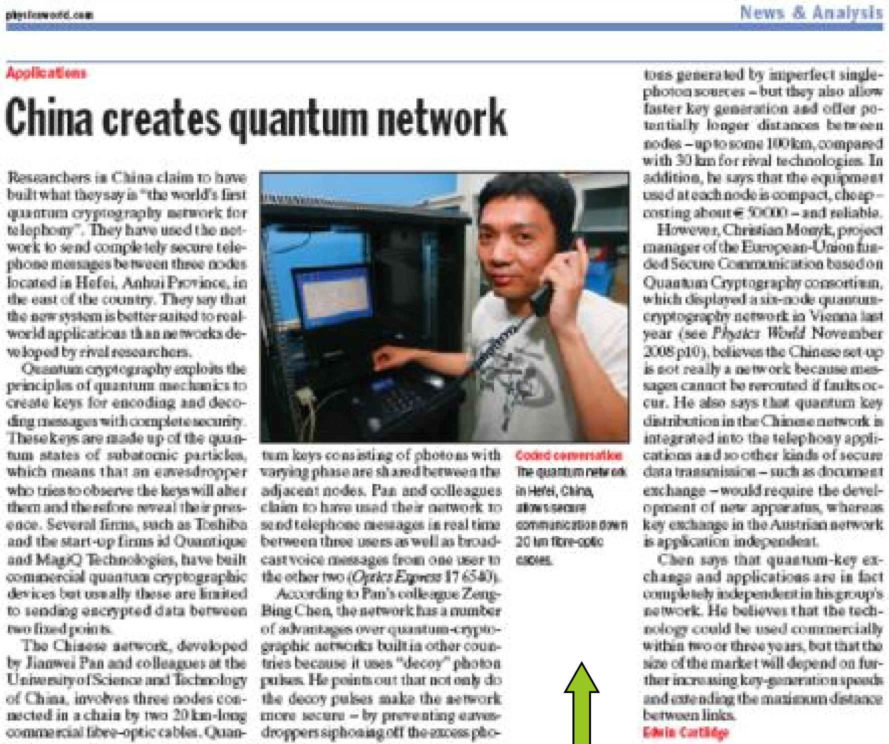
knowledge that the message cannot be opened by an eavesdropper, at least not without alerting you to the breach. Chen *et al.* demonstrate a quantum key distribution protocol in a real-world application scenario, with the quantum
uted over a network consisting of
ons linked by 20 km of commercial
er. The generated keys can be used
ely in the context of encrypted real-
elephone conversations between the separated stations. With such a demonstration, quantum privacy in your own home may not be a too distant prospect. — ISO

有了这样的演示，量子隐私进入千家万户不会是很遥远的未来。

*Science*的报道

中国科学技术大学 陈凯

- 任意两节点间的量子电话
- 任意节点对于另外两个节点的加密广播



physicsworld.com

News & Analysis

Applications

## China creates quantum network

Researchers in China claim to have built what they say is "the world's first quantum cryptography network for telephony". They have used the network to send completely secure telephone messages between three nodes located in Hefei, Anhui Province, in the east of the country. They say that the new system is better suited to real-world applications than networks developed by rival researchers.

Quantum cryptography exploits the principles of quantum mechanics to create keys for encoding and decoding messages with complete security. These keys are made up of the quantum states of subatomic particles, which means that an eavesdropper who tries to observe the keys will alter them and therefore reveal their presence. Several firms, such as Toshiba and the start-up firms id Quantique and MagiQ Technologies, have built commercial quantum cryptographic devices but usually these are limited to sending encrypted data between two fixed points.

The Chinese network, developed by Jianwei Pan and colleagues at the University of Science and Technology of China, involves three nodes connected in a chain by two 20 km-long commercial fibre-optic cables. Quantum keys consisting of photons with varying phase are shared between the adjacent nodes. Pan and colleagues claim to have used their network to send telephone messages in real time between three users as well as broadcast voice messages from one user to the other two (*Optics Express* 17 6540).

According to Pan's colleague Zeng-Bing Chen, the network has a number of advantages over quantum-cryptographic networks built in other countries because it uses "decoy" photon pulses. He points out that not only do the decoy pulses make the network more secure – by preventing eavesdroppers siphoning off the excess photons generated by imperfect single-photon sources – but they also allow faster key generation and offer potentially longer distances between nodes – up to some 100 km, compared with 30 km for rival technologies. In addition, he says that the equipment used at each node is compact, cheap – costing about €50000 – and reliable.

However, Christian Monyk, project manager of the European-Union-funded Secure Communication based on Quantum Cryptography consortium, which displayed a six-node quantum-cryptography network in Vienna last year (see *Physics World* November 2008 p10), believes the Chinese set-up is not really a network because messages cannot be rerouted if faults occur. He also says that quantum key distribution in the Chinese network is integrated into the telephony applications and so other kinds of secure data transmission – such as document exchange – would require the development of new apparatus, whereas key exchange in the Austrian network is application independent.

Chen says that quantum-key exchange and applications are in fact completely independent in his group's network. He believes that the technology could be used commercially within two or three years, but that the size of the market will depend on further increasing key-generation speeds and extending the maximum distance between links.

Edwin Cartlidge

Coded conversation
The quantum network in Hefei, China, allows secure communication down 20 km fibre-optic cables.

*Physics World*的报道

T.-Y. Chen *et al.*, *Optics Express* Vol. 17, Iss. 8, pp. 6540–6549 (2009).

# 5节点星型量子密钥分配网络系统

全通型量子通信网络

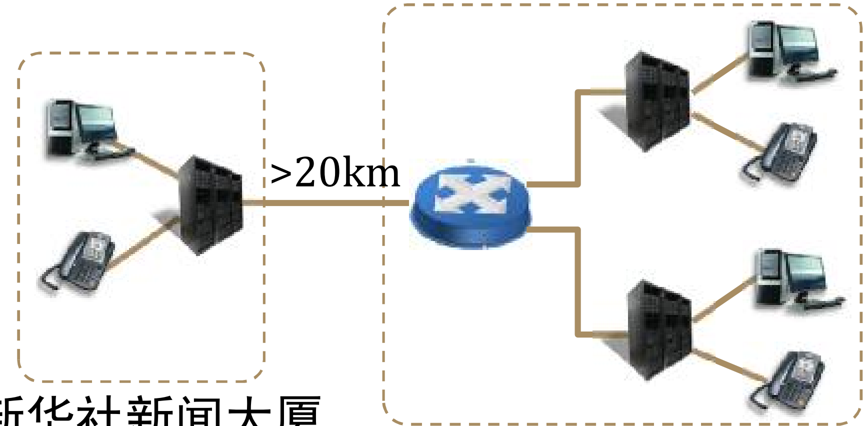

Chen *et al.*, Optics Express 18, 27217 (2010)

# 实用化城域量子通信网络


合肥全通型城域量子通信网络

Chen *et al.*, Opt. Express 17, 6540 (2009)

Chen *et al.*, Opt. Express 18, 27217 (2010)




新华社新闻大厦

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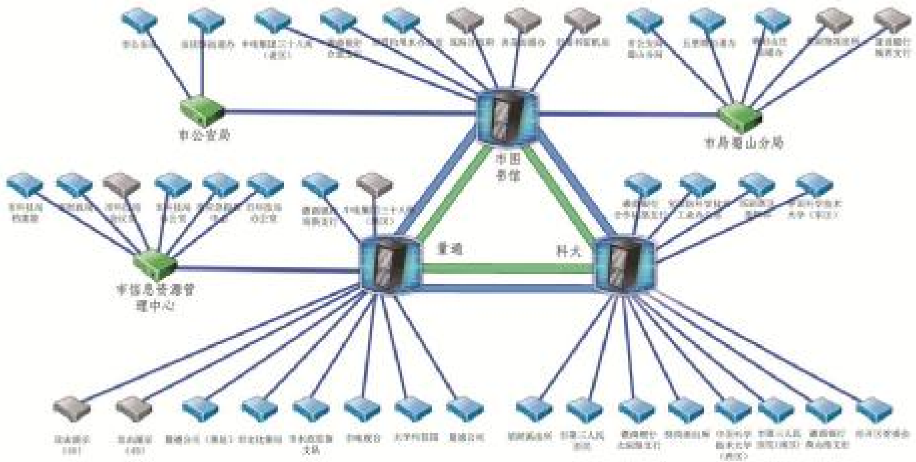
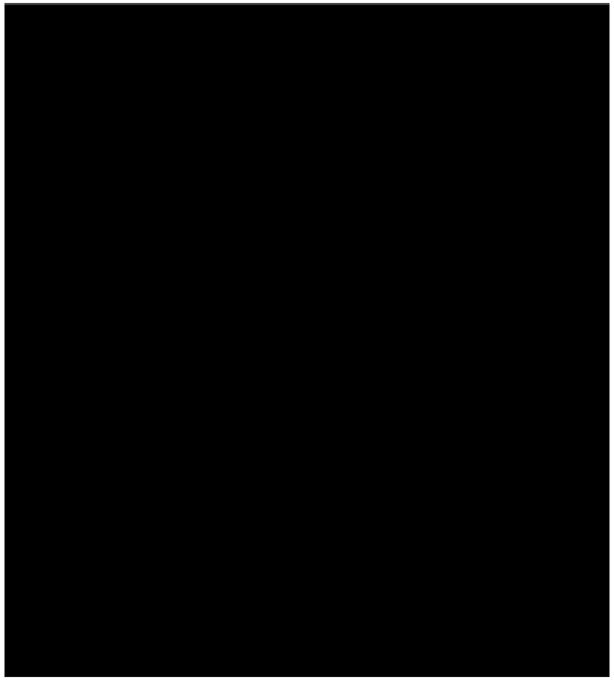
金融信息量子通信验证网(2012)




合肥城域量子通信试验示范网
(46个节点, 2012年)

# 系统集成



# 实用化城域量子通信网络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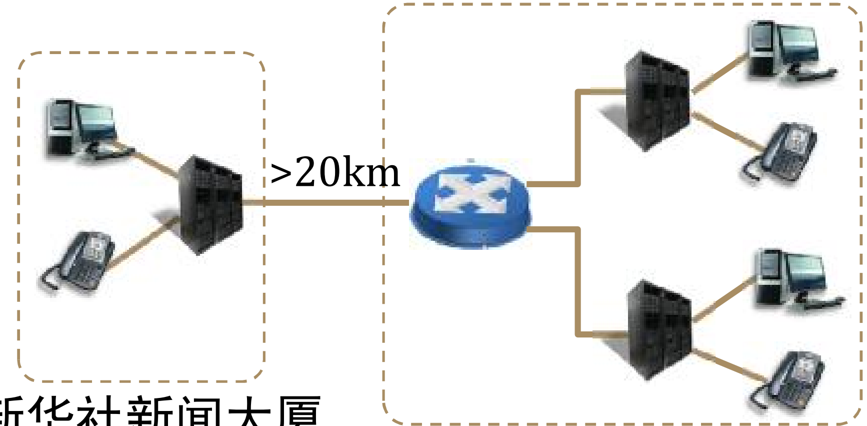


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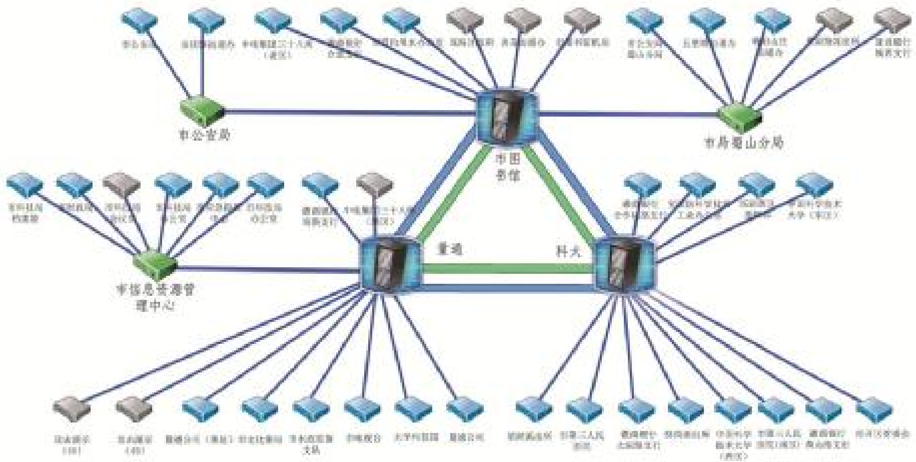
金融信息量子通信验证网(2012)



合肥城域量子通信试验示范网
(46个节点, 2012年)

# 第四章 量子通信

1. 保密通信
2. QKD基本原理
3. BB84协议过程
4. QKD安全性
5. 诱骗态(Decoy-state QKD)
   ① Decoy QKD原理
   ② 实用Decoy QKD
   ③ Decoy QKD实验
6. QKD的现实安全性
   ① 探测端的安全性 à MDI-QKD
   ② 设备无关的 à DI-QKD
7. 量子隐形传态(Quantum Teleportation) [原理、实验]
8. 量子纠缠交换(Entanglement Swapping)
9. 量子通信网络
10. **量子通信商用公司**
11. 量子通信发展与实用化QKD之路

# 商用QKD产品

MagiQ


id Quantique

# MagiQ

- 1999建立于美国， 目前设有Boston总部和纽约Office。
- 大致从2008年起建立了MagiQ Research Labs， 与US Army, DARPA, NASA以及与包括世界500强的多个公司进行联合研究。

MagiQ

MAGIQ QPN™ 8505

Army DARPA JTRS NASA Navy

# MagiQ


MagiQ
MagiQ QPN™
Ultimate Cryptography Solution for Network Security


DEFENSE
EXPLORE
TELECOMMUNICATIONS
EXPLORE
ENERGY EXPLORATION
EXPLORE
NETWORK SECURITY
MAGIQ QPN™
EXPLORE


U.S.ARMY
DARPA
NASA
Army
DARPA
JTRS
NASA
Navy

# MagiQ

## MagiQ QPN™: State of the Art Quantum Cryptography

MagiQ QPN is a market leading Quantum Cryptography solution that delivers advanced network security and fool-proof defense against the numerous cryptographic key distribution and management challenges.

Keys generated and disseminated using QPN quantum cryptography consist of truly random characters that are distributed based upon the laws of quantum mechanics, which guarantees that **keys cannot be intercepted during the key exchange session.** Therefore, MagiQ QPN provides security that will remain secure against future advances in algorithms, computational power, hardware design, and even quantum computing.

How It Works | Who Needs It? | Features & Benefits

Protecting **financial information** is one of the highest priorities of corporations and entities involved in financial management and securities exchange. With MagiQ QPN, financial organizations can secure their most critical communication links to prevent intrusion and data theft. MagiQ QPN supports a variety of network architectures and provides the cryptographic key exchange infrastructure to protect the information channels.

**Storage area networks** offer the promise of protecting corporate assets offsite by creating electronic copies of critical information for future retrieval. Encryption is used to protect the data link to the storage site (data in transit) and to protect the data at the site (data at rest). QPN guarantees high-security in storage area network applications to better meet customer security requirements now and for the future.

### Military and Government

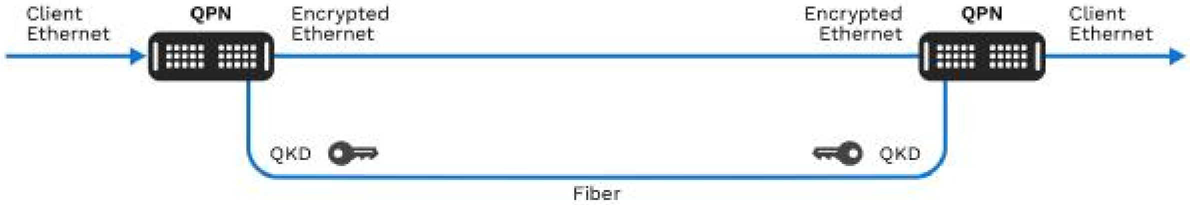
Hostile forces are a real and a continuous threat to government and military network security. QPN can safeguard against hackers and unwanted network security breaches by "trusted" insiders attempting to access highly-classified government and military information.

MagiQ QPN enables future-proof quantum security for other industries as well:

- R&D companies looking to protect trade secrets, intellectual properties, patents and business plans
- Voice and data service providers who need to secure confidential customer data and/or access to the network command channel
- Large Power Grid Providers open to terrorist or malicious hacking into the command and control channel interfaces

How it Works | Who Needs It? | Features & Benefits

The security of quantum cryptography lies in its ability to exchange the encryption keys with absolute security – Quantum Key Distribution. By sending the key bits encoded at the single photon level on a photon-by-photon basis, quantum mechanics guarantees that the act of an eavesdropper observing a photon irretrievably changes the information encoded on that photon. Therefore, the eavesdropper can neither copy nor clone, nor read the information encoded on the photon without modifying it; eavesdropping is instantly detected making this key exchange uncompromisingly secure.



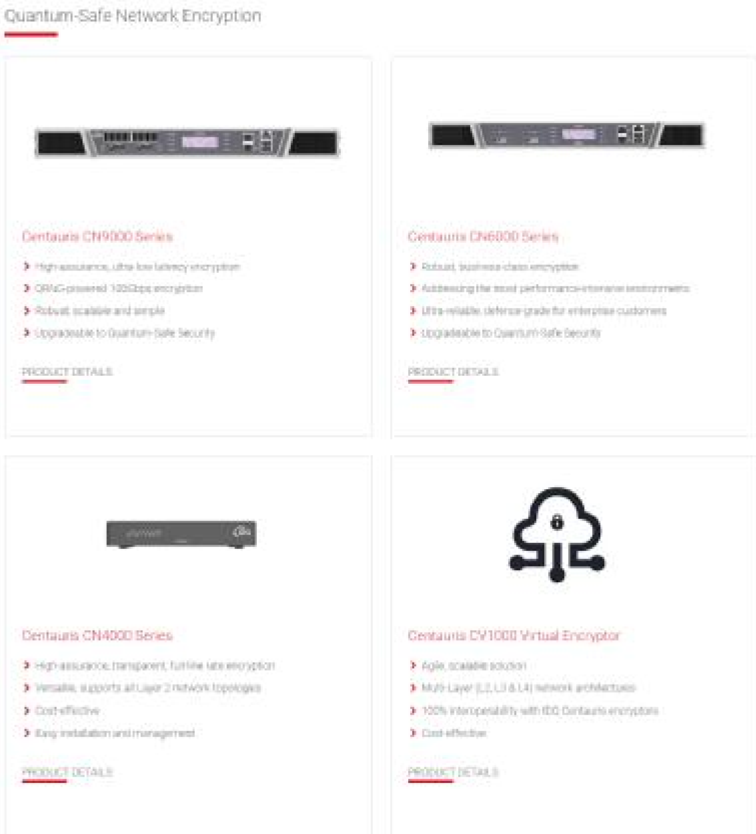

QPN implements the BB84 protocol, invented by Bennet and Brassard in 1984. This protocol assumes that the sender and recipient share an optical link (fiber) and a classical (non-quantum) unsecured communication channel, for example, a standard internet link.

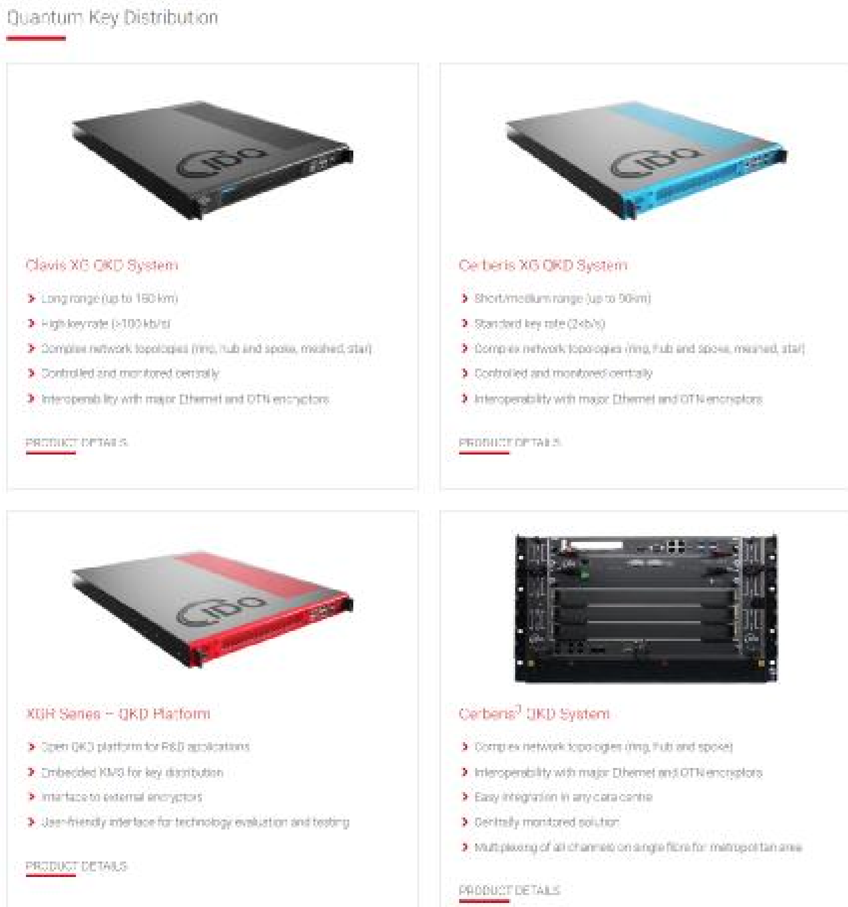
QPN sends photons over the fiber to create the secure keys between two QPN stations. A photon is an elementary light particle that has measurable properties, like polarization, which can be 'up' or 'down'. These can be used to encode and transmit a value of a bit from one QPN station to the other. The transmitting QPN station uses a truly random number generator to come up with the value of the bit encoded on the photon.

The security of the BB84 protocol is based on the fundamental Heisenberg Uncertainty Principle, that states that observing a photon (eavesdropping) does change its properties, i.e., in the presence of eavesdropping, the values of the received bits will differ from the values of the bits sent. This fundamental principal eliminates the ability of any eavesdropper to hide his/her 'footprints on the photon.

# ID Quantique 产品

- id Quantique (IDQ) 在2001年建于Geneva
- 公司产品
  - Centauris Layer 2 Encryptors: High speed multi-protocol encryptors
  - Cerberis: A fast and secure solution of high speed encryption combined with quantum key distribution。典型的基于AES应用
  - Clavis$^2$:  QKD for R&D Applications
  - 探测器，随机数发生器，短脉冲激光源等

# ID Quantique

## 2010 FIFA 世界杯

Durban, South Africa – The first use of ultra secure quantum encryption at a world public event，基于AES 256

## 2019 SK Telecom Continues to Protect its 5G Network with Quantum Cryptography Technologies


**SK Telecom Continues to Protect its 5G Network with Quantum Cryptography Technologies**

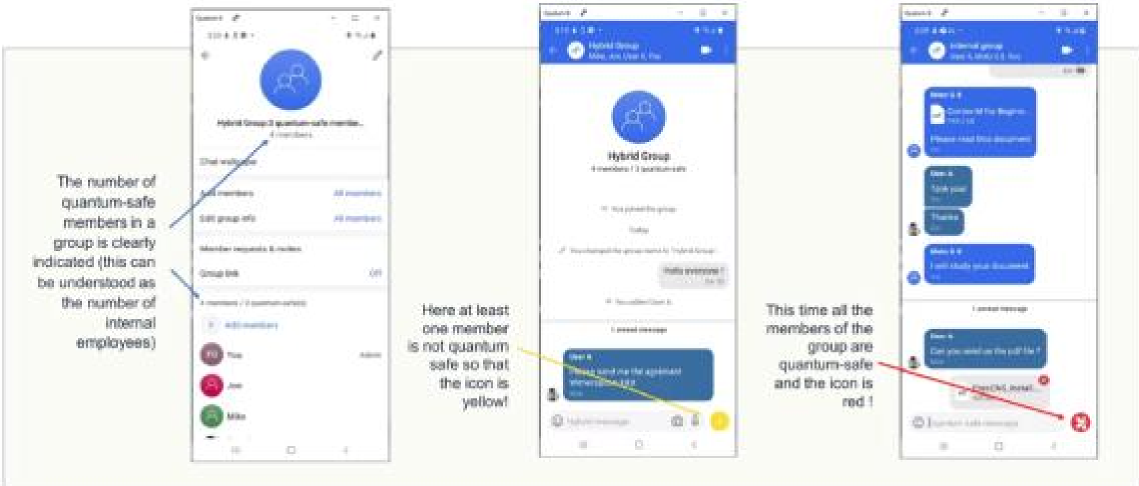
- SK Telecom applied Quantum Random Number Generator (QRNG) to the subscriber authentication center of its 5G network

- SK Telecom plans to apply Quantum Key Distribution (QKD) technology to the Seoul-Daejeon section of its LTE and 5G networks to prevent hacking and eavesdropping

- SK Telecom is playing a pivotal role in global standardization of QKD and QRNG technologies at ITU-T.

# ID Quantique

Quantique and CryptoNext partner to deliver next-gen, quantum-safe messaging




The solution aims at enabling governments, enterprises and organizations of all types to manage sensitive communications for specific groups of people, such as executive teams, and/or specific projects.


## Telefonica, Fortinet & IDQ demonstrate the first Quantum-Safe IPVPN connection suitable for managed datacentre interconnect

7th October 2021

Telefonica, Fortinet and IDQ have jointly demonstrated the first Quantum-Safe IPVPN connection suitable for offering a fully managed datacenter interconnection service.

DISCOVER MORE

# 量子通信产业化


我们的征程是星辰大海
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新闻中心
人才招聘
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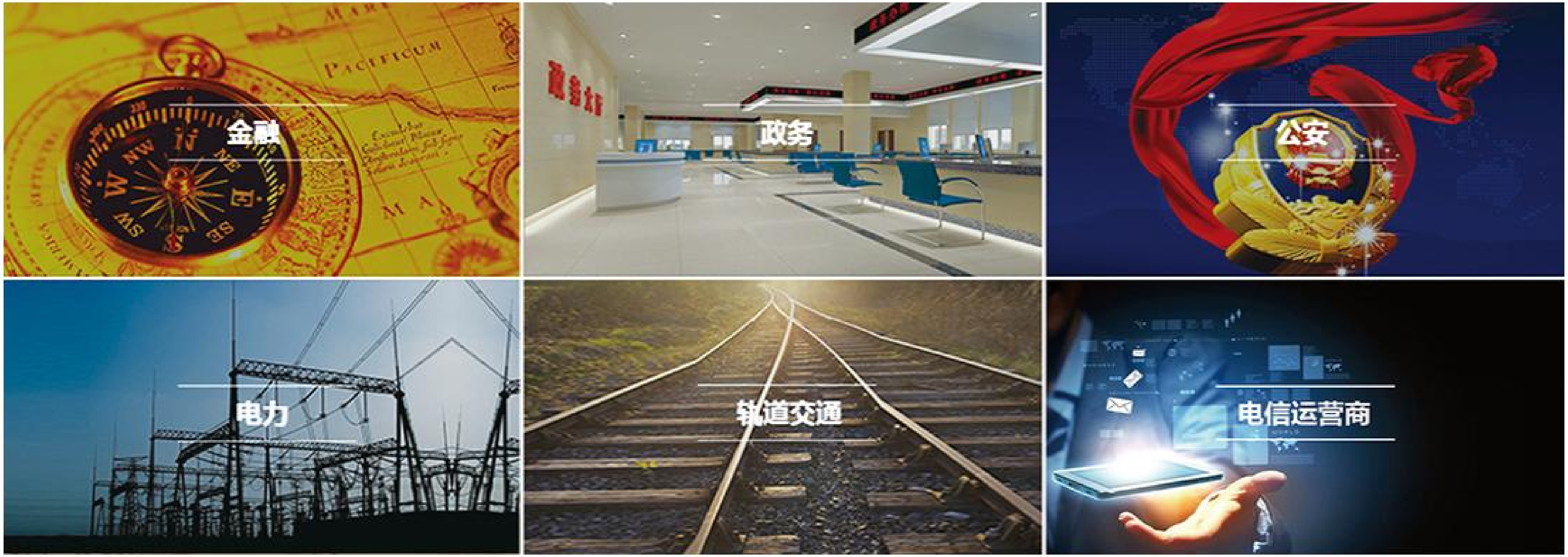
专业从事量子信息安全服务

# 科大国盾量子技术股份有限公司

# （QuantumCTek Co., Ltd.）

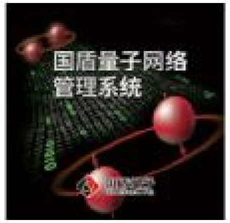



# 科大国盾量子技术股份有限公司
# （QuantumCTek Co., Ltd.）

量子保密通信网络核心设备

量子安全应用产品


管控软件




核心组件

科学与科研仪器

大容量商用化超长距量子共纤传输应用

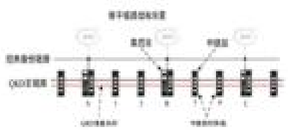
北京农商银行城域环网量子技术应用

交通银行企业网银用例建设

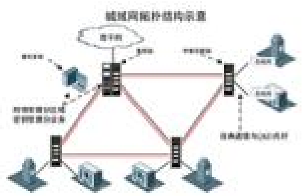
网商银行云上量子加密通信案例


工商银行异地数据千公里级量子加密传输应用

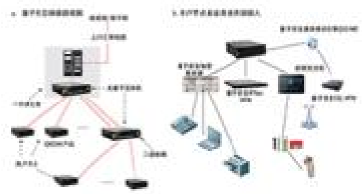

骨干网应用



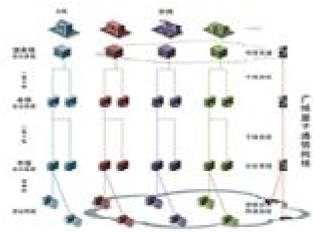
城域网应用



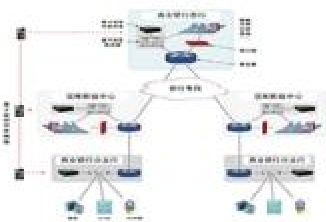
局域网应用



政务应用



金融应用



# 国盾量子


QuantumCTek
用量子技术保护每一个比特
Quantum Secures Every Bit
开拓者 实践者 引领者


国盾量子
QuantumCTek
股票简称：国盾量子
股票代码：688027
不忘初心 光量未来
科大国盾量子技术股份有限公司首次公开发行股票并在科创板上市仪式
保荐机构（主承销商）：国元证券股份有限公司
二〇二〇年七月九日

# 科大国盾量子技术股份有限公司


### 量子安全加密路由器

量子安全加密路由器是结合量子保密通信技术与经典通信技术的高保密量子安全产品。该产品采用量子保密通信技术，结合设计理念和模块化可扩展的平台，凭借"安全可靠、性能强劲、一机多能、弹性扩展、轻松易维、绿色节能"六大特性，满足用户当前和未来各种业务部署的需求，为实现信息高安全传送提供智能而有弹性的设备平台。


### 国盾安全手机A2021H

关键特性
- 量子密钥级安全保护
- 自主安全操作系统
- 方便易用
- 5G先锋
- AI智能系统引擎

典型应用
- 移动办公/作业
- 移动电子政务
- 物联网
- 移动支付

中国科学技术大学 陈凯


### 量子安全SSL VPN

量子安全SSL VPN产品是结合量子保密通信技术与SSL VPN技术的一款高保密量子安全产品，该产品为科大国盾量子携手深信服科技推出的量子安全SSL VPN产品，具备量子密钥保护、全面安全、快速接入等特性。


ez-Q™ Engine超导量子计算操控系统

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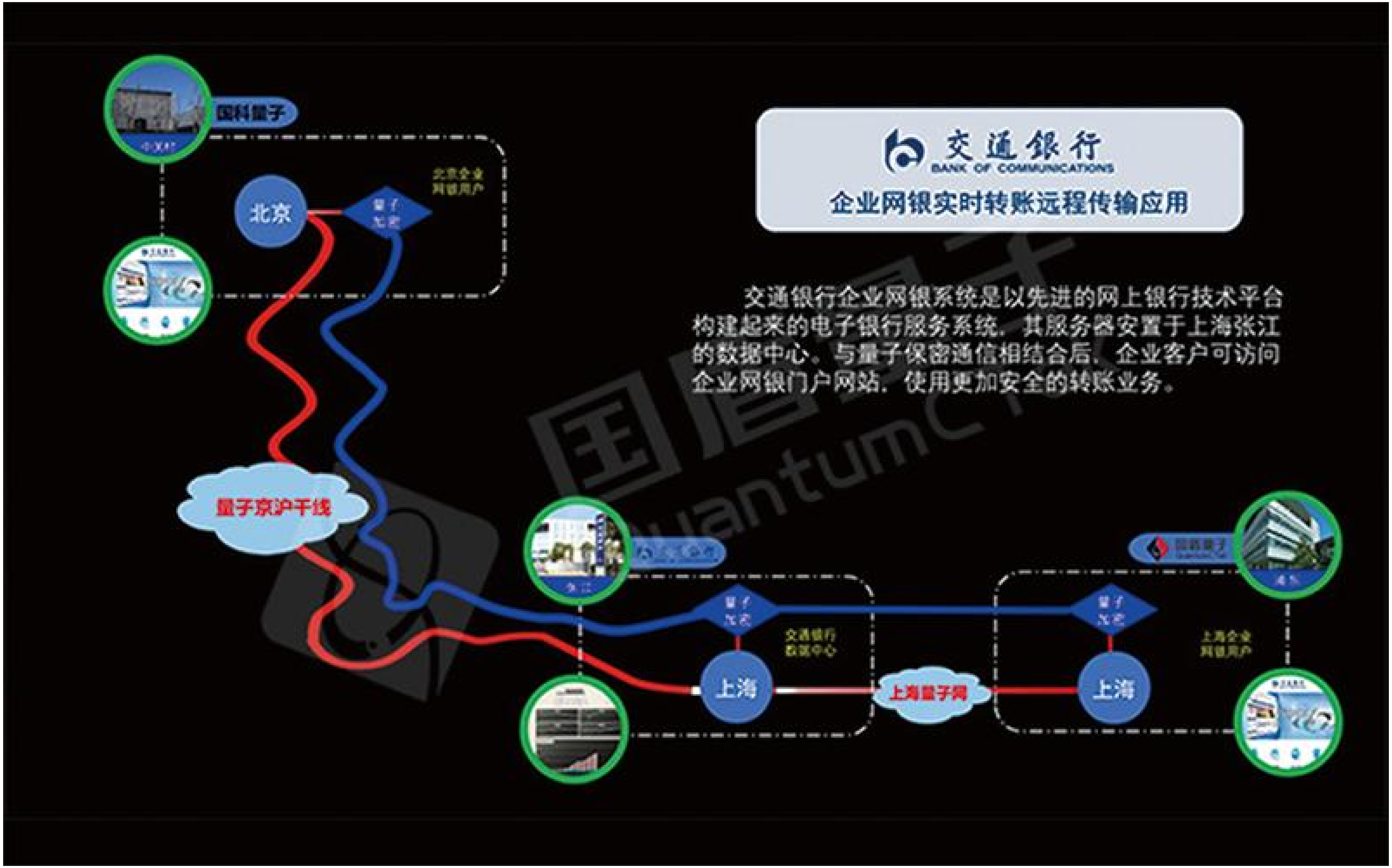
# 科大国盾量子技术股份有限公司

# （QuantumCTek Co., Ltd.）

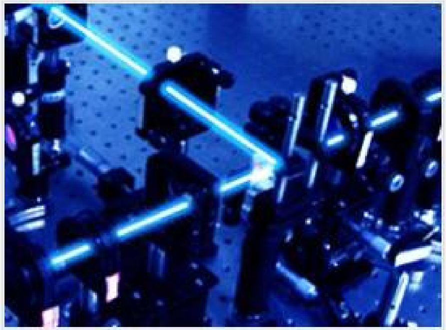


# 安徽问天量子科技股份有限公司




量子密钥分配终端

量子密码通信应用设备



量子密钥分配实验系统

激光器

中国科学技术大学 陈凯

# 第四章 量子通信

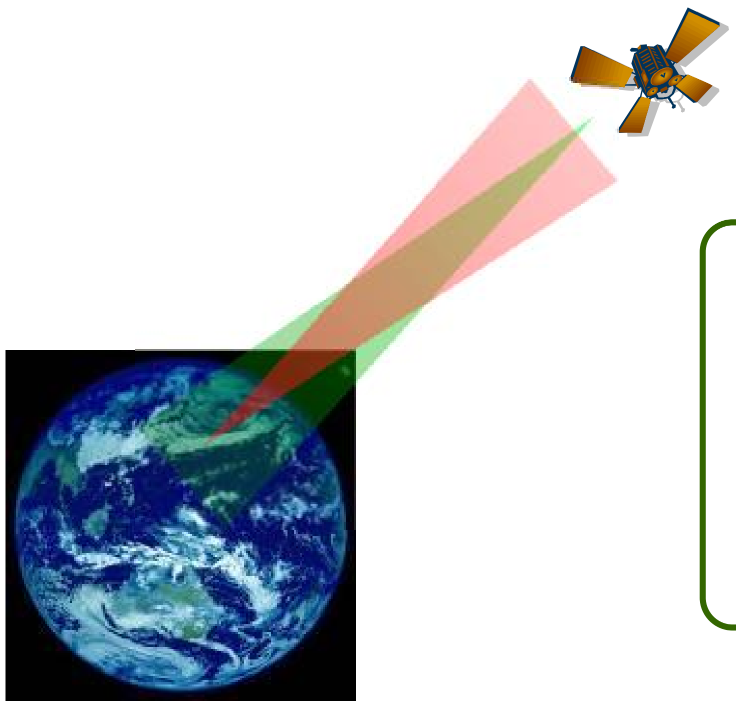
1. 保密通信
2. QKD基本原理
3. BB84协议过程
4. QKD安全性
5. 诱骗态(Decoy-state QKD)
   ① Decoy QKD原理
   ② 实用Decoy QKD
   ③ Decoy QKD实验
6. QKD的现实安全性
   ① 探测端的安全性 à MDI-QKD
   ② 设备无关的 à DI-QKD
7. 量子隐形传态(Quantum Teleportation) [原理、实验]
8. 量子纠缠交换(Entanglement Swapping)
9. 量子通信网络
10. 量子通信商用公司
11. **量子通信发展与实用化QKD之路**

# 量子通信的发展

地面量子通信实验在几百公里以上存在技术障碍

光纤量子信道 —— 最小损耗：0.2dB/km ——→ 空间量子通信

地面自由空间信道 —— 地球曲率和大气衰减 ——→

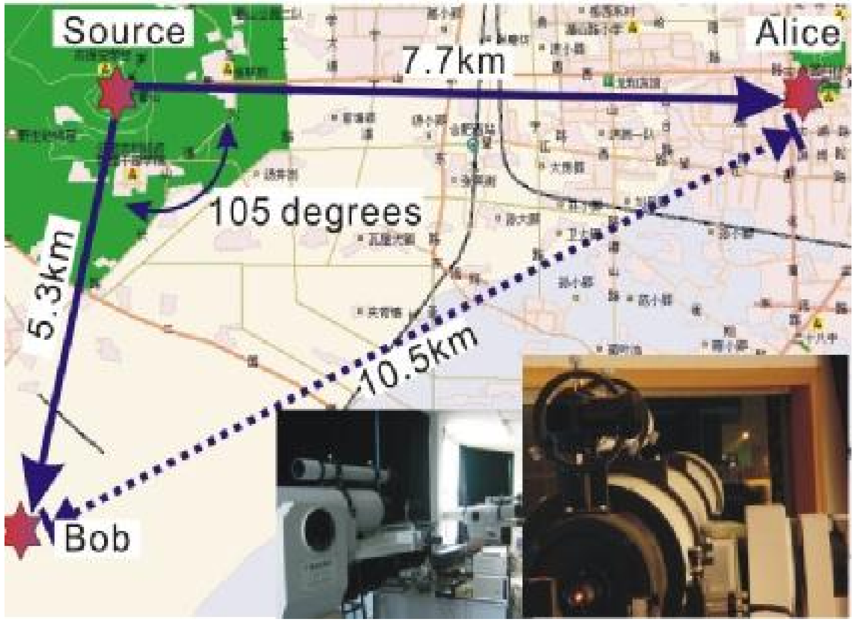


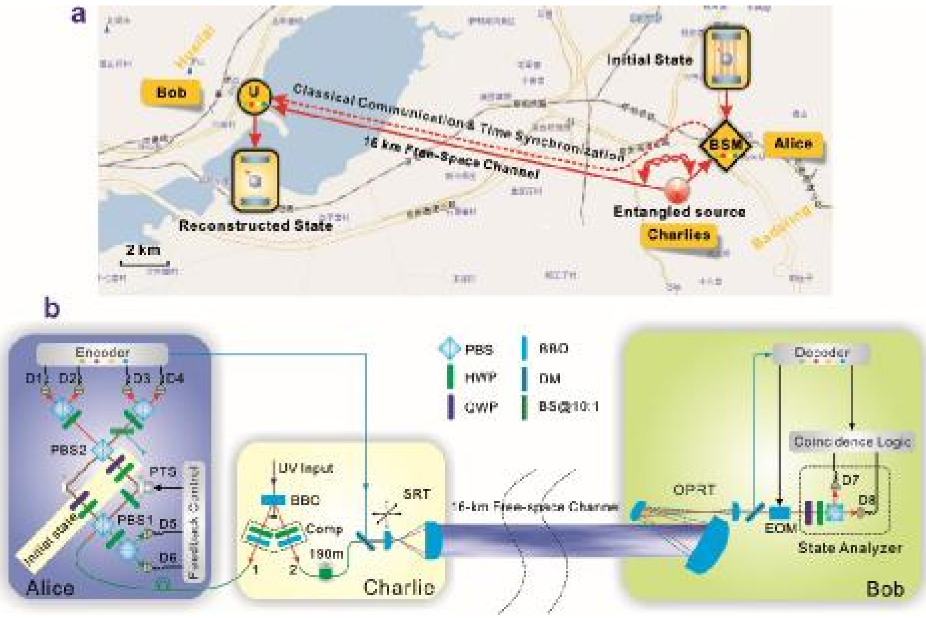
1、全球量子密钥分发网络

2. 在空间大尺度下的量子通信实现

# Free-Space Quantum Communication

Phase 1: Test the possibility of single photon and entangled photons passing through atmosphere




- Free-space quantum entanglement distribution ~13km
  Peng *et al.*, PRL 94, 150501 (2005)

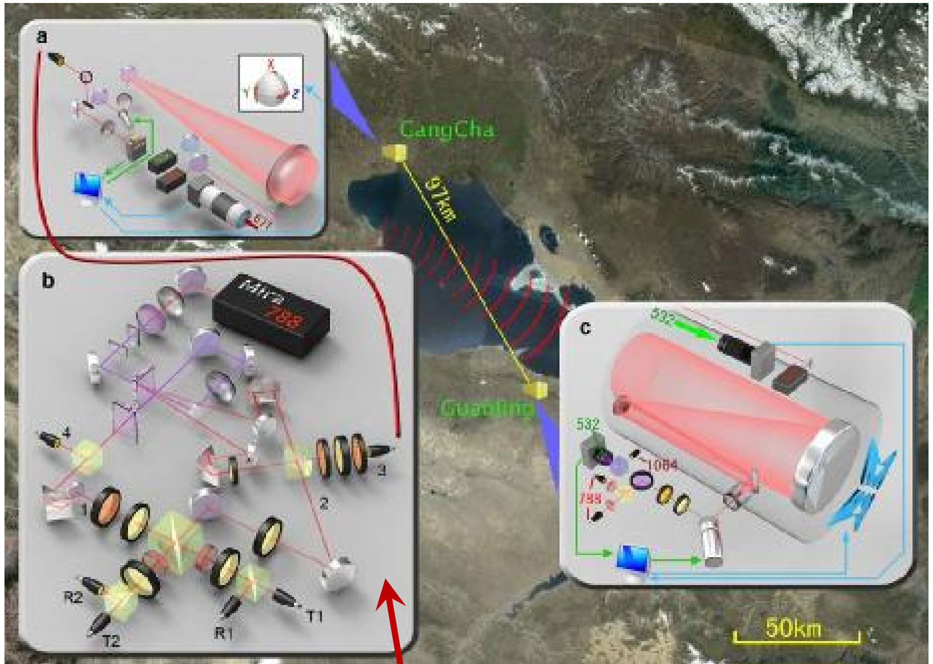
- Free-space quantum teleportation (16km)
  - Scheme: Boschi *et al.*, PRL 80, 1121(1998)
  - Experiment: Jin *et al.*, Nature Photonics 4, 376 (2010)

*Well beyond the effective thickness of the aerosphere!*

# Free-Space Quantum Communication

Phase 2: Test the feasibility of quantum communication via high-loss ground-to-satellite channel

- Free-Space Quantum Teleportation (97km)




| State | Fidelity |
|---|---|
| $H$ | 0.814±0.031 |
| $V$ | 0.886±0.024 |
| $+$ | 0.773±0.031 |
| $-$ | 0.781±0.031 |
| $R$ | 0.808±0.026 |
| $L$ | 0.760±0.027 |

Four-photon quantum teleportation experiment

- Entanglement source: 450000/s
- Four-photon coincidence rate: 1500/s

high-brightness entangled photon source technology used in our 8-photon entanglement experiment

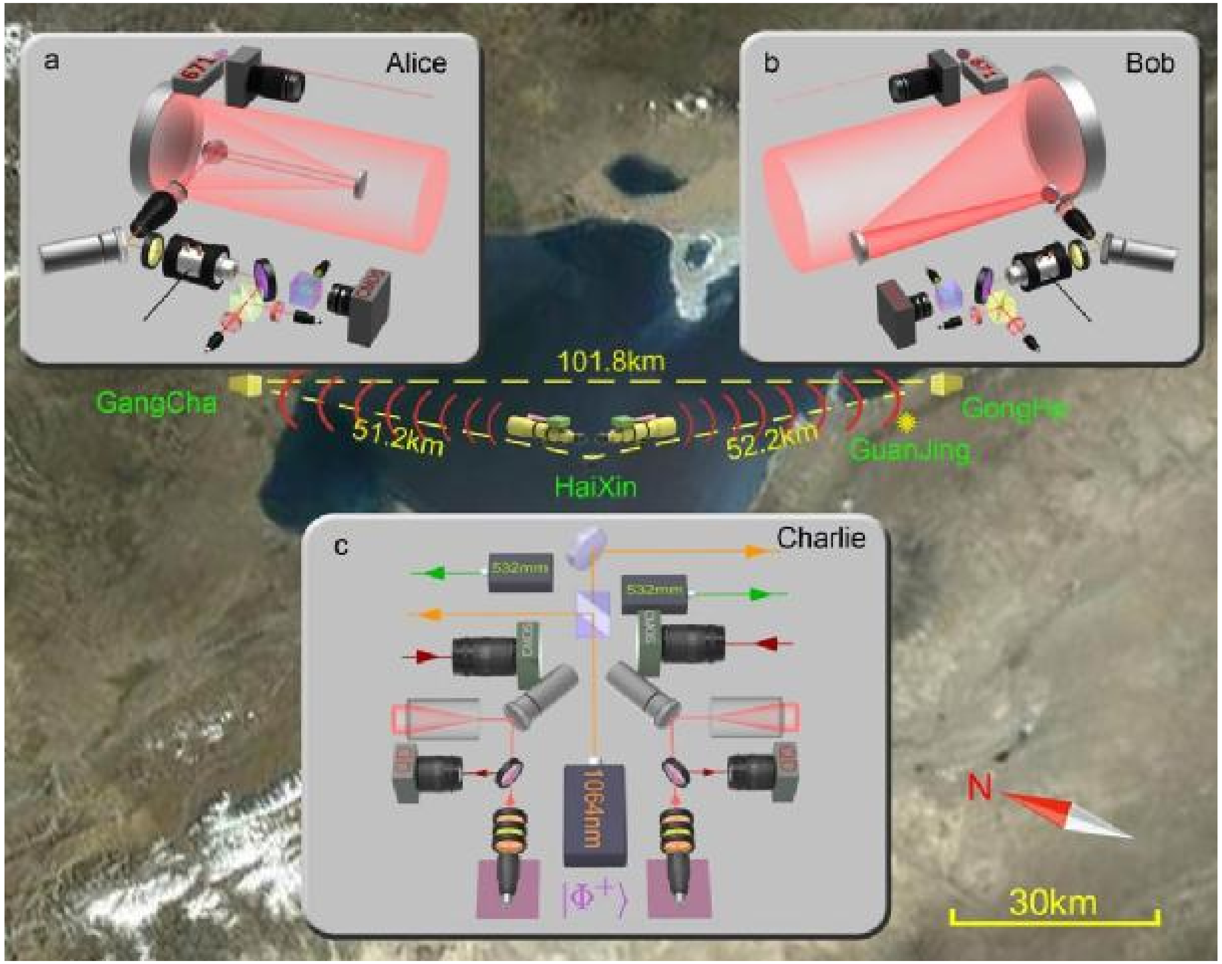
Channel loss: 35-53dB

V. S.

Loss for an uplink of ground to satellite: 45dB

# Free-Space Quantum Communication

- and Free-space quantum entanglement distribution (over 100km)
  Yin *et al.*, **Nature** 488, 185 (2012)




Violation of CHSH inequality:

2.51±0.21

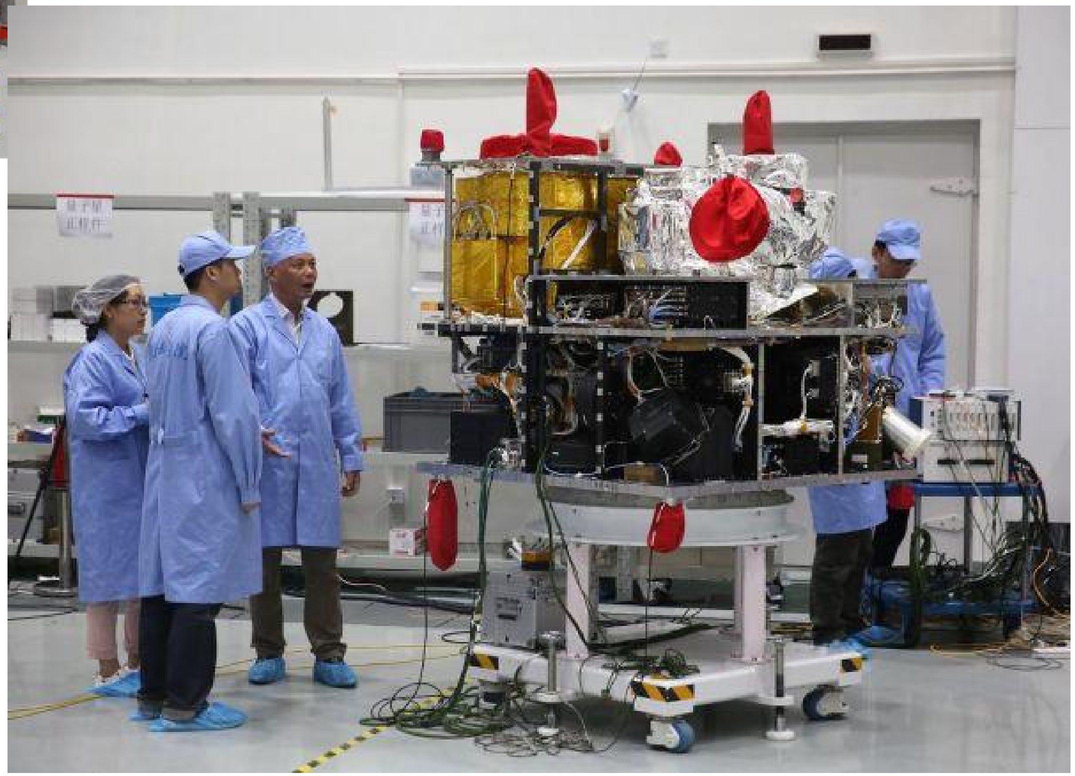
Channel loss:
66-85dB

V. S.

Loss for two-downlink between satellite and two ground stations: 75dB

# 世界首颗量子卫星



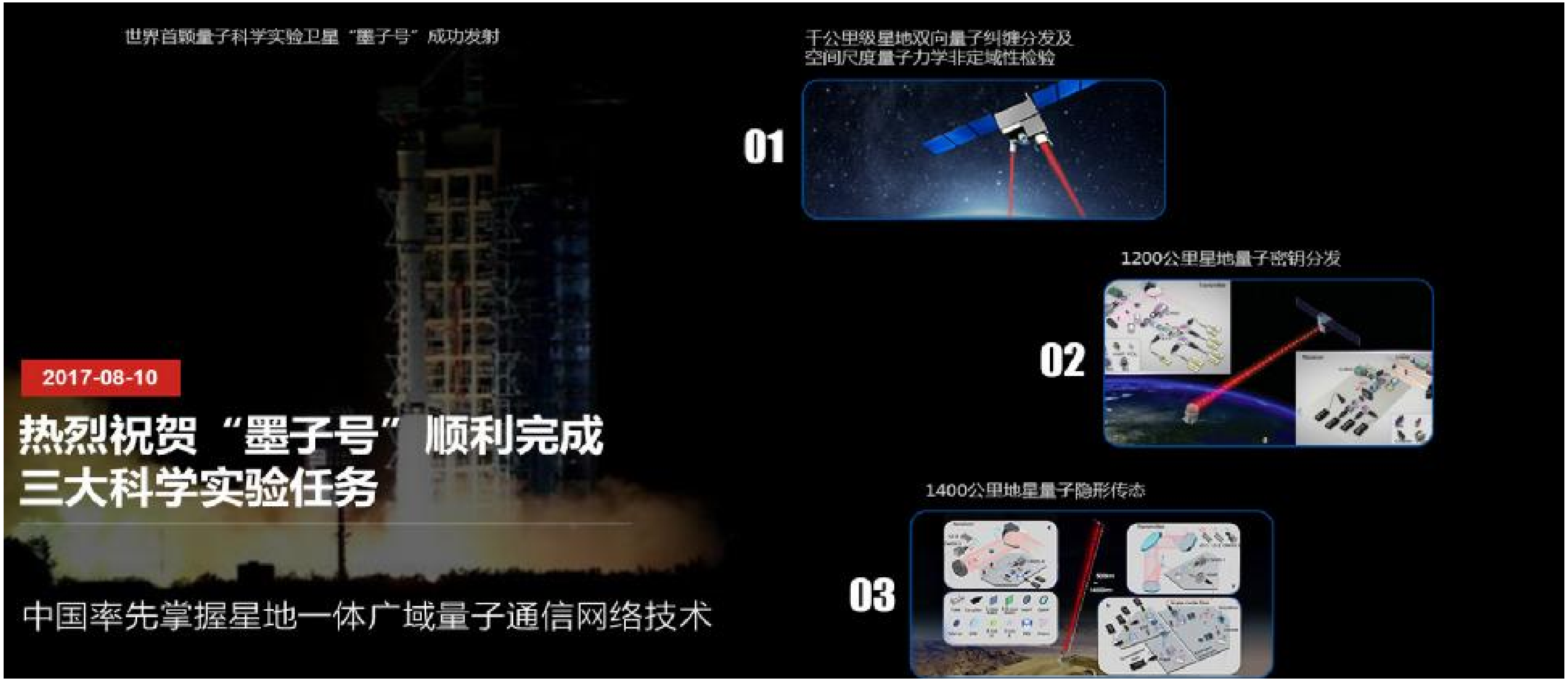


# “墨子号”量子卫星与地面站通信试验照片公布



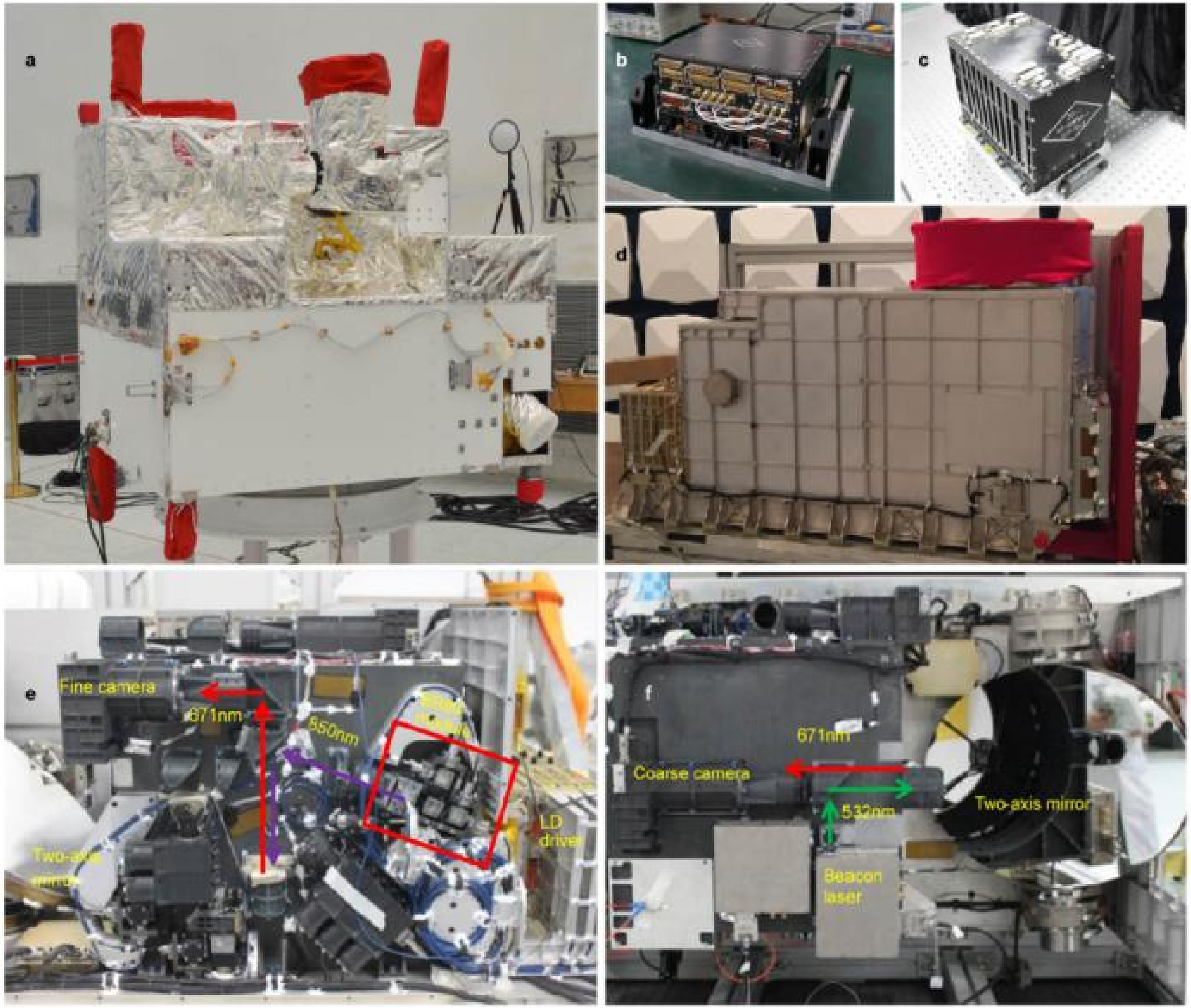
中国科学技术大学 陈凯

# “墨子号”量子卫星与地面站量子通信



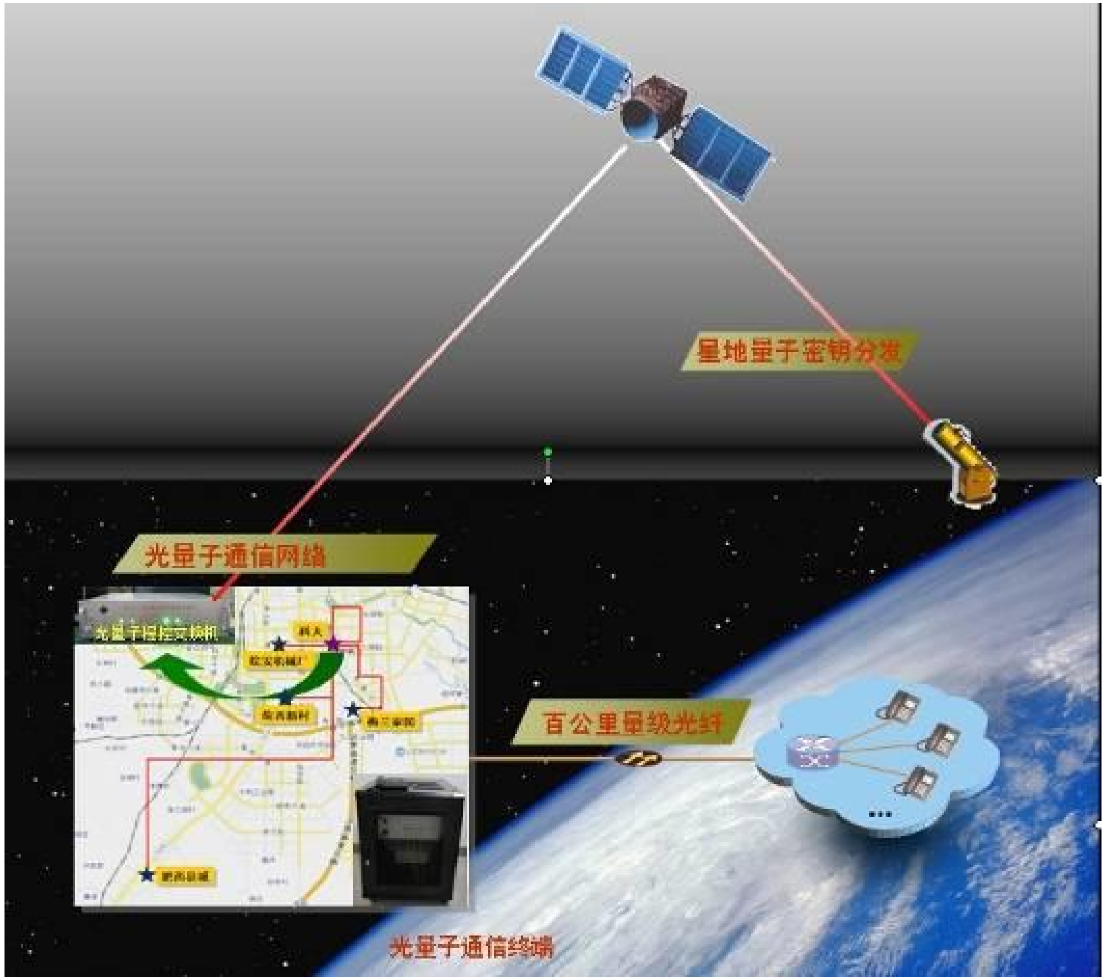

摘自国盾量子新闻

# “墨子号”量子卫星与地面站装置图




Extended Data Figure 2 | The Micius satellite and the payloads. a, A full view of the Micius satellite before being assembled into the rocket. b, The experimental control box. c, The APT control box. d, The optical transmitter. e, Left side view of the optical transmitter optics head. f, Top side view of the optical transmitter optics head.

# 广域量子通信




城域量子通信网络的规模化＋
可信中继和量子中继器的城际量子网络＋
星地量子通信

→ 广域量子通信网络

# 实用化QKD之路

TABLE I. List of quantum hacking strategies.

| Attack | Source or detection | Target component | Manner | Year |
|---|---|---|---|---|
| Photon number splitting (Brassard et al., 2000; Lütkenhaus, 2000) | Source | WCP (multiphotons) | Theory | 2000 |
| Detector fluorescence (Kurtsiefer et al., 2001) | Detection | Detector | Theory | 2001 |
| Faked state (Makarov and Hjelme, 2005; Makarov, Anisimov, and Skaar, 2006) | Detection | Detector | Theory | 2005 |
| Trojan horse (Vakhitov, Makarov, and Hjelme, 2001; Gisin et al., 2006) | Source and detection | Backreflection light | Theory | 2006 |
| Time shift (Qi, Fung et al., 2007; Zhao et al., 2008) | Detection | Detector | Experiment[a] | 2007 |
| Time side channel (Lamas-Linares and Kurtsiefer, 2007) | Detection | Timing information | Experiment | 2007 |
| Phase remapping (Fung et al., 2007; Xu, Qi, and Lo, 2010) | Source | Phase modulator | Experiment[a] | 2010 |
| Detector blinding (Makarov, 2009; Lydersen et al., 2010) | Detection | Detector | Experiment[a] | 2010 |
| Detector blinding (Gerhardt et al., 2011a; Gerhardt et al., 2011b) | Detection | Detector | Experiment | 2011 |
| Detector control (Lydersen, Akhlaghi et al., 2011; Wiechers et al., 2011) | Detection | Detector | Experiment | 2011 |
| Faraday mirror (Sun, Jiang, and Liang, 2011) | Source | Faraday mirror | Theory | 2011 |
| Wavelength (Li et al., 2011; Huang et al., 2013) | Detection | Beam splitter | Experiment | 2011 |
| Dead time (Henning et al., 2011) | Detection | Detector | Experiment | 2011 |
| Channel calibration (Jain et al., 2011) | Detection | Detector | Experiment[a] | 2011 |
| Intensity (Jiang et al., 2012; Sajeed, Radchenko et al., 2015) | Source | Intensity modulator | Experiment | 2012 |
| Phase information (Sun et al., 2012, 2015; Tang et al., 2013) | Source | Phase randomization | Experiment | 2012 |
| Memory attacks (Barrett, Colbeck, and Kent, 2013) | Detection | Classical memory | Theory | 2013 |
| Local oscillator (Jouguet, Kunz-Jacques, and Diamanti, 2013; Ma et al., 2013a)[b] | Detection | Local oscillator | Experiment | 2013 |
| Trojan horse (Jain et al., 2014, 2015) | Source and detection | Backreflection light | Experiment | 2014 |
| Laser damage (Bugge et al., 2014; Makarov et al., 2016) | Detection | Detector | Experiment | 2014 |
| Laser seeding (Sun et al., 2015) | Source | Laser phase or intensity | Experiment | 2015 |
| Spatial mismatch (Sajeed, Chaiwongkhot et al., 2015; Chaiwongkhot et al., 2019) | Detection | Detector | Experiment | 2015 |
| Detector saturation (Qin, Kumar, and Alléaume, 2016)[b] | Detection | Homodyne detector | Experiment | 2016 |
| Covert channels (Curty and Lo, 2019) | Detection | Classical memory | Theory | 2017 |
| Pattern effect (Yoshino et al., 2018) | Source | Intensity modulator | Experiment | 2018 |
| Detector control (Qian et al., 2018) | Detection | Detector | Experiment | 2018 |
| Laser seeding (Sun et al., 2015; Huang et al., 2019; Pang et al., 2019) | Source | Laser | Experiment | 2019 |
| Polarization shift (Wei, Zhang et al., 2019) | Detection | SNSPD | Experiment | 2019 |

[a]Demonstration on a commercial QKD system.
[b]Continuous-variable QKD.

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**Feihu Xu *et al.*, Secure quantum key distribution with realistic devices**
***Rev. Mod. Phys.* 92, 025002 (2020).**

# 实用化QKD之路

TABLE II. List of decoy-state QKD experiments and their performance.

| Reference | Clock rate | Encoding | Channel | Maximal distance | Key rate (bits/s) | Year |
|---|---|---|---|---|---|---|
| Zhao *et al.* (2006a, 2006b) | 5 MHz | Phase | Fiber | 60 km | 422.5 | 2006 |
| Peng *et al.* (2007) | 2.5 MHz | Polarization | Fiber | 102 km | 8.1 | 2007 |
| Rosenberg *et al.* (2007) | 2.5 MHz | Phase | Fiber | 107 km | 14.5 | 2007 |
| Schmitt-Manderbach *et al.* (2007) | 10 MHz | Polarization | Free space | 144 km | 12.8[a] | 2007 |
| Yuan, Sharpe, and Shields (2007) | 7.1 MHz | Phase | Fiber | 25.3 km | 5.5 K | 2007 |
| Yin *et al.* (2008) | 1 MHz | Phase | Fiber | 123.6 km | 1.0 | 2008 |
| Wang *et al.* (2008)[b] | 0.65 MHz | Phase | Fiber | 25 km | 0.9 | 2008 |
| Dixon *et al.* (2008) | 1 GHz | Phase | Fiber | 100.8 km | 10.1 K | 2008 |
| Peev *et al.* (2009) | 7 MHz | Phase | Fiber network | 33 km | 3.1 K | 2009 |
| Rosenberg *et al.* (2009) | 10 MHz | Phase | Fiber | 135 km | 0.2 | 2009 |
| Yuan *et al.* (2009) | 1.036 GHz | Phase | Fiber | 100 km | 10.1 K | 2009 |
| Chen *et al.* (2009) | 4 MHz | Phase | Fiber network | 20 km | 1.5 K | 2009 |
| Liu *et al.* (2010) | 320 MHz | Polarization | Fiber | 200 km | 15.0 | 2010 |
| Chen *et al.* (2010) | 320 MHz | Polarization | Fiber network | 130 km | 0.2 K | 2010 |
| Sasaki *et al.* (2011) | 1 GHz | Phase | Fiber network | 45 km | 304.0 K | 2011 |
| Wang *et al.* (2013) | 100 MHz | Polarization | Free space | 96 km | 48.0 | 2013 |
| Fröhlich *et al.* (2013) | 125 MHz | Phase | Fiber network | 19.9 km | 43.1 K | 2013 |
| Lucamarini *et al.* (2013) | 1 GHz | Phase | Fiber | 80 km | 120.0 K | 2013 |
| Fröhlich *et al.* (2017) | 1 GHz | Phase | Fiber | 240 km[c] | 8.4 | 2017 |
| Liao *et al.* (2017a) | 100 MHz | Polarization | Free space | 1200 km | 1.1 K | 2017 |
| Yuan *et al.* (2018) | 1 GHz | Phase | Fiber | 2 dB | 13.7 M | 2018 |
| Boaron *et al.* (2018) | 2.5 GHz | Time bin | Fiber | 421 km[c] | 6.5 | 2018 |

[a]Asymptotic key rate.
[b]Heralded single-photon source.
[c]Ultra-low-loss fiber.



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TABLE III. List of MDI-QKD experiments and their performance.

| Reference | Clock rate | Encoding | Distance or loss | Key rate (bits/s) | Year | Notes |
|---|---|---|---|---|---|---|
| Rubenok *et al.* (2013)[a] | 2 MHz | Time bin | 81.6 km | 0.24[b] | 2013 | Field-installed fiber |
| Liu *et al.* (2013) | 1 MHz | Time bin | 50 km | 0.12 | 2013 | First complete demonstration |
| Ferreira da Silva *et al.* (2013)[a] | 1 MHz | Polarization | 17 km | 1.04[b] | 2013 | Multiplexed synchronization |
| Z. Tang *et al.* (2014) | 0.5 MHz | Polarization | 10 km | $4.7 \times 10^{-3}$ | 2014 | Active phase randomization |
| Y.-L. Tang *et al.* (2014) | 75 MHz | Time bin | 200 km | 0.02 | 2014 | Fully automatic system |
| Tang *et al.* (2015) | 75 MHz | Time bin | 30 km | 16.9 | 2015 | Field-installed fiber |
| C. Wang *et al.* (2015) | 1 MHz | Time bin | 20 km | 8.3[b] | 2015 | Phase reference free |
| Valivarthi *et al.* (2015) | 250 MHz | Time bin | 60 dB | $5 \times 10^{-2}$ | 2015 | Test in various configurations |
| Pirandola *et al.* (2015)[a] | 10.5 MHz | Phase | 4 dB | 0.1 | 2015 | Continuous variable |
| Y.-L. Tang *et al.* (2016) | 75 MHz | Time bin | 55 km | 16.5 | 2016 | First fiber network |
| Yin *et al.* (2016) | 75 MHz | Time bin | 404 km | $3.2 \times 10^{-4}$ | 2016 | Longest distance |
| G.-Z. Tang *et al.* (2016) | 10 MHz | Polarization | 40 km | 10 | 2016 | Include modulation errors |
| Comandar *et al.* (2016)[a] | 1 GHz | Polarization | 102 km | 4.6 K | 2016 | High repetition rate |
| Kaneda *et al.* (2017)[a] | 1 MHz | Time bin | 14 dB | 0.85 | 2017 | Heralded single-photon source |
| C. Wang *et al.* (2017) | 1 MHz | Time bin | 20 km | $6.3 \times 10^{-3}$ | 2017 | Stable against polarization change |
| Valivarthi *et al.* (2017) | 20 MHz | Time bin | 80 km | 100 | 2017 | Cost-effective implementation |
| H. Liu *et al.* (2018) | 50 MHz | Time bin | 160 km | 2.6[b] | 2018 | Phase reference free |
| H. Liu *et al.* (2019) | 75 MHz | Time bin | 100 km | 14.5 | 2019 | Asymmetric channels |
| Wei *et al.* (2019) | 1.25 GHz | Polarization | 20.4 dB | 6.2 K | 2019 | Highest repetition or key rate |

[a]No random modulations.
[b]Asymptotic key rate.



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# 实用化QKD之路

TABLE IV. List of TF-QKD experiments.

| Reference | Distance or loss | Key rate (bits/s) | Year |
|---|---|---|---|
| Minder *et al.* (2019) | 90.8 dB | 0.045[a] | 2019 |
| Wang, He *et al.* (2019) | 300 km | $2.01 \times 10^3$ [a] | 2019 |
| Y. Liu *et al.* (2019) | 300 km | 39.2 | 2019 |
| Zhong *et al.* (2019) | 55.1 dB | 25.6[a] | 2019 |
| Fang *et al.* (2019) | 502 km[b] | 0.118 | 2019 |
| J.-P. Chen *et al.* (2020) | 509 km[b] | 0.269 | 2019 |

[a]Asymptotic key rate.
[b]Ultra-low-loss fiber.



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# 实用化QKD之路

TABLE V. List of some recent CV-QKD experiments and their performance.

| Reference | Clock rate | Distance or loss | Key rate (bits/s) | Year | Notes |
|---|---|---|---|---|---|
| Jouguet *et al.* (2013) | 1 MHz | 80.5 km | ~250 | 2013 | Full implementation |
| Qi *et al.* (2015) | 25 MHz | ··· | ··· | 2015 | Local LO |
| Soh *et al.* (2015) | 250 kHz | ··· | ··· | 2015 | Local LO |
| Huang, Huang *et al.* (2015) | 100 MHz | 25 km | 100 K | 2015 | Local LO |
| Pirandola *et al.* (2015) | 10.5 MHz | 4 dB | 0.1 | 2015 | CV MDI-QKD |
| Huang, Lin *et al.* (2015) | 50 MHz | 25 km | ~1 M | 2015 | High key rate |
| Kumar, Qin, and Alléaume (2015) | 1 MHz | 75 km | 490 | 2015 | Coexistence with classical |
| Zhang *et al.* (2020) | 5 MHz | 202.8 km[a] | 6.2 | 2020 | Long distance |

[a]Ultra-low-loss fiber.

TABLE VI. List of chip-based QKD experiments.

| Reference | Clock rate | Distance or loss | Key rate (bits/s) | Year | Notes |
|---|---|---|---|---|---|
| C. Ma *et al.* (2016) | 10 MHz | 5 km | 0.95 K | 2016 | Silicon, decoy BB84 |
| Sibson *et al.* (2017) | 1.72 GHz | 4 dB | 565 K | 2017 | InP, DPS |
| Sibson, Kennard *et al.* (2017) | 1.72 GHz | 20 km | 916 K | 2017 | Silicon, COW |
| Bunandar *et al.* (2018) | 625 MHz | 43 km | 157 K | 2018 | Silicon, decoy BB84 |
| Ding *et al.* (2017) | 5 kHz | 4 dB | ~7.5 | 2018 | Silicon, high dimension |
| G. Zhang *et al.* (2019) | 1 MHz | 16 dB | 0.14 K | 2019 | Silicon, CV-QKD |
| Paraïso *et al.* (2019) | 1 GHz | 20 dB | 270 K | 2019 | InP, modulator free |
| Wei *et al.* (2019) | 1.25 GHz | 140 km | 497 | 2019 | Silicon, MDI-QKD |



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# 其他QKD协议

TABLE VII. List of recent experiments of other QKD protocols.

| Reference | Clock rate | Distance or loss | Key rate (bits/s) | Year |
|---|---|---|---|---|
| Quantum access network (Fröhlich *et al.*, 2013) | 125 MHz | 19.9 km | 259 | 2013 |
| Centric network (Hughes *et al.*, 2013) | 10 MHz | 50 km | ··· | 2013 |
| RRDPS (Guan *et al.*, 2015) | 500 MHz | 53 km | ~118.0 | 2015 |
| RRDPS (Takesue *et al.*, 2015) | 2 GHz | 20 km | 2.0 K | 2015 |
| RRDPS (S. Wang *et al.*, 2015) | 1 GHz | 90 km | ~800 | 2015 |
| RRDPS (Li *et al.*, 2016) | 10 kHz | 18 dB | 15.5 | 2016 |
| High dimension (Lee *et al.*, 2014) | 8.3 MHz | ··· | 456 | 2014 |
| High dimension (Zhong *et al.*, 2015) | cw | 20 km | 2.7 M | 2015 |
| High dimension (Mirhosseini *et al.*, 2015) | 4 kHz | ··· | 6.5 | 2015 |
| High dimension (Sit *et al.*, 2017) | ··· | 0.3 km | ~30 K | 2017 |
| High-dimension (Islam *et al.*, 2017) | 2.5 GHz | 16.6 dB | 1.07 M | 2017 |
| Coherent one way (Korzh *et al.*, 2015) | 625 MHz | 307 km | 3.2 | 2015 |
| Modulator free (Yuan *et al.*, 2016) | 1 GHz | 40 dB | ~10 | 2016 |



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# 其它量子安全协议

TABLE VIII. List of recent developments of other quantum-cryptographic protocols beyond QKD.

| Protocol | Theory or experiment | Notes |
|---|---|---|
| Noisy quantum storage (Damgård *et al.*, 2008; Wehner, Schaffner, and Terhal, 2008; Konig, Wehner, and Wullschleger, 2012) | Theory | Unconditional security |
| Oblivious transfer (Erven *et al.*, 2014) | Experiment | Noisy-storage model |
| Bit commitment (Ng *et al.*, 2012) | Experiment | Noisy-storage model |
| Bit commitment (Kent, 2012) | Theory | Relativistic assumption |
| Bit commitment (Lunghi *et al.*, 2013; Liu *et al.*, 2014) | Experiment | Relativistic assumption |
| Bit commitment (Chakraborty, Chailloux, and Leverrier, 2015; Lunghi *et al.*, 2015; Verbanis *et al.*, 2016) | Experiment | Long commitment time |
| Digital signature (Clarke *et al.*, 2012) | Experiment | First demonstration |
| Digital signature (Collins *et al.*, 2014; Dunjko, Wallden, and Andersson, 2014) | Experiment | No quantum memory |
| Digital signature (Donaldson *et al.*, 2016; Yin *et al.*, 2017a) | Experiment | Insecure channel |
| Coin flipping (Berlín *et al.*, 2011; Pappa *et al.*, 2014) | Experiment | Loss tolerance |
| Data locking (Fawzi, Hayden, and Sen, 2013; Lloyd, 2013; Lupo, Wilde, and Lloyd, 2014) | Theory | Loss tolerance |
| Data locking (Liu *et al.*, 2016; Lum *et al.*, 2016) | Experiment | Loss tolerance |
| Blind quantum computing (Broadbent, Fitzsimons, and Kashefi, 2009; Barz *et al.*, 2012) | Theory and experiment | No quantum memory |
| Blind quantum computing (Reichardt, Unger, and Vazirani, 2013; Huang *et al.*, 2017) | Theory and experiment | Classical clients |



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# QKD发展

TABLE IX. List of reviews related to QKD.

| Reference | Subject |
|---|---|
| Gisin *et al.* (2002) | Experimental basics of QKD |
| Scarani *et al.* (2009) | Theoretical basics of QKD |
| Lo, Curty, and Tamaki (2014), Diamanti *et al.* (2016), and Zhang *et al.* (2018) | Practical challenges of QKD |
| Jain *et al.* (2016)) | Quantum hacking attacks |
| Xu, Curty, Qi, and Lo *et al.* (2015) | Measurement-device-independent QKD |
| Hadfield (2009) and Zhang *et al.* (2015) | Single-photon detector |
| X. Ma *et al.* (2016) and Herrero-Collantes and Garcia-Escartin (2017) | Quantum random number generator |
| Coles *et al.* (2017) | Entropy uncertainty relation |
| Weedbrook *et al.* (2012), Diamanti and Leverrier (2015), and Laudenbach *et al.* (2018) | Continuous-variable QKD |
| Sangouard *et al.* (2011), Pan *et al.* (2012), and Munro *et al.* (2015) | Quantum repeaters |
| Kimble (2008) and Wehner, Elkouss, and Hanson (2018) | Quantum internet |
| Brunner *et al.* (2014) | Bell nonlocality or device-independent QKD |
| Fitzsimons (2017) | Blind quantum computing |
| Xavier and Lima (2020) | High-dimensional QKD |



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# 自由空间量子光学实验



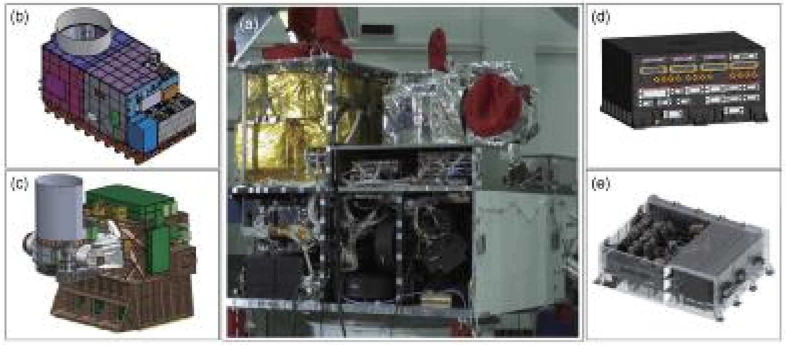

FIG. 18. Full view of the Micius satellite and the main payloads. (a) Photograph of the Micius satellite prior to launch. (b) Transmitter 1 for QKD, entanglement distribution, and teleportation. (c) Transmitter 2, especially designed for entanglement distribution. (d) Experimental control box. (e) Entangled-photon source.

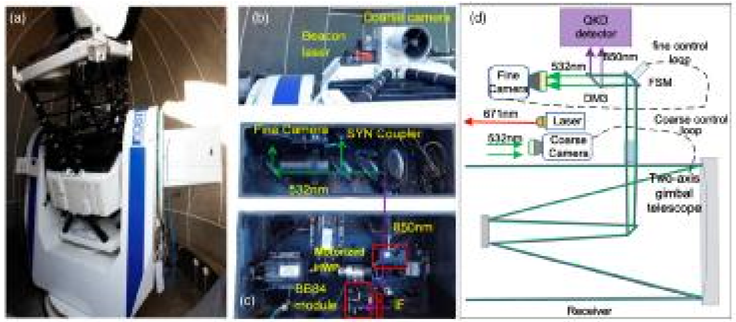


FIG. 23. Typical receiving ground station for the Micius satellite. (a) Two-axis gimbal telescope. (b) Beacon laser and coarse camera. (c) One of the two layers of the optical receiver box. (d) Typical optical design of the receiver including the receiving telescope, the ATP system, and the QKD-detection module. From Liao *et al.*, 2017a.

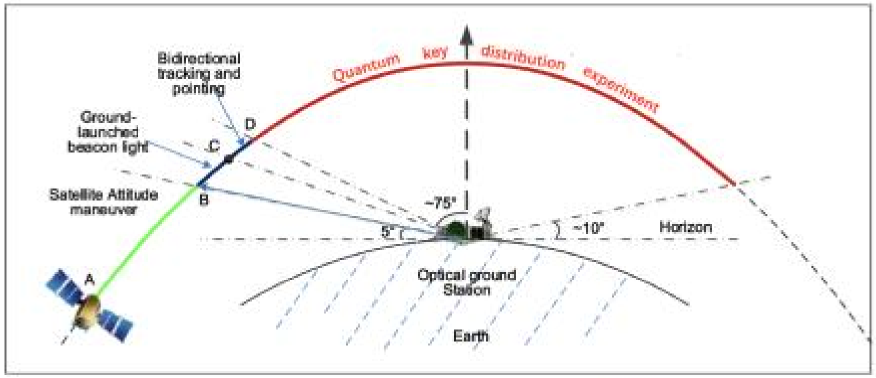


FIG. 27. Tracking and QKD processes during an orbit. From Liao *et al.*, 2017a.



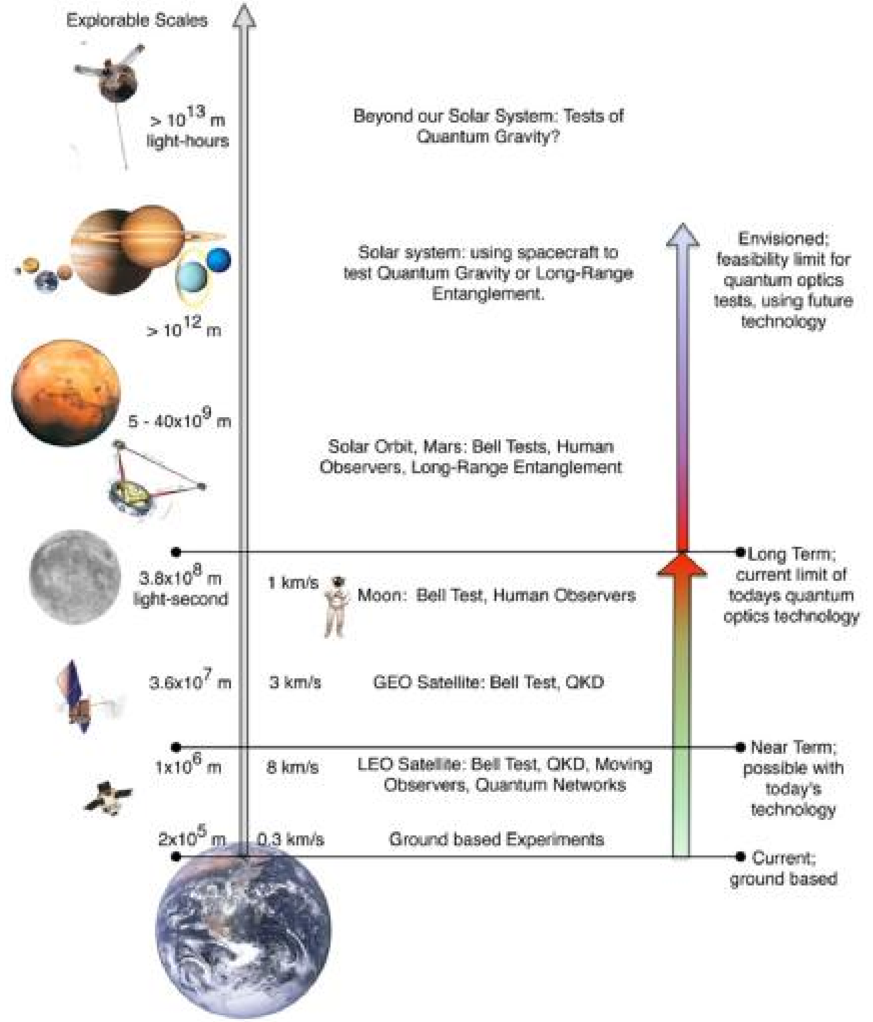


**Figure 1.** Overview of the distance and velocity scales achievable in a space environment explorable with man-made systems, with some possible quantum optics experiments at each given distance.

C.-Y. Lu *et al.*, Micius quantum experiments in space, Rev. Mod. Phys., 94 (2022) 035001.

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# 谢谢

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# 乔布斯语录：
# 2005年斯坦福大学毕业典礼上的讲话

*Your time is limited, so don't waste it living someone else's life. Don't be trapped by dogma, which is living with the results of other people's thinking. Don't let the noise of other's opinions drown out your own inner voice.*

*And most important, have the courage to follow your heart and intuition. They somehow already know what you truly want to become. Everything else is secondary.*

# 乔布斯语录

Innovation distinguishes between a leader and a follower.

The only way to do great work is to love what you do. If you haven't found it yet, keep looking. Don't settle. As with all matters of the heart, you'll know when you find it.

Design is not just what it looks like and feels like. Design is how it works.