**Quantum Internet**

---Protocols

1. **Quantum teleportation**

To transfer an unknown state between different nodes is an essential and necessary function for future network. However, it is impossible to obtain all the information of an unknown state and reconstruct it remotely, because one can not get all the information by just once measurement of an unknown state and various measurements are necessary, which needs multiple copies of an unknown state, but it is forbidden to clone a quantum state. Fortunately, quantum teleportation provides a method to transfer an unknown state from one location to another with the aid of previously shared quantum entanglement and classical communications. Since it was firstly proposed in 1993 [Phys. Rev. Lett. 70, 1895], quantum teleportation has attracted extensive and persistent attention. It has become one of the most important protocols in quantum information science.

In the original protocol, two critical necessaries are needed to implement quantum teleportation: quantum entanglement and Bell state measurement (BSM) to distinguish one Bell state from the other three. For the generation of quantum entanglement, a significant breakthrough came in 1995: a technique to generate high-intensity source of polarization-entangled photon pairs was proposed and demonstrated by Kwiat et al [Phys. Rev. Lett. 75, 4337]. For the BSM of two photon polarization qubits, a 50:50 beam splitter [Europhys. Lett. 25, 559] could distinguish the anti-symmetric state and to implement the BSM. After satisfing the two necessaries, the first experimental demonstration of quantum teleportation was accomplished with photons in 1997 [Nature 390, 575] by Bouwmeester et al. They prepared two pairs of photons by twice pumping a single nonlinear crystal BBO (beta-barium borate): one pair generated as the entanglement source and the other pair utilized to prepare the state to teleport by triggering one photon. The BSM was carried out by a BS: when two photons enter the BS from two different input port, only the anti-symmetric state always resulted in one and only one photon in each output port, and the two photons in the remaining three state always exited via the same output port. Therefore, only the anti-symmetric state could lead to a two-fold coincidence detection behind the BS and the BSM could be implemented with an efficiency of 25%. From that time on, great effort has been paid to experimentally demonstrate various types of quantum teleportation with not only photons but also other many different quantum systems.

One main experimental development for quantum teleportation is to lengthen the transmission distance either in fiber or free space. In the pioneering works, Marcikic et al [Nature 421, 509 (2003)] experimentally demonstrate quantum teleportation from one laboratory to another, separated by 55 m but connected by 2 km ﬁber with photons at telecommunication wavelengths, and Ursin et al [Nature 430, 849 (2004)] implemented quantum teleportation over a distance of 600 meters across the River Danube in Vienna through a fiber. Due to the relatively low photon detection efficiencies at telecommunication wavelengths, quantum teleportation over long distance optical fiber became challenging. In 2010, Jin et al. [Nature Photonics 4, 376 (2010)] demonstrated quantum teleportation in a 16 km, noisy, free-space channel on the ground. This distance is towards space-based experiments, because it is significantly longer than the effective aerosphere thickness, which is equivalent to 5-10 km of ground atmosphere [Phys. Rev. Lett. 94, 150501 (2005)]. Two years later in 2012, the teleportation distance in free space was lengthened to 97 km over Qinghai Lake by Yin et al [Nature 488, 185 (2012)] and 143 km between the two Canary Islands of La Palma and Tenerife by Ma et al [Nature 489, 269 (2012)]. These two works overcame the true challenges of the acquiring, pointing and tracking techniques for long-distance free-space quantum teleportation, and paved the way for future satellite-based quantum teleportation. Accompanying with the breakthrough of superconducting single photon detectors with near unity efficiency, the 3-fold photon detection for quantum teleportation was greatly enhance to more than 2 orders at telecommunication wavelengths, and the teleportation distance in optical fiber was lengthened to 100 km in 2015 by Takesue et al [Optica 2, 832 (2015)]. Very recently, [Nature Photonics 10, 671 (2016)] and Valivarthi et al [Nature Photonics 10, 676 (2016)] demonstrated the quantum teleportation in the real world over fiber networks in Hefei and Calgary respectively with length of dozens of kilometers. Another milestone work towards future quantum teleportation was that the first quantum satellite was launched in August 2016 in China. We are expecting the exciting and amazing quantum teleportation between a ground station and a satellite, and even between two ground stations over 1000 km with the previous shared entanglement from a quantum satellite. [Nature, 2016, 535: 478-479.]

With the development of numerous quantum control technologies, more and more complex experiments of quantum teleportation have been demonstrated. In 2005, with a five-photon entanglement, Zhao et al implemented an open-destination teleportation [Nature 430, 54 (2004)]. In that work, an unknown quantum state was teleported onto a superposition of 4 photons and the teleported state could be read out at any location of the 4 photons. In 2006, Zhang et al [Nature Physics, 2 678 (2006)] successfully teleported the state of a two-photon composite system, making a breakthrough for teleportation form one particle to a complex system with multiple particles. In 2015, Wang et al [Nature, 518, 516 (2015)] achieved a quantum teleportation of multiple degrees of freedom of a single photon, making another breakthrough from one to multiple degrees of freedom towards a real object.

Besides the widely used qubits encoded by discrete variables, the continuous variable of optical modes could also be utilized to encode quantum state and further to be teleported. The first experimental demonstration of this type was carried out by Furusawa et al in 1998 [Science 282, 706 (1998)]. The advantage of this teleportation was that it could be deterministic in principle, which teleportation of a qubits was always probabilistic because of the limited success probability of BSM. 15 years later in 2013, Takeda et al [Nature 500, 315 (2013)] exploited this advantage with a hybrid technique and demonstrated the deterministic teleportation of photonic qubits.

In addition to linear optical system, quantum teleportation also attracted great attention in other quantum systems. Numerous demonstrations of quantum teleportation have been carried out in various systems including atoms [Nature Phys. 9, 400 (2013)], ions [Nature 429, 734 (2004); Nature 429, 737 (2004)], electrons [Science 345, 532 (2014)], and superconducting circuits [Nature 500, 319 (2013)]. Hybrid teleportation between different systems also have been successfully demonstrated, such as quantum teleportation between light and matter [Nature 443, 557 (2006)]; Quantum teleportation from a photonic qubit to a solid-state spin qubit [Nature Communications 4, 2744 (2013)]. These hybrid quantum teleportation technologies are expected to play an important role for future quantum network, because photon qubits are flying and suitable for communication between different nodes and long-lived qubits are appropriate for quantum information processing within a node.

1. **Entanglement swapping and Quantum repeaters**

Entanglement swapping can be regard as a variant of teleportation, which allows one to entangle photons that have no common past. This function makes entanglement swapping play an irreplaceable role in quantum networks. Entanglement swapping was originally proposed by M. Żukowski et al. [Phys. Rev. Lett. 71, 4287] in 1993. They noted that entanglement swapping provides a way to perform an event-ready test of Bell’s inequality. The first experiment of entanglement swapping was proposed by Jianwei Pan et al. in 1998 [Phys. Rev. Lett. 80, 3891]. By pumping a BBO in a double pass configuration, two pairs of polarization entangled photons are generated to demonstrate the scheme. A visibility of 0.65 is observed, which clearly surpasses the 0.5 limit of a classical interference. A performance later by Jianwei Pan et al. in 2001 [Phys. Rev. Lett. 86, 4435] improved to 0.84, which violates the Bell inequality (the threshold is 0.71).

Entanglement swapping provides an important value of fundamental research in quantum information science. At the same time, these fundamental researches also promote the development of entanglement swapping experiments. Aside from event-ready mode, Peres [J. Mod.Opt, 2000, 47(2-3)] proposed a delayed-choice mode of the entanglement swapping in 2000, where entanglement is produced a posteriori, after the entangled particles have been measured and may no longer exist. In 2001, T. Jannewein et al. [Phys. Rev. Lett. 88, 017903] designed and realized a delay-choice entanglement swapping. Such a delayed-choice experiment was performed by including two 10 m optical fiber delays about 50 ns for both outputs of the Bell-state measurement. Fabio Sciarrino et al. [Phys. Rev. A 66, 024309] realized a delayed-choice entanglement swapping experiment with vacuum–one-photon quantum states in 2002. However, none of these demonstrations implemented an active, random and delayed choice, which are required to ensure that photons can not know in advance the settings for future measurements. In 2012, X-S Ma et al. [Nature Physics 8, 479] demonstrated an entanglement swapping experiment with active delayed choice. In their experiment, they designed the special interferometer to realize the active switching between the Bell state measurement and the separation state measurement, and experimentally verified the entanglement-separability duality of the two photons.

Subsequently, the experiments of entanglement swapping have been developed to be more complex and rigorous. The developments of these technologies can be used for more complex quantum networks. Goebel et al. [Phys. Rev. Lett. 101, 080403] used three pairs of polarization entangled photons and conducted two Bell-state measurements to realize the multistage entanglement swapping in 2008. Lu et al. [Phys. Rev. Lett. 103, 020501] demonstrated multiparticle entanglement swapping using a three-photon Greenberger-Horne-Zeilinger (GHZ) state. In 2013, E. Megidish et al. [Phys. Rev. Lett. 110, 210403] demonstrated the entanglement swapping between photons that have never coexisted. In their experiment, entangled photons are not only separated spatially, but also temporally spatially. In 2015, Shuntaro Takeda et al. [Phys. Rev. Lett. 114, 100501] experimentally realized the “hybrid” entanglement swapping between discrete-variable (DV) and continuous-variable (CV) optical systems.

To develop a practical quantum network, the entanglement swapping between independent entangled photon sources is an important technique. In the past two decades, entanglement swapping has been achieved in a large number of experiments. However, in most experiments, entangled photons are generated by using the same laser, and do not meet the requirements of independence. Entanglement swapping based on the independent entangled photon source has been verified in the laboratory [Phys. Rev. Lett. 96, 110501, Nature Physics 3, 692 - 695 (2007), Phys. Rev. A 79, 040302(R)], but the distinguishability caused by the photon propagation in the channel is still a great obstacle to realize the entanglement swapping experiment using the independent source under realistic conditions. Until 2015, B. Hensen et al. [Nature 526, 682] achieved entanglement swapping using independent entangled photon sources separated by 1.3 kilometres for the first time in the real environment. However, the wavelength of the photon used in this experiment is 637 nm (the transmission loss in the fiber is about 15dB/km), which is not conducive to achieving long-distance entanglement swapping since it is far greater than transmission loss (~ 0.2 dB/km) of communication band photons in the fiber. Based on the techniques in [Nature Photonics 10, 671 (2016)] and [Nature Photonics 10, 676 (2016)], longer-distance quantum swapping may be possible in the near future.

Entanglement swapping can also be directly used to quantum key distribution, Alice and Bob each have an entangled photon source, and one photon of each EPR pair is sent to a third-party measurement node, Eve. Similar to the MDI-QKD, the security of the generated key does not depend on Eve's faithful execution of the operation, that is, Eve can be an untrusted third party. This MDI property also reflects the physical beauty of quantum teleportation. Bell-state measurements do not reveal any information about the quantum state, but can be used to restore the transmitted quantum state. On the other hand, quantum entanglement occurs between the remaining photons in the EPR pair of Alice and Bob. M. Koashi et al. [Phys. Rev. Lett. 90, 057902] and X. Ma et al. [New J. Phys, 2008, 10(7)] suggest that an entangled photon source can be considered as a base-independent light source for quantum key distribution. Thus, the quantum key distribution realized by entanglement swapping has the characteristics of measurement device independent and light source independent.

An interesting application of entanglement swapping is that we can entangle distant and independent matter qubits by the photon for the medium, which is an important technique for the hybrid quantum networks. Starting with two entangled atom-photon pairs, we can project the two atomic qubits into a maximally entangled state by performing a Bell-state measurement on the two photons [Nature 428, 153; Phys. Rev. Lett. 96, 030404]. In 2007, Moehring et al. [Nature 449, 68] entangled two trapped atomic ions separated 1 m apart using entanglement swapping exploiting interference of photons emitted by the ions. The fidelity of the states of the entangled ions was 0.63(3). In the subsequent experiments of Matsukevich et al. [Phys. Rev. Lett. 100, 150404], the ion-ion entanglement fidelity was improved to 0.81. Similarly, Yuan et al. [Nature 454, 1098] entangled two atomic ensembles, each originally with a single emitted photon, by performing a joint Bell state measurement on the two single photons after they have passed through a 300-m fibre-based communication channel. In 2015, B. Hensen et al. [Nature 526, 682] generated robust entanglement (estimated state fidelity of 0.92 ± 0.03) between the two distant spins by entanglement swapping in the Barrett–Kok scheme [Phys. Rev. A 71, 060310 (2005), Nature 497, 86–90 (2013)], such a high fidelity is sufficient to successfully complete loophole-free Bell inequality test.

Entanglement swapping is a core element of quantum repeaters, which is of great significance to realize long-distance quantum communication. At present, the maximum transmission distance that can be achieved by quantum key distribution is 400 km [arXiv:1606.06821, 2016]. Therefore, the communication distance is still a bottleneck restricting the development of quantum communication. Quantum repeater, proposed in 1998 by Briegel et al. [Phys. Rev. Lett. 81, 5932 (1998)], combines entanglement swapping and quantum memories, which provides a potential solution to this problem. The first proposed practical quantum repeater architecture was proposed in 2001 by Duan, Lukin, Cirac and Zoller (DLCZ) [Nature 414, 413 (2001)], using atomic ensembles and linear optics. To increase the repeater count rate, various protocols [Rev. Mod. Phys. 83, 33 (2011), Phys. Rev. A 79, 042340 (2009), Phys. Rev. A 92, 012307 (2015), Phys. Rev. A 81, 052311 (2010), Phys. Rev. A 81, 052329 (2010), Nature Photon. 6, 777 (2012), Phys. Rev. Lett. 112, 250501 (2014)] was proposed. In 2015, Koji Azuma et.al [ncomms7787] introduced the concept of all-photonic quantum repeaters based on flying qubits, and the matter quantum memory is not necessary. The experimental demonstration of elementary segment of quantum repeaters were achieved by C.-W. Chou et al. [Science 316, 1316(2007)] and S. Yuan et al. [Nature 454, 1098 (2008)]. In order to develop practical quantum repeaters, there are many experimental technique needs to develop. For example, the multiplexing technique [Phys. Rev. A 76, 050301(R)(2007), Phys. Rev. A 82, 010304(R) (2010), Phys. Rev. Lett. 113, 053603 (2014), Phys. Rev. Lett. 98, 060502 (2007)], which can be used to construct multimode memories. Techniques based on non-degenerate photon pair sources [Nature 469, 508(2011), Nature 469, 512 (2011), Phys. Rev. Lett. 112, 040504 (2014), Phys. Rev. A 92, 012329 (2015)] and quantum frequency conversion [Nature Phys.6, 894 (2010), Nature Commun. 5, 3376(2014)] are being developed to obtain quantum memories compatible with photons at telecom wavelengths. Aside from photonic system, techniques based on other physics system have also been developed [Nature Physics 11, 37(2015), Science 337, 72(2012), Nature 484, 195 (2012), Nature 497, 86 (2013)]. In general, to enable scaling up to repeaters with several links, lots of technique need to be considerably improved and simplified, there is still a long way to go before building a practical quantum repeater.

1. **Quantum key distribution**

With the development of quantum technology, quantum key distribution will gradually enter the practical stage. Bennett, one of the proposers of BB84 protocol, firstly demonstrated the protocol on an optical platform with distance of 30 cm [Journal of Cryptology, 1992, 5(1):3–28]. After that, Experiments have been developed rapidly from indoor to outdoors, and from short distance to long distance. In 1993, Muller experimentally demonstrated quantum cryptography using polarized photons in optical fiber over more than 1 km [Europhysics Letters, 1993, 23(6):383]; Townsend operated QKD experiment over 10 km using phase encoding [Electronics Letters, 1993, 29(7):634–635]. In 1995, Stucki et al. [quant-ph/0203118, 2002] in Gisin's group realized an experiment at outdoors over 67km using a plug&play system to keep stabilization automatically. In 2007, Janwei Pan's group [Phys. Rev. Lett. 98, 010505], Los Alamos Nation Laboratory [Phys. Rev. Lett. 98, 010503] and Zeilinger's group [Phys. Rev. Lett. 98, 010504] completed QKD experiments based on decoy-state over more than 100 km almost simultaneously, which marks the beginning of long-distance QKD. In 2010, Jianwei Pan’s group reported an implementation of decoy-state QKD over 200 km optical fiber cable through photon polarization with final key rate of 15 Hz [Optics express, 2010, 18(8):8587–8594]. In 2007, Takesue et al. firstly realized DPS protocol QKD over 42.1 dB channel loss and 200 km of optical dispersion-shifted fiber [Nature Photonics, 2007, 1(6):343–348]; In 2012, Guangcan Guo's group realized DPS protocol over 50 dB channel loss and 260 km optical fiber using superconductive detector, this is the first implementation of QKD over more than 50 dB channel loss [Opt. Lett., 2012, 37(6):1008–1010]. In 2009, Stucki et al. realized the coherent one way (COW) protocol QKD system with a maximum range of 250 km at 42.6 dB channel loss using ultra-low loss fiber, the secret bit rates is up to 15 bps. [New Journal of Physics, 2009, 11(7):075003].

Apart from using the QKD scheme based on state preparation and measurement, QKD schemes based on entanglement distribution mainly including E91 protocol [Phys. Rev. Lett., 1991, 67:661–663] and BBM92 protocol [Phys. Rev. Lett., 1992, 68:557–559], which also are developed and applied widely in many practical systems. In 2005, Zeilinger's group distributed entanglement and single photons through free-space quantum channel, demonstrated the feasibility of free-space quantum communication [Optics Express, 2005, 13(1):202–209]. In 2006, Ivan Marcikic et al. reported a complete experimental implementation of a QKD protocol through a free-space link using polarization-entangled photon pairs. [Applied Physics Letters, 2006, 89(10):101122]. In 2007, Zeilinger's group realized BBM92 protocol QKD based on polarization encoding over 144 km [Nature physics, 2007, 3(7):481–486]. The experiments listed above indicated the QKD protocols based on free-space entanglement distribution have the advantage of being less affected by decoherence, which lay solid foundation for global and satellite-to-ground quantum communication.

The fiber loss increases exponentially with distance increases. However, the loss of free-space transmission increases little with the increase of the distance, which is mainly related to the thickness of the atmosphere. Therefore, it is a perfect solution to construct the global quantum communication basing on the satellite. To verify the feasibility of a quantum channel between space and earth, a European Union group successfully received the weak light pulse emitted from a ground station and reflected by a mirror placed on a low orbiting satellites with orbital altitude of 1485 km in 2008[New Journal of Physics, 2008, 10(3):033038]. To verify the feasibility of QKD between satellite and ground with rapidly moving platforms, Weinfurter's group realized QKD over 20km from an airplane to the ground in 2013[Nature Photonics, 2013, 7(5):382–386]. In the same year, Jianwei Pan's group successfully accomplished quantum communication based on hot-air balloon floating platform [Nature Photonics, 2013, 7(4):387–393]. The experiments on airplane and hot-air balloon system demonstrate the feasibility under conditions of rapid motion, vibration, and random movement of satellites. At present, many countries including America, Canada, European Union, China and Japan pay high attention and support to accelerate the development of satellite-ground quantum communication. The first quantum satellite was launched in August 2016 in China will open a platform for satellite-ground quantum communication [Nature, 2016, 535: 478-479.]

In addition to the continuous expansion of the distance, the QKD is also developed from point-to-point experiment to the quantum communication network with multi-customers and various topological structure. There are many competition and cooperation in this area. The network of American Defense Advanced Research Projects Agency (DARPA) connected the three nodes, Harvard University and Boston University in Boston and BBN company in 2005, and then increased to 10 nodes [Quantum Communications and cryptography, 2006. 83–102]. Since 2006, the EU has established a "SECOQ" network, which unifying the efforts of 41 research and industrial organizations from 12 countries, including the UK, France, Germany, Austria, etc. A typical network used a trusted repeater paradigm including 6 nodes and 8 links was demonstrated in Vienna in 2008 [New J. Phys.,2009,11(7):075001]. In 2010, National Institute of Communication Technology, together with Nippon Telegraph and Telephone Corporation, Nippon Electric Company, Mitsubishi Electric Corporation, Toshiba European company, Switzerland IDQ Company and Austria All Vienna team constructed a Tokyo QKD Network in a metropolitan area and demonstrate the world-first secure TV conferencing over a distance of 45km [Opt. Express, 2011, 19(11):10387–10409]. The maximum distance is 90 km, and the point to point bit rate can reach 65kbps using superconductive detector over 45 km.

In China, the quantum network is also developed rapidly. In 2009, Jianwei Pan's group designed and constructed 3 nodes network with chained architecture, which demonstrated quantum unbreakable real-time voice telephone [Opt. Express, 2009, 17(8):6540–6549]. In the same year, Jianwei Pan's group designed metropolitan all-pass and inter-city quantum communication network in field fiber for four nodes, Any two nodes of them can be connected in the network to QKD [Optics Express, 2010, 18(26):27217–27225]. In 2009, Guangcan Guo's group constructed a topological structure with wavelength division multiplexers, realizing 4 nodes [Physics Letters A, 2008, 372(22):3957–3962] and 5 nodes star-type [Optics letters, 2010, 35(14):2454–6] QKD network. In 2012, Jianwei Pan's group constructed the largest metropolitan area quantum network in Hefei, linking 46 nodes to allow real-time voice communications, text messages and file transfers. A more than 2,000-km quantum communication used by government bodies and banks under construction in Beijing and Shanghai will be fully operational soon. With the help of the new satellite, scientists will be able to test quantum key distribution between the satellite and ground stations, and conduct secure quantum communications between Beijing and Xinjiang's Urumqi.

With distance and network coverage of quantum communication gradually increased, the security of QKD system draw more and more attention. Since 2012, the MDI-QKD protocol has been widely concerned, because of the features of safety and practicability. Tittel's group [Phys. Rev. Lett., 2013, 111:130501] demonstrated the protocol in the laboratory over more than 80 km of spooled fiber with time-bin encoding, they also tried outdoors experiment over 18.6 km. Brazilian Weid' group [Phys. Rev. A, 2013, 88:052303] demonstrated the protocol using polarization encoding scheme. However, these two demonstrations did not really distribute random key bits between two parties, and thus were not full MDI-QKD demonstrations. Additionally, the system of Tittel's group can be attacked by PNS or USD sources and cannot generate secure code in principle. A full demonstration of time-bin phase encoding MDI-QKD was reported by Jianwei Pan's group [Phys. Rev. Lett. 111, 130502] over 50 km fiber link. Lo's group [Phys. Rev. Lett., 2014, 112:190503] implemented polarization encoding MDI-QKD with commercial off-the-shelf devices over 10 km, and the secure key rate is 0.0047 bps. Subsequently, Jianwei Pan’s group continue to upgrade the performance of MDI-QKD system, making the distance of the experiments has reached 200 km [Phys. Rev. Lett. 113, 190501] and 400 km [arXiv:1606.06821].

1. **Entanglement purification**

Entanglement purification is originally proposed in [Phys. Rev. A 53, 2046, Phys. Rev. A 54, 3824, Phys. Rev. Lett. 77, 2818] in 1996, which is essential to distil highly entangled states from less entangled ones. In order to meet the experimental requirements, a more feasible purification scheme only needed polarizing beam splitter and post-selection was proposed and demonstrated by Jianwei Pan et al. [Nature 410, 1067]. Then the scheme was demonstrated by Jianwei Pan et al. [Nature 423, 417] in 2003, they prepared a mixed state with fidelity of 0.75 (0.8), a significant improvement of entanglement fidelity to the value 0.92 (0.94) is achieved after the purification operation. In 2005, Walther et al. performed a Bell experiment with purified states, a state below the threshold of Bell inequality successfully passed the Bell test after entanglement purification [Phys. Rev. Lett. 94, 040504]. Unfortunately, the theoretical efficiency of the purification scheme [Nature 410, 1067] is only 1/4, which still need to improve in theory and experiment.

1. **Superdense coding**

The idea of quantum dense coding was introduced by Bennett and Wiesner [Phys. Rev. Lett. 69, 2881], which can be used to send two bits of classical information using only one particle in a Bell state. In 1996, Mattle et al. [Phys. Rev. Lett. 76, 4656 (1996)] realized quantum dense coding experimentally for the first time in photonic system. However, they cannot realized a complete Bell-state analyzer, only three different messages could be encoded by a single qubit. Thus, an increase of channel capacity to  bits was possible.

To distinguish between all four polarization Bell states of two photons, Schuck et al. [Phys. Rev. Lett. 96, 190501 (2006)] developed a method that using hyperentangled source to realize a complete linear-optical Bell state analyzer in 2006, and achieved an overall channel capacity of 1.18(3) bits per photon in their experiment. In 2008, Kwiat's group [Nature Phys. 4, 282 (2008)] achieved channel capacity of 1.63 bits using pairs of photons simultaneously entangled in spin and orbital angular momentum, successfully beating the channel capacity limit for linear photonic superdense coding.

In other aspect, due to the noises in channel, researches hope to successfully achieve high efficiency dense coding over the noise channel. In 2013, A. Chiuri et al. successfully demonstrated dense coding over a depolarising channel [Phys. Rev. A, 87 (2013) 022333]. In 2014, Liu et al. [Europhysics Letters, 114(1), 10005(2016)] developed a superdense coding protocol in the presence of non-Markovian noise, they proved that loss of entanglement during encoding procedure will not reduce efficiency of information transmission. Their experiment reached the values of mutual information close to 1.52±0.02 (1.89±0.05) with 3-state (4-state) encoding.

Besides photonic system, superdense coding are also implemented in other systems, such as NMR system [Phys. Rev. A 61, 022307 (2000)] and atomic qubits [Phys. Rev. Lett. 93, 040505 (2004)]. In 2002, Li et al. [Phys. Rev. Lett. 88, 047904 (2002)] realized quantum dense coding by using continuous variables optics.

1. **Quantum Secrete Sharing**

In 1999, Richard Cleve, Daniel Gottesman, and Hoi-Kwong Lo firstly proposed the concept of quantum secret sharing [Phys. Rev. Lett. 83, 648 (1999)]. Quantum secret sharing can enhance the security of classical information. In 2001, Gisin's group demonstrated the protocol for the first time based on energy-time entanglement, and this is also the first application of a quantum communication protocol based on more than two qubits [Phys. Rev. A 63,042301 (2001)]. In 2005, Jianwei Pan's group developed an ultra-stable four-photon GHZ states, and then realized 3-party quantum secret sharing [Phys. Rev. Lett. 95, 200502 (2005)]. In the same year, Weinfurter's group proposed and demonstrated a new quantum secret sharing protocol by sequential transformation of single qubit, without involving multiparticle GHZ states [Phys. Rev. Lett. 95, 230505 (2005)]. In 2007, Weinfurter's group realized four-party quantum secret sharing for the first time via the resource of four-photon entanglement [Phys. Rev. Lett. 98, 020503 (2007)]. In 2014, Tame's group realized four-party graph-state quantum secret sharing with a five-qubit graph state, which is meaningful to the integration of quantum networks via the measurement-based paradigm .[Nat. Commun. 5, 5480 (2014)].

The protocol can also be utilized as distribute quantum state securely, named as quantum state sharing. In 2004, Lam 's group demonstrated a multipartite protocol to securely distribute to 3 parties and reconstruct a quantum state with a fidelity average of 0.73 [Phys. Rev. Lett. 92, 177903 (2004)].

Theoretically, quantum secret sharing should satisfy three criteria: reliability, confidentiality [Commun. ACM 22, 612 (1979)] [G. R. Blakley, Safeguarding cryptographic keys, in Proc. Of the National Computer Conference, 1979, Vol. 48 (1979), p. 313], and capability of sharing entangled states. However, the experiments stated above cannot satisfy the second and third criterions simultaneously. In 2016, Jianwei Pan's group realized the fully quantum secret sharing, satisfying all of the three criteria simultaneously [PRL 117, 030501 (2016)].