Survey of Emerging Information Teleportation Networks and Protocols

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Abstract

Quantum-communications technologies, especially involving teleportation, will play an increasingly important role in both the domestic and defense sectors because of the promise for improved security, distributed quantum computing, and quantum sensing. This paper presents a review of this emerging field, summarizing key protocols as well as some representative quantum teleportation experiments conducted both in the laboratory and in the field. Briefly, in recent years, quantum teleportation has been demonstrated in both optical-fiber networks and in long-distance free-space channels, using entanglement on photonic chips as well as between photonic and atom/ion or solid-state qubits.

1. Introduction

The development of emerging information teleportation networks, involving new non-classical technologies such as quantum teleportation, is critically important for the future US Army because it will allow operations and applications that are not feasible using classical techniques. Quantum teleportation relates to the non-local transfer of quantum information between two or more nodes by entanglement of quantum particles [1-5]. Quantum teleportation uses entanglement in a non-local and non-classical way to transfer information between a sender and a receiver, without actually sending the photons that carry the information through the physical space in between. Classical communication techniques do not allow teleportation because they rely on inadequate measurements of and local approximations to the underlying physics. Short-range teleportation can be performed using just photons. However, long-distance communication and network applications require long-time storage and entanglement purification that can only be accomplished with matter qubits such as atoms, ions, or solid-state emitters.

In recent years, the field of quantum-communication technology has been growing in importance as cyber-security concerns rise. Future advances in fundamental quantum protocols and experimental demonstrations of teleportation are needed to enable development of the much-needed quantum-network capabilities. Initially, quantum communications such as teleportation may not have the communication speeds of classical networks. However, it must be kept in mind that quantum communications can exploit a richer set of physics and are qualitatively different from classical communications methods, which are fundamentally limited in their applications. Quantum physics needs to be further exploited to advance and apply teleportation for practical benefit. Research is underway on the process of manipulating photons, or photons in combination with matter such as atoms and ions, to efficiently perform teleportation by quantum means. The field of quantum-communication technology is growing in importance. Advances in fundamental quantum protocols and teleportation experiments will enable development of needed information teleportation-network capabilities [6-8]. By reviewing the past and current state-of-the-art, we expedite this process by avoiding duplication and identifying critical areas that need additional research in the near future.

This paper presents a summary of key quantum protocols in Table 1, and recently developed quantum-inspired classical protocols in Table 2. Fundamental protocols include those related to various aspects of teleportation, including entanglement verification, non-locality, non-classicality, and privacy. Representative quantum-teleportation experiments performed in the laboratory and in the field are highlighted in Table 3. Experimental demonstrations include those using: (a) polarization-entangled photons, (b) time-bin-entangled photons, (c) hyper-entangled (polarization and angular momentum) photons and hybrid (spin and orbital momentum) entangled states, (d) teleportation on a photonic and/or solid-state chip, (e) establishing quantum information transfer from a propagating photonic qubit to a stationary solid-state-spin qubit, (f) teleportation between two macroscopic atomic ensembles, and (g) teleportation between two single trapped atoms/ions. Table 3 also summarizes recent free-space quantum-teleportation experiments with multi-photon entanglement, and includes several recent experiments related to emerging teleportation-network technologies.

2. Quantum Protocols

In this section, we discuss quantum protocols for quantum applications, technologies, and analysis. Quantum protocols can be broadly classified to include not only quantum communications, but also non-locality tests, non-classicality tests, quantum memories, quantum repeaters, and quantum networks.

2.1 Non-Locality, Non-Classicality and Bell-State Protocols (Table 1a)

Table 1a presents protocols for determining the degree to which the quantum nature of the physical process is expressed (i.e., defining metrics to measure the degree to which a process is non-classical). The earliest indication of the consequences of quantum science relating to non-classical communication was described by Einstein, Podolsky, and Rosen [9] in 1935. They showed that if correct, quantum theory must have correlations between particles that classical physics could not predict. Einstein referred to this as "spooky action at a distance," and it is now know as the EPR effect. This important paper was the foundation for quantum communications and teleportation. Later, John Bell devised a test for the EPR effect that could be implemented in an experiment [10], thereby making Einstein's predictions accessible to experimentalists. Clauser, Horne, Shimony, and Holt (CHSH) followed Bell, and devised a test that could be implemented with optics and the polarization of photons [11]. The CHSH test was one of the first to be used by experimentalists to show violations of Bell inequalities and thus the validity of quantum theory. Certain measurement-related loopholes of the original CHSH test were closed by Clauser and Shimony in the C-S protocol [12].

Table 1a. A summary of key quantum protocols: non-locality, non-classicality, and Bell state protocols.

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2015	Dist.-based analysis	Christensen, Nam Kwiat, Knill ...	Non-Locality	Bell inequality test	USA, CA USA, CA	Christensen [29] Knill et al. [30]
2015 2012	CPM	Sheng, Zhou	Bell state analysis	Complete Parity Check Measur.	CN JP, UK	Munro et al. [21] Sheng & Zhou [22]
2014	Multi-party Q comm	Erven, Meyer-Scott Jennewein, Resch	Non-Locality	3 photons entangled	CA, UK, AT USA, AU	Erven et al. [18]
1978	C–S	Clauser, Shimony	Non-Locality	Bell inequality	USA	Clauser & Shimony [12]
1969	CHSH	Clauser, Horne, Shimony, Holt	Non-Locality	Bell inequality test	USA	Clauser et al. [11]
1964	Bell violation	Bell	Non-Locality	Bell inequality	USA, CH	Bell [10]
1963 2015	Multi-boson correlation	Glauber Tamma, Laibacher	Multi-boson measurement	Multi-bosonic interference	USA GER	Glauber [23-25] Tamma & Laibacher [26]
1935	EPR	Einstein, Podolsky, Rosen	Non-Locality	Entanglement	USA	Einstein et al. [9]
2012	CSI	Cauchy, Schwarz	Non-Classicality	Cauchy–Schwarz inequality	AU, FR PL	Kheruntsyan et al. [17]
2000 1999	MDS/MSS	An, Tinh	Non-Classicality	Multimode sum/ differ. squeezing	KR, VN VN	An & Tinh [16] An & Tinh [15]
1989	SDS	Hillery	Non-Classicality	Sum/difference squeezing	USA	Hillery [14]
1987	QS	Loudon, Knight	Non-Classicality	Quadrature squeezing	UK	Loudon & Knight [13]

Table 1b. A summary of key quantum protocols: quantum communication network protocols

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2016	Degraded state swap	Kirby	Q comm networks	Degraded state swapping	USA	Kirby et al. [19]
2016	Switching for entanglement	Drost	Q comm networks	Entanglement distribution	USA	Drost et al. [20]
2014	Loss based error correct.	Munro, Nemoto...	Q comm networks	Qcomm w/out Q memories	JP JP, UK	Munro et al. [21] Munro et al. [27]
2014	Quantum relay	Khalique, Sanders	Q comm networks	Concatenated entangle. swap	PK, CN, CA	Khalique & Sanders [28]

In 1987, Loudon and Knight provided an overview of the physics, generation, measurement, and possible application of squeezed light [13]. Squeezed light takes advantage of the properties of the Heisenberg uncertainty principle by reducing uncertainty in one variable while increasing the uncertainty in the conjugate variable. This squeezing can provide advantages to low-power (i.e., quantum-optical) communication, increased sensitivity in interferometric sensing, and spectroscopy. Hillery [14] introduced the idea of sum and difference squeezing of single-mode fields to expand the classes of non-classical squeezed states. This was followed by An and Tinh [15, 16], who extended the work to the more-general multimode case. In 2012, Kheruntsyan reported a violation of a Cauchy-Schwarz inequality (CSI) in matter waves as an indicator of non-classicality [17]. They recognized that a CSI violation implies but does not assure that the system may be in an EPR state or a Bell state.

In 2014, Erven et al. [18] provided an experimental demonstration of non-locality for a three-photon state. This experiment was important because entanglement between even greater numbers of particles is crucial to some quantum information processing and quantum communications protocol efficiency. Both Munro [21] and Sheng [22] theoretically investigated the use of "logical qubits" for application to quantum communications. A logical qubit is a qubit that is made up of one or more physical qubits, i.e., polarization states of a photon to hold and carry information from a sender to a receiver. They found that with small overhead in terms of physical qubits, quantum communication and measurements could be made more efficient than configurations that employed only the physical qubit. It must be mentioned that the notion of multi-photon interference introduced by Glauber [23-25] forms the basis for much of the theoretical work about entanglement and associated quantum information processing. This includes work on interferometry between n-photon states and single photons in an arbitrary state [26].

2.2 Quantum-Communication Network Protocols (Table 1b)

Quantum communications in a networked environment are currently an active area of research. The media through which quantum communication propagates may degrade the quality of the state of the quantum system, for example, through scattering and absorption. To overcome a significant bottleneck in networked quantum communications, Nemoto and Munro developed the idea of quantum communications without quantum memories [21, 27]. This concept overcomes the need for nodes to notify their neighbor that an entanglement swap was successful by instead transmitting between nodes a logical qubit consisting of many quantum states. Here, local operations on the logical qubit can recover from losses through quantum-error correction, and a new logical qubit with additional photons can be sent to the next node. Similarly, Khalique and Sanders [28] introduced the notion of concatenated-entanglement swapping between intermediate nodes in a quantum network as a type of quantum relay to entangle remote memory nodes. An analysis by Kirby et al. [19] analytically derived the error bounds when entanglement swapping is performed with degraded states. Another quantum-communications concern in a networked environment is the distribution of the entanglement to distant nodes for use in teleportation or other quantum-communications processes. Adapting typical configurations for scalable, reconfigurable optical-communications networks, Drost et al. [20] derived efficient entanglement distribution-routing protocols for N-node networks.

2.3 Quantum-Communication Protocols (Table 1c)

The earliest quantum-communications protocols were developed for quantum-key distributions (QKD). The first by Bennett and Brassard [38] in 1984 – the so-called BB84 protocol – employed two polarization states in two bases between a sender (Alice) and a receiver (Bob). Later, in 1992, a simplified quantum-key distributions protocol was developed by Bennett [36] (B92) that only used two bases and polarization orientations, and was not as secure as the BB84 protocol. Entangled photons are also able to be used for quantum-key distributions, as shown by Ekert [37] in 1991. Ekert's protocol is as secure as BB84, but due to the use of entangled photons, it is somewhat more complex to implement. One of the most important non-quantum-key distributions quantum-communications protocols was proposed by Bennett. It described a means

Table 1c. A summary of key quantum protocols: quantum communications protocols

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2015	SDT	Graham, Bernstein, Wei, Junge, Kwiat	Q comm	SuperDense Teleportation	USA	Graham et al. [31]
2015	DSQC/ QSDC	Banerjee, Pathak	Q comm	Direct Secure Qcomm	IN, CZ	Banerjee & Pathak [32]
2006	QSDC	Zhu, Xia, Fan, Zhang	Q comm	Q secure direct comm	CN	Zhu et al. [33]
2005	DSQC w/out entangle	Lucamarini & Mancini	Q comm	Deterministic Secure Qcomm	IT	Lucamarini & Mancini [34]
2002	DSQC with entangle	Bostrom & Felbinger	Q comm	Deterministic Secure Qcomm	GER	Bostrom & Felbinger [35]
1993	Teleportation	Bennett, Brassard, Peres, Wootters..	Q comm	EPR correlated particle pair	USA, CA FR, IL	Bennett et al. [1]
1992	B92	Bennett	Q comm	QKD	USA	Bennett [36]
1991	E91	Ekert	Q comm	Entangled QKD	UK	Ekert [37]
1984	BB84	Bennett, Brassard	Q comm	QKD	USA, CA	Bennett & Brassard [38]

for quantum teleportation [1] by which the quantum state of a particle could be sent to a receiver with an overhead of only two classical bits. Many advanced quantum-communications and quantum-networking protocols are based on teleportation.

A deterministic quantum-communications protocol was proposed in 2002 by Bostrom and Felbinger [35]. Their protocol requires Bob to retain one photon of an entangled pair of photons and to transmit the other photon to Alice. Alice encodes a message by performing a local operation on her photon to change the Bell state. After the operation, Alice sends the photon back to Bob, who makes a Bell-state measurement. The outcome of the Bell measurement is the encoded message sent by Alice. It was shown that protocols of this type can be developed using non-orthogonal-polarization states, and do not rely on entanglement properties [34].

Other methods, such as secure direct quantum communication using entangled particles, have been proposed. This was first reported in 2006 by Zhu et al. [33], and was followed by a similar protocol in 2015 by Banerjee and Pathak [32]. Neither of these protocols uses teleportation, and they are forms of direct quantum communications. Lastly, a new and promising protocol using hyper-entanglement [31] has been demonstrated that can encode more information per entangled pair than the usual teleportation protocols. This increases the amount of information teleported per entangled pair.

Tables 1d through 1f present summaries of quantum information transfer, privacy, quantum repeater, and quantum memory protocols.

2.4 Quantum Information Transfer and Privacy Protocols (Table 1d)

In 2013 and 2015, Chiribella and Dur investigated protocols to replicate quantum states and unitary operations. Chiribella et al. [39] found that by relaxing the requirement of a perfect copy it is possible to make imperfect copies of a quantum state within certain error bounds based on probability. The research by Dur et al. [40] found that it is possible to deterministically replicate unitary operations that act on a quantum state multiple times at the expense of success probability. Concerning the goal of privacy, in 2014 Ekert and Renner [41] showed that while research is still needed on the ultimate physical bounds to privacy,

Table 1d. A summary of key quantum protocols: quantum information transfer and privacy protocols

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2015	Super-replicate	Dur, Sekatski, Skotiniotis	Quant. info. transfer	Deterministic Q cloning	AT	Dur et al. [40]
2013	Super-replicate	Chiribella, Yang, Yao	Quant. info. transfer	Probabilistic Q cloning	CN	Chiribella et al. [39]
2014	Privacy	Ekert, Renner	Privacy	Phys. limits of privacy	UK, SG, CH	Ekert & Renner [41]

Table 1e. A summary of key quantum protocols: quantum repeater protocols.

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2016	Rydberg	Solmeyer, Li, Quraishi	Q repeater	Entanglement	USA	Solmeyer et al. [42]
2010	Rydberg	Zhao, Zoller,...	Q repeater	Entanglement	AT	Zhao, et al. [43]
2010	Rydberg	Han, Simon,..	Q repeater	Entanglement	CN, CA	Han et al. [44]
2015	M–M S-R, M–S	Jones, Kim, Rakher, Kwiat, Ladd	Q repeater networks	Entanglement distribution	USA	Jones et al. [45]
2015	Time reversal; Cluster state	Azuma, Tamaki, Lo	Q repeaters	All photonic repeaters	JP, CA	Azuma et al. [46]
2011	SPS	Sangouard, Simon, deRiedmatten, Gisin	Q repeaters	Entangle distant memories	CH, FR, CA, ES	Sangouard et al. [47]
2001	DLCZ	Duan, Lukin, Cirac, Zoller	Q repeaters	Entangle distant memories	AT, CN USA	Duan et al. [49]
1998	BDCZ	Briegel, Dur, Cirac, Zoller	Q repeaters	Entangle distant memories	AT, ES	Briegel et al. [48]

under rather weak assumptions it is possible to keep information private.

3. Quantum-Repeater Protocols (Table 1e)

Quantum repeaters and the distribution of entanglement are vital components for an information-teleportation network. In the following, several important and promising quantum-repeater protocols are discussed. The BDCZ and DLCZ protocols that actually entangle atomic quantum memories were developed by Briegel et al. [48] and Duan et al. [49], respectively. The BDCZ and DLCZ protocols use one-photon interaction with a quantum memory, or interactions between one photon each from two different quantum memories to entangle the memories, and are the focus of intense experimental research. Sangouard et al. [47] described a quantum network comprising nodes of atomic-based quantum memories and entanglement swapping to distribute entanglement to remote nodes. One protocol for entanglement distribution, developed by Jones et al. [45], highlighted that the node-to-node protocol has a large impact on network performance. They found that a mid-point-source-protocol configuration could yield orders-of-magnitude increased performance. A protocol was also suggested in which quantum memories at intermediate nodes could be eliminated in an all-photonic configuration [46]. Proposed by Azuma, this protocol avoids the complexity of interactions with matter-based qubits at nodes in favor of large-photon-number states and efficient photon routing. A recently proposed protocol involves using Rydberg states and Rydberg blockades in atomic ensembles to potentially increase bit rates in neutral-atom-ensemble repeaters by orders of magnitude [42-44].

3.1 Quantum-Memory Protocols (Table 1f)

Quantum-memory protocols use physical interactions between light (photons) and matter (atoms) to store quantum information. One low-noise and efficient scheme is controlled reversible inhomogeneous broadening (CRIB) [50-52], and has been typically used with solid-state rare-earth-doped crystal or fiber quantum memory. Atomic-frequency-comb-based quantum memories also show good results, and have been demonstrated to store multimode quantum information [53]. An early use of the CRIB protocols were the quantum memories that demonstrated the use of gradient echo to store quantum information [54, 55], and are usually fairly easy to implement. Electromagnetically induced transparence (EIT) protocols that can have long storage times with high efficiency and low noise have been shown to be optimal for storage in optically dense media [56, 57].

Table 2 presents a summary of quantum-inspired protocols. In particular, the paper by Qian et al. [58] highlighted the difficulty in determining what is and what is not quantum, and how the quantum features of a phenomenon are determined. As they demonstrated with a particular experimental setup using a diode light source, many of the "standard" tests of entanglement can be met. Similarly, the paper by Rafsanjani et al. [59] experimentally demonstrated that particular states of light encoded into alternate degrees of freedom, such as orbital angular momentum (OAM) or polarization, can be used to transfer information from a sender to a receiver in a manner similar to teleportation but without the benefits of non-locality. Investigations by Banaszek on low-power optical communication showed that even using known

Table 1f. A summary of key quantum protocols: quantum memory protocols.

Year	Protocol	Investigator(s)	Application	Description	Country	Reference
2010 2010 2006	CRIB CRIB CRIB	Longdell, Sellars. Sangouard, Gisin. Tittel, Nilsson.	Memory	Controll. Revers. Inhomogeneous Broadening	AU, NZ, CN CH, ES CH, SE, GER	Hedges et al. [51] Lauritzen et al. [52] Kraus et al. [50]
2009	AFC	Afzelius, Simon deRiedmatten, Gisin	Memory	Atomic Freq. Comb	CH	Afzelius et al. [53]
2008 2006	GEM GEM	Sellers, Longdell... Alexander, Hetet	Memory	Gradient Echo Memory	AU, NZ AU	Hetet et al. [55] Alexander et al. [54]
2007 1991	EIT EIT	Gorshkov, Lukin... Boller, Imamoglu...	Memory	Electromagnet. Induced Trans.	USA, GER DK, USA	Gorshkov et al. [57] Boller et al. [56]

classical-communications encodings, such as pulse-phase modulation and on-off keying, that the information content per photon in the low-mean-photon-number limit can exceed that of bright optical channels [60]. These bounds are useful for the design and development of low-power mobile ad-hoc networks.

4. Teleportation and Related Quantum Information Science Experiments

This section discusses recent laboratory and field teleportation experiments (see Tables 3a-3g).

4.1 Teleportation Using Polarization, Time-Bin and Hybrid Entangled Photon States (Table 3a)

Quantum teleportation experiments have been conducted in the laboratory using different forms of entanglement, e.g., polarization, time-bin, as well as hyperentangled (polarization and angular orbital momentum) and hybrid (spin and orbital angular momentum) entangled states [31, 61-64]. These expand the variety of entanglements researchers can use to teleport quantum information between distant locations.

Laboratory and field demonstrations of entanglement swapping and teleportation at telecom wavelengths have been reported using single-photon detectors to perform multi-photon coincidence measurements and Bell-state measurements [65-70]. In particular, exploratory teleportation field demonstrations were achieved by the Pan [67] and Tittel [68] research groups. Entanglement swapping at telecom wavelengths is a major step for developing networked quantum storage and teleportation between remote quantum memories. Interfacing of telecom wavelength photons with atomic memories generally requires frequency conversion from telecom to atomic wavelengths and back. Frequency-conversion research and experiments have demonstrated promising results [71-73].

In addition, there have been demonstrations of continuous-variable teleportation of photonic time-bin qubits [74-76]. Interestingly, quantum storage of time-bin-entangled photons at 795 nm and 1532 nm was experimentally demonstrated in cryogenically cooled rare-earth-ion erbium-doped optical fiber [77, 78], which

Table 2. Summary of quantum inspired classical protocols.

Year	Protocol name	Investigator(s)	Application	Description	Country	Reference
2015	Stat. optical entanglement	Qian, Little, Howell, Eberly	Classical Bell-analysis	Stat. classical optical fields	USA	Qian et al. [58]
2015	PPM encode	Banaszek	Low power Class. Comm.	Quantum measurement	PL	Banaszek [60]
2015	DoF state transfer	Rafsanjani, Mirhosseini Magana-Loaiza, Boyd	Classical teleportation	Classical nonseparability	USA CA	Rafsanjani et al. [59]

Table 3a. Summary of quantum teleportation experiments: Teleportation experiments using different types of entanglement.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2016	2 m	FWM 1550nm	Polarization EPS teleportation	- -	USA	Meyers et al. [138]
2016	12.5 km	FWM 1549.36nm & 1555.73nm	Polarization urban network teleportation.	91 ± 0.02%	CN, CA JP	Sun et al. [67]
2016	8.2 km	PPLN 795nm & 1532nm	Time-bin network teleportation.	78 ± 1 %	CA, USA	Valivarthi et al. [68]
2015	102 km	PPLN 1546.2nm & 1555.8nm	Time-bin entangled photons	82.9 ± 1.7%	JP, USA	Takesue et al. [69]
2015	- -	792nm → 1584nm PPKTP	Entang. swap & teleportation	76.3%	JP	Jin et al. [70]
2015	20 m	1047 nm → PPLN 795nm, 1532nm	Quantum storage: telecom photons	80.8 ± 4.8%	CA, USA	Saglamyurek et al. [77, 78]
2015	- -	394nm pump BBO type-I	Spin-orbit hybrid entangled states	63%	CN	Wang et al. [64]
2014	2 km	795nm, 1621nm 1560nm	Polarization EPS; InGaAs SPD	- -	FR	Kaiser et al. [65, 66]
2014	- -	405nm pump BBO type-I	Teleportation & local noise	- -	AR	Knoll et al. [85]
2014		351nm AR^+ BBO	Hyperentangled photons	87 ± 0.1%	USA	Graham et al. [31, 61, 62]
2014	- -	355nm pump BBO type-I	Spin-orbit hybrid entangled states	99.4%	CA USA	Erhard et al. [63]
2013	- -	860nm	Time-bin entangled qubits	79-82%	JP, GER	Takeda et al. [74-76]
2013	- -	ELED: QD InAs/GaAs	Entangled light emitting diode	77%	UK	Nilsson et al. [81, 82]
2012	104 m	404nm pump BBO type-II	Delayed-choice entanglement swap	68.1 ± 3.4%	AT	Ma et al. [80]
2011	- -	- -	Schrodinger's cat state	$\frac{75 \pm 0.5\%}{\text{input}}$ $\frac{46 \pm 1.0\%}{\text{output}}$	JP, AU	Lee et al. [86]

is relevant for future realization of fiber-based quantum networks. The wavelengths selected for this experiment were wavelengths that are useful for storage not only in doped fibers, but also in atomic (Rubidium) quantum memories. In fiber, there was also an experimental realization of the Peres [79] delayed-choice entanglement-swapping Gedanken experiment [80].

It was recently demonstrated that polarization-entangled photon pairs, generated by an entangled-light-emitting diode (ELED) [81, 82], can be used in quantum teleportation. The ELED light source was comprised of InAs/GaAs quantum dots. More recently, Varnava et al. [83] reported on a quantum relay over 1 km in optical fiber to teleport photonic qubits to a receiver, using their entangled-LED light source. Note that an earlier paper by Jacobs et al. [84] discussed some of the basic differences between a quantum relay and a quantum repeater, e.g., a quantum-relay system does not require the ability to store photons.

Finally, Knoll et al. [85] conducted an experiment testing how a new quantum-teleportation scheme was affected by local noise, since entangled photon pairs may suffer from de-coherence by interactions with the outdoor environment, producing mixed entangled states. According to Knoll et al. [85], testing on particular teleportation protocols can lead to the design of more-robust, noise-insensitive implementations of quantum information processes. As an example of progress in fielding quantum networks, first explored in the laboratory, it is noteworthy that in 2016, Pan et al. reported a fielded multi-node quantum network test bed to explore teleportation over a 12.5 km range [67]. In 2016, Tittel et al. [68] also fielded a teleportation network with time-bin encoded Teleportation of highly non-classical states of light (i.e., Schrödinger-cat

Table 3b. Summary of quantum teleportation experiments: teleportation experiments implemented on photonic and/or solid-state chips.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2015	- -	244 nm	Reconfigurable photonic chip	81%	UK, IT	Walmsley et al [87]
2014	- -	244 nm	Reconfigurable photonic chip	81%	UK, IT, CN NL	Metcalf et al. [88]
2013	6 mm	Microwave gate lines	Solid-state super-conducting circuit	62-80%	CH	Steffen et al. [89]

states) has been demonstrated in the laboratory [86]. These types of non-classical states are useful for fault-tolerant quantum information processing and distributed quantum computing.

In summary, representative demonstrations of teleportation show that differing types of entanglement are feasible. These may be selectively chosen for operation in particular environments, i.e., free space, or to transfer entanglement between different wavelengths for long-distance propagation and storage in quantum memories.

4.2 Teleportation on Photonic and Solid-State Chips (Table 3b)

Quantum teleportation experiments in the laboratory have been implemented on photonic and/or solid-state chips [87-89]. Walmsley et al. reported teleportation and quantum-interference experiments involving three single photons on a reconfigurable integrated photonic chip. The integrated photonic chip was coupled with superconducting-transition edge detectors [87]. Metcalf et al. [88] described a fully integrated implementation of quantum teleportation, such that all the parts of the circuit – i.e., entangled-state preparation, Bell-state analysis, and tomographic-state measurements – were performed on a reconfigurable photonic chip. Here, the individual waveguides were written with a computer-controlled continuous-wave 244 nm laser onto a germanium-doped silica photosensitive waveguide core. Steffen et al. [89] described a laboratory realization of deterministic quantum teleportation in a solid-state chip-based superconducting circuit architecture. The quantum states (transmon qubits) were teleported between two macroscopic systems separated by 6 mm at a rate of 10,000/s.

Note that Masada et al. [98] reported on the generation and characterization of entangled photon beams in an integrated photonic chip. Entangled photons generated on-chip can greatly increase stability and simplify alignment difficulties, which can be problematic for complex systems. These chip-based photonic and solid-state teleportation experiments demonstrated a means by which quantum information processing and quantum communications can be integrated on a component level with existing computing and communications technologies. For a recent review of the current state-of-the-art for on-chip entangled-photon generation and manipulation, see Matsuda and Takesue [99].

4.3 Quantum Information Transfer from a Propagating Photonic Qubit to a Stationary Solid-State Spin Qubit (Table 3c)

Quantum information transfer was also achieved experimentally from a propagating photonic qubit to a stationary solid-state spin qubit [91-97]. As an example, Hanson's group [91, 92] discussed the teleportation of arbitrary quantum states between diamond spin qubits on

Table 3c. Summary of quantum teleportation experiments: teleportation experiments between two stationary solid-state qubits,

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2016	- -	780nm, 645nm Diamond	Teleportation photon to vibrational	90.6 ± 1%	CN, USA	Hou et al. [90]
2014	3 m	532 nm, 575 nm, 637 nm	Diamond spin qubits	86%	NL, UK CA	Pfaff et al. [91, 92]
2014	25 km	532 nm, 883 nm & 1338 nm	Teleport polariza-tion state to rare earth ion state	81 ± 4%	CH, AT, GER FR, USA	Bussieres et al.[93-95]
2013	5 m	- -	Teleport QD spin states	78 ± 3%	CH	Gao et al. [96, 97]

Table 3d. Summary of quantum teleportation experiments: teleportation experiments implemented between two atomic ensembles.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2013	0.5 m	- -	C-V teleportation: cesium atoms	60-75%	DK, ES, UK	Krauter et al. [102]
2012	150 m (0.6 m)	Memory storage time: ~ 129 μs	Heralded teleport: cold ^{87} Rb atoms	88%	CN, GER, TW	Bao et al. [103]
2008	300 m	Memory storage time: 500 ns	Entanglement swap: cold ^{87} Rb atoms	83 ± 2%	GER, CN, AT	Yuan et al. [104]

separate setups in laboratories separated by 3 m. Here, a photonic channel was used to generate heralded remote entanglement between two nitrogen-vacancy (NV) center electronic spins. In 2016, an experiment by Hou et al. [90] demonstrated the teleportation of a photonic state of light to the mechanical vibrational phonon modes of a diamond crystal memory. This experiment suggested promising applications of macroscopic diamonds to quantum control and quantum information science.

In a step towards teleportation between distant quantum memories, Bussieres et al. [93] reported on quantum teleportation through 25 km of optical fiber. The polarization state of a telecom-wavelength photon was transferred to the state of hyperentangled energy-time and polarization photons at 883 nm and 1338 nm in a solid-state quantum memory comprised of a rare-earth-ion crystal. Bussieres' group [94, 95] experimentally demonstrated quantum storage and retrieval in a solid-state quantum memory (i.e., Nd^{3+}:Y_2SiO_5 rare-earth-ion crystals). Similarly, de Riedmatten's group [100] experimentally showed quantum storage (126 4.5 μs) of heralded single photons in a rare-earth Praseodymium-doped crystal (Pr^{3+}:Y_2SiO_5)m where the signal photons were 606 nm and the idler photons were 1436 nm. Later, de Riedmatten's group [101] demonstrated an example of a spin-wave solid-state quantum memory using the same rare-earth Praseodymium-doped crystal for time-bin qubits that enabled on-demand readout of the stored qubits.

Alternately, Gao et al. [96] described teleportation of the quantum state of a single photon generated by one quantum dot (QD) in a superposition of two frequency components to the spin-state of another quantum dot located in a different cryostat. To generate a photonic qubit in this experiment, a neutral self-assembled InGaAs quantum dot was used. Gao et al. [96] reported that the photon-correlation measurements performed on the emitted light from the two dots showed strong anti-bunching, proving that the experimental scheme generated nearly ideal single-photon pulses.

In summary, these representative experiments demonstrated solid-state quantum memory nodes comprised of different materials. They indicated that a solid-state quantum memory can achieve high entanglement rates and be used to make quality quantum networking nodes.

4.4 Teleportation Between Two Macroscopic Atomic Ensembles (Table 3d)

Quantum teleportation experiments in the laboratory were also implemented between two atomic ensembles. Atomic ensembles are generally well-understood physical systems, and have been shown to have long coherence times (memory time). As such, atomic ensembles are often used to test ideas and implementations of teleportation. For example, Krauter et al. [102] reported on an experimental demonstration of deterministic continuous-variable (CV) teleportation between distant (0.5 m separated) macroscopic atomic ensembles (cesium atoms) at room temperature. Interestingly, the continuous-variable teleportation was able to teleport a sequence of time-evolving spin states, which may find other applications for quantum networks. Similarly, Bao et al. [103] reported on heralded, high-fidelity quantum teleportation between two atomic ensembles (rubidium atoms) linked by a 150 m optical fiber using narrow-band single photons to establish the entanglement

Table 3e. Summary of quantum teleportation experiments: teleportation experiments implemented between two single atoms/ions.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2013	21 m	Coherence time: >0.1 s	Teleport: two single ^{87}Rb atoms	88 ± 1.5%	GER	Nolleke et al. [105]
2012	60 m	Coherence time: >100 μs	Entanglement: two single ^{87}Rb atoms	84 ± 1.0%	GER	Ritter et al. [106]
2009	1 m	Coherence time: >2.5 s	Teleport: Yb^+ ions	- -	USA	Olmschenk et al. [107]

Table 3f. Summary of quantum teleportation experiments: free-space quantum teleportation experiments.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2017	500-1200 km	Sagnac SPDC	Entanglement	In Progress	CN	Pan et al. [108, 109]
2015	143 km	808 nm, type-I BBO 404 nm, type-II BBO	Entanglement swapping	- -	AT	Herbst et al. [111]
2014	772 m 686 m	3-photon GHZ entangled states	Non-locality exp.: 3 qcomm nodes	- -	CA, UK, USA, AT, AU	Erven et al. [18]
2012	97 km	788 nm, LiB3O5 394 nm, type-II BBO	Teleport: multi-photon entangled	80.4 ± 0.9%	CN	Yin et al. [112]
2012	143 km	808 nm, type-I BBO 404 nm, type-II BBO	Quantum teleport independent qubits	86.3 ± 3.8%	AT, GER CA	Ma et al. [113]
2012	10 m	808 nm, type-I BBO 404 nm, type-II BBO	Quantum teleport: high loss channel	82 ± 1.0%	AT GER	Ma et al. [114]
2010	16 km	405 nm, type-II BBO SPDC: 810nm	Free-space teleportation	89%	CN	Jin et al. [115]
1997		394 nm, type-II SPDC: 788nm	Free-space teleportation	70% visibility	AT	Bouwmeester, Pan, Mattle, Eibl, Weinfurter, Zeilinger [2]

(physical separation of 0.6 m). The fidelities of the teleported quantum states in this experiment exceeded 90% for the six input states tested.

Alternately, Yuan et al. [104] reported on a laboratory experiment to demonstrate entanglement swapping with storage and retrieval of light using the BDCZ quantum-repeater protocol [48]. The experiment consisted of (1) two sources of atom-photon entanglement, (2) sending the entangled photons to an intermediate station for a Bell-state measurement, and (3) verifying the entanglement between the stationary qubits (i.e., the two remote atomic ensembles). In this case, the atomic memory storage time was 500 ns.

These kinds of teleportation experiments between atomic ensembles showed that atomic ensembles may have use as a long-time storage media for quantum states. Research still needs to be performed to determine the scalability of atomic-ensemble networks.

4.5 Teleportation Between Two Single Trapped Atoms/Ions (Table 3e)

Teleportation between single atoms/ions is an important step in efficient quantum networks. Quantum memories that consist of many atoms in an ensemble or rare-earth-doped crystals must contend with internal atom-atom interactions and motional degrees of freedom that make entanglement purification problematic. An example of quantum teleportation implemented between two single atoms/ions was reported by Nolleke et al. [105], who demonstrated teleportation of quantum bits between two single ^{87}Rb atoms in distant (21 m separated) laboratories. This experiment, while only attaining teleportation fidelities of 72% to 90%, nevertheless was an important step towards quantum networks with many nodes. Similarly, Ritter et al. [106] used single rubidium atoms trapped in optical cavities to demonstrate the transfer of an atomic quantum state, and the creation of entanglement between two identical nodes in separate laboratories, which resulted in the experimental realization of an elementary quantum network.

Earlier, Olmschenk et al. [107] reported on the teleportation of quantum information between atomic (ion) quantum memories separated by about 1 m. A quantum bit stored in a single trapped ytterbium ion (Yb^+) was teleported to a second Yb^+ ion using a teleportation protocol based on the heralded entanglement of the atoms through interference and detection of photons emitted from each ion and guided through optical fibers. More recently, Casabone et al. [125] described the heralded entanglement of two Ca^+ ions in an optical cavity. Slodicka et al. [126] reported on an experiment where the detection of a single scattered photon generated entanglement between two $^{138}Ba^+$ ions. Similarly, Kurtsiefer's group reported on Hong-Ou-Mandel interference experiments with single photons generated from (1) scattering by a single rubidium (^{87}Rb) atom, and (2) parametric generation through a four-wave-mixing process in a cloud of cold rubidium atoms [127]. Here, the observed interference between photons emitted by a single atom and those generated from an atom ensemble demonstrated the entanglement between distant nodes made up of different physical systems. Note also that Reiserer and Rempe [128] recently provided a detailed discussion of optical-cavity-based quantum networks with single atoms and photons. As an example, Rempe's group experimentally demonstrated the high-efficiency transfer of a photonic-polarization qubit onto a single rubidium atom within an optical cavity [129].

The recent teleportation experiments between single trapped atoms/ions have demonstrated that these systems, having very long storage times, can teleport quantum states with high fidelity. It is an active area of research to implement these types of single atom/ion memories on a chip, which can improve scalability and simplify their integration into a network of information teleportation nodes.

4.6 Free-Space Quantum Teleportation Experiments (Table 3f)

While implementations of quantum teleportation technologies in fiber have been demonstrated in the laboratory, it is important to also consider free-space quantum communications, which will play an important role in applications such as Earth-to-satellite quantum networking [130-132]. It was recently reported that China has launched a satellite to conduct teleportation and entanglement experiments, such as Bell-inequality measurements over distances from 500 km to 1200 km [108-110]. They reported that the satellite will attempt to teleport a state from a ground station while orbiting at 500 km.

Several free-space quantum teleportation experiments have accomplished transmission and detection of photons over long distances. For example Herbst et al. [111] and Ma et al. [113] reported on the free-space implementation of quantum teleportation and entanglement swapping over a 143 km path in the Canary Islands. This very-long-distance entanglement-swapping experiment was important as a fundamental benchmark for global entanglement distribution and Earth-to-satellite entanglement distribution. Ma et al. [114] reported on a free-space teleportation experiment in the laboratory (10 m) using a high-loss channel (36 dB attenuation), similar to a ground-to-satellite link, that was simulated using neutral-density filters to show that quantum teleportation is experimentally feasible in adverse conditions.

Alternately, Yin et al. [112] and Jin et al. [115] reported on free-space quantum teleportation with multi-photon entanglement in China over distances of 97 km in 2012 and 16 km in 2010, respectively. In contrast, Erven et al. [18] discussed a quantum non-locality experiment that connected three quantum communications nodes. The nodes shared entanglement that was distributed from one node to two distant nodes through free-space links that were 772 m and 686 m apart. This was a proof-of-principle experiment that may lead to multi-party quantum secret sharing and multi-party teleportation.

Finally, we note that a helpful review of the physics of free-space and atmospheric quantum communications, including discussions on teleportation and quantum measurement processes, can be found in the book chapter by Meyers et al. [7]. Figure 1, updated from the book chapter, illustrates the quantitative relationship between the propagation distance and the year the free-space quantum-communication experiment was conducted. In summary,

Table 3g. Summary of quantum teleportation experiments: related quantum information science experiments.

Year	Dist.	Lasers	Description	Fidelity	Country	Reference
2017	- -	- -	NV centers diamond entanglement distillation	- -	NL, UK	Kalb et al. [116]
2016	300 m	SPDC 850 nm 755 nm	OAM QKD	- -	CA, USA IR, GER	Sit et al. [142]
2016	26 km	FWM 1550 nm	Entanglement distribution over installed fiber	USA	Meyers et al. [138]	
2016	- -	860 nm CW	CV entanglement & EPR on a chip	- -	JP	Masada, Furusawa [117]
2015	- -	Nonclassical HOM effect for QIP	Synchronized HOM 2-photon interference	- -	JP, GER	Makino et al. [118]
2015	1.3 km	NV centers, diamond; red & yellow lasers	Loophole free Bell inequality violation	$92 \pm 3\%$	NL, ES, UK	Hensen et al. [119]
2015	3 km	Sagnac-type EPS	Entanglement in turbulence	- -	AT	Krenn et al. [120]
2015	3.7 km	403 nm $\rightarrow$ type II PPKTP $\rightarrow$ 806 nm	Loophole free Bell test in fiber	- -	CL, ES, SE, IT	Carvacho et al. [121]
2014	- -	CW 860 nm Ti:sapphire:	Nonlocal wave-function collapse	JP, PL, AU	Fuwa et al. [123]	
2014	35.5 km	405 nm $\rightarrow$ type-I BBO: 760 nm & 867 nm	Test flight: corr. photon system	SG, CH	Tang et al. [124]	

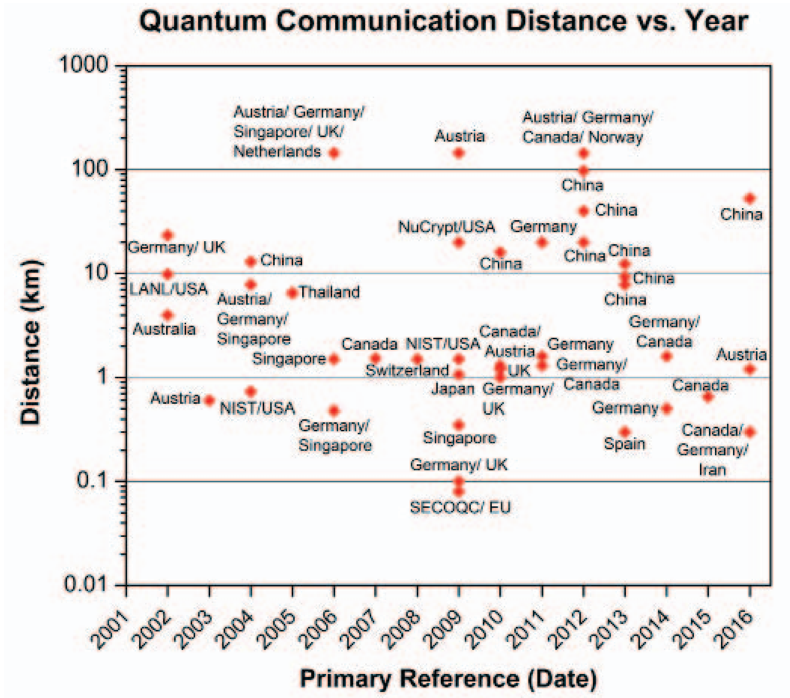

Figure 1. The quantitative relationship between the propagation distance and the year the cited free-space quantum communication experiment was executed (updated from Meyers et al. [7], *Free-Space and Atmospheric Quantum Communications*, New York, Springer, 2014).

the free-space teleportation experiments highlighted above show that long-distance teleportation, such as from ground to satellite, is an achievable goal. Such ground-to-satellite and satellite-to-ground entanglement distribution is a needed technology for a teleportation network with global reach.

4.7 Related Quantum Information Science Experiments (Table 3g)

An example of a related quantum information science experiment that facilitated the development of a quantum network was reported in 2017 by Kalb et al. [116], on distilling entanglement on a cluster of nitrogen-vacancy diamond nodes. In 2016, Furusawa's group experimentally demonstrated generation of continuous-variable entangled photon beams and EPR beams using an integrated photonic waveguide [117]. They also demonstrated the synchronization of optical photons from independent quantum memories to bring about non-classical HOM two-photon interference [118], which may be scalable for quantum information processing. Another example is from Hanson's group in the Netherlands [119], which presented the results of an experiment where they used entangled electron spins from nitrogen-vacancy diamond centers to achieve a loophole-free CHSH Bell-inequality violation over a distance of 1.3 km. Krenn et al. [120] reported the results of an outdoor, long-distance (3 km) entanglement-distribution experiment that used orbital-angular-momentum photons generated from a high-fidelity Sagnac-type polarization-entanglement source. The benefit of this type of experiment is that orbital-angular-momentum entanglement allows for larger alphabets and an increased number of quantum channels to exploit for increased data rates. Other experiments have explored using orbital angular momentum in quantum-key-distribution atmospheric applications, but did not use entanglement or teleportation [142]. To show that entanglement is a practical resource for quantum communications, in 2016, Meyers et al. [138] demonstrated two-photon polarization-entanglement distribution over an installed 27 km fiber network loop from ARL to JQI and back. The ambient environment experiment verified the survival of entanglement over the intercity optical-fiber network that ran under the Washington DC beltway.

Two related quantum information science experiments included examination of loopholes in Bell-inequality tests. Carvacho et al. [121] experimentally demonstrated Bell-inequality tests over 3.7 km of optical fiber, which mitigated post-selection process loopholes that can lead to communications security vulnerabilities. This work suggested that their energy-time entanglement setup could be used to implement practical secure communications over existing telecommunication infrastructure. Similarly, Christensen et al. [29] presented an analysis of coincidence-time loopholes in experimental Bell tests. They applied the distance-based Bell-test analysis method of Knill et al. [30] to three experimental data sets where conventional analyses had failed or required additional assumptions. As a result of this analysis, Christensen et al. [29] reported an improved protocol for Bell tests.

For a global quantum network, various environmental and relativistic effects must be examined. For example, Lin et al. [122] conducted experiments to explore relativistic effects and environmental influences in quantum teleportation. Here, relativistic effects included those related to reference-frame dependence on quantum entanglement, time dilation, and relativistic Doppler shift. The environmental influences studied were related to quantum de-coherence and the Unruh effect. In this paper, Lin et al. [122] discussed the fidelity of quantum teleportation results from four representative teleportation cases where Alice was at rest and (1) Bob was also at rest, (2) Bob was uniformly accelerated, (3) Bob was the traveling twin in the twin problem, and (4) Bob experienced alternating uniform acceleration. Understanding of these effects is important when considering teleportation of quantum information between ground-to-satellite, air-to-satellite, air-to-air, moving platforms, and ground-to-air stations. In another example, Furusawa's group [123] experimentally demonstrated the non-local wavefunction collapse of a single photon, which in essence was a proof of Einstein's EPR [9] concept of "spooky action at a distance." They argued that a single photon split between two spatially distant modes is an important entanglement resource for quantum information applications, and that their experiment was a verification of this type of entanglement.

Finally, Tang et al. [124] presented the results of a high-altitude balloon test flight of a rugged, compact, and power-efficient device for generating and monitoring polarization correlations between photon pairs at 760 nm and 867 nm under adverse ascent and descent conditions to 35.5 km. The Center for Quantum Technologies (CQT) group aims to deploy the compact device on a platform such as a nanosatellite operating at a low-Earth-orbiting altitude of 400 km [133]. CQT's recent test results demonstrated that an entangled photon source and detector package could be designed and manufactured to withstand mechanical vibrations, accelerations, changes in internal and external temperature, relative humidity and pressure, i.e., environmental conditions that most setups in the laboratory cannot endure.

Entanglement has been shown to be a phenomenon vital to modern quantum information processing. Scientific experiments are investigating both such fundamentals as non-classicality, the relation of quantum and relativistic physics, and also such practical applications as high-order entanglement for increased quantum-channel capacity. It was also shown that entanglement sources and measurements can be engineered to be robust to harsh, non-laboratory challenges.

5. Summary

The *quantum Internet*, with fixed, free-space, and atmospheric quantum network channels, is becoming a reality [134, 135]. Quantum information will be teleported through *information teleportation networks* that necessarily will include satellites. This paper has presented a review and discussion of key quantum protocols and recent developments in quantum teleportation experiments. These all contribute to the development of future quantum networks with increased security, bandwidth, and speed beyond classical capabilities. Achieving a quantum information teleportation network will require further advances in research involving both theory and experiments. For this purpose, the US Army Research Laboratory (ARL) has been developing quantum communication technologies [136-141], and is performing additional experiments to advance the state-of-the-art. Advancement in fundamental quantum protocols and teleportation technology, both involving experimental exploration, are necessary to implement future information teleportation networks.

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Appendix

Table 4. List of symbols, abbreviations, and acronyms.

ARL	US Army Research Laboratory
AR+	Argon ion
AFC	Atomic frequency comb
B92	A simplified QKD protocol developed by Bennett in 1992
BB84	First protocol for QKD developed by Bennett and Brassard in 1994
BBO	Beta Barium Borate
BDCZ	Briegel, Dur, Cirac, and Zoller
BPSK	Binary phase shift keying
CHSH	Clauser, Horne, Shimony, and Holt
CPM	Complete parity check measurement
CQT	Center for Quantum Technologies
CRIB	Controlled reversible inhomogeneous broadening
C-S	Clauser and Shimony
CSI	Cauchy-Schwarz inequality
CV	Continuous variable
DLCZ	Duan, Lukin, Cirac and Zoller
DoF	Degree(s) of freedom
DSQC	Direct secure quantum communications
E91	QKD protocol for entangled photons developed by Ekert in 1991
EIT	Electromagnetically induced transparency
ELED: QD	Entangled light emitting diode: Quantum dot
EPR	Einstein, Podolsky, and Rosen
EPS	Entangled photon source
FWM	Four wave mixing
GEM	Gradient echo memory
GHZ	Three-photon Greenberger-Horne-Zeilinger state
HOM	Hong-Ou-Mandel
InGaAs	Indium gallium arsenide
JQI	Joint Quantum Institute
LBO	Lithium borate
M-M, S-R, M-S	Protocols for distributing entanglement between two neighboring repeaters using single photons labeled as MeetInTheMiddle, SenderReceiver, and MidpointSource
MDS	Multimode difference squeezing
MSS	Multimode sum squeezing
NV	Nitrogen vacancy
OAM	Optical orbital angular momentum
PPKTP	Periodically poled potassium titanyl phosphate
PPLN	Periodically poled lithium niobate
PPM	Pulse position modulation
Qcomm	Quantum comunications
QIP	Quantum information processing
QKD	Quantum key distribution
QS	Quadrature squeezing
QSDC	Quantum secure direct communications
SDS	Sum/difference squeezing
SDT	Super dense teleportation
SPDC	Spontaneous parametric down conversion
SPD	Single photon detector
SPS	Single-photon source based protocol

Table 5. Country abbreviation list.

AR	Argentina
AT	Austria
AU	Australia
CA	Canada
CH	Switzerland
CL	Chile
CN	China
CZ	Czech Republic
DK	Denmark
ES	Spain
FR	France
GER	Germany
IL	Israel
IN	India
IR	Iran
IT	Italy
JP	Japan
KR	South Korea
NL	Netherlands
NZ	New Zealand
PK	Pakistan
PL	Poland
SE	Sweden
SG	Singapore
TW	Taiwan
UK	United Kingdom
USA	United States of America
VN	Vietnam