Topical:
Long-baseline quantum teleportation: towards Earth-Moon distances

Primary author: Thomas Jennewein
Institute for Quantum Computing and Department of Physics and Astronomy,
University of Waterloo, Canada
Email: tjennewe@uwaterloo.ca
Phone: +1-519-888-4567 ext. 37485

Co-authors:
Bei-Lok Hu
Joint Quantum Institute and Maryland Center for Fundamental Physics,
University of Maryland, USA

Shih-Yuin Lin
Department of Physics,
National Changhua University of Education, Taiwan

I. Introduction

One of the most important prerequisites for deep-space quantum networks will be the capability to perform quantum teleportation and entanglement swapping over large baselines. Extending this truly fundamental quantum protocol to Earth-Moon distances will expand validity tests of quantum mechanics and act as a precursor for quantum networks that can be useful for sensing, secure communications, dense-coding and interlinking of quantum computers in the context of Deep-Space missions. To date, only long-baseline *passive* teleportation (Pirandola2015) has been demonstrated over long distances, including into space (Ren et al., 2017). In this White Paper we discuss implementing a *complete* quantum teleportation beyond the planetary scale, initiated through the Deep Space Quantum Link (DSQL) collaboration (Mohageg2018). We propose to implement demonstrations of teleportation at distances up to the Earth-Moon distanced by, connecting a ground receiver (or the International Space Station - ISS) with the lunar Gateway.

Quantum State Teleportation (Bennett1993) is a uniquely non-classical concept, as it perfectly transfers an unknown quantum state from one system to another by using two channels: a maximally entangled state and a classical signal. The first step is to establish long-distance distribution of entangled photons, see Figure 1(a), over large distances in space, as shown by the *Micius* mission, which performed a Bell-test over 1200 km by measuring the photons at different ground sites with fast varying analyzers. Quantum teleportation utilizes such remote entanglement as follows (Bouwmeester1997): first, an entangled photon pair is generated by Charlie [photons A and B in Figure 1(b)], and *A* is sent to Alice, and *B* to Bob. Alice performs a Bell State Measurement (BSM) (Weinfurter1994, Mattle1996, Casmaglia2001) on photon *A* jointly with the unknown quantum state carried by another photon, *C*, thereby projecting her two photons into an entangled state. This BSM will project Bob's photon *B* onto one of four possible states depending on the BSM outcome. Bob, in the meanwhile must retain photon *B* after its arrival in a quantum memory until he receives Alice's BSM result via the classical channel, which he then uses to apply a unitary operation to fully recover the original input state. Note that neither Alice, Charlie nor Bob obtain any knowledge on the input state, and the final unitary transformation depends only on the (random) BSM result, and thus the protocol fully obeys quantum-no-cloning (Wooters1982).

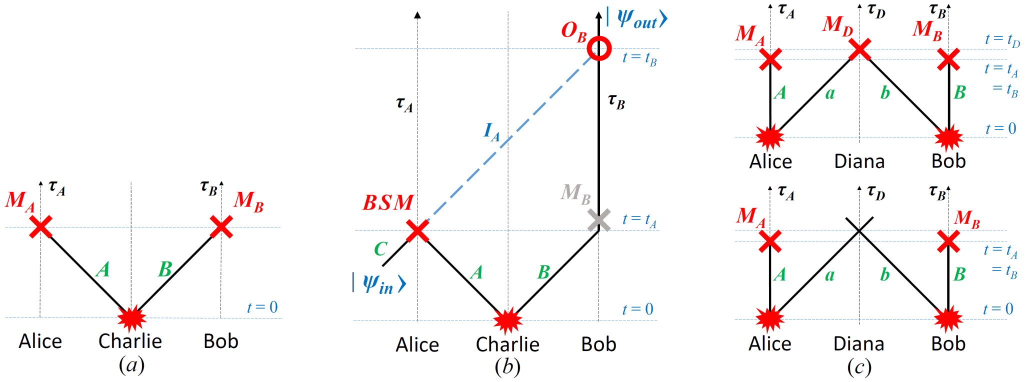

Figure 1. Spacetime diagrams of the Bell test (*a*), quantum teleportation (*b*) and delayed-choice entanglement swapping (c), where Diana may choose to perform a joint measurement (M_D) or not. Here, **X** and **O** represent local measurement and operation events, respectively. The black solid lines represent the worldlines of the participating quantum objects, angled worldlines are flying photons, while vertical worldlines correspond to quantum memories. Note that Charlie / Diana could also reside at Alice or Bob.

Standard quantum theory places no bound on the distance over which entanglement or teleportation may be accomplished, however, the classical and entanglement channels impose practical limits on a teleportation implementation. First, the transfer speed for quantum teleportation is limited to luminal signaling due to the classical channel: even if the entangled "receiving" particle is already at its destination, the correct input state can only be retrieved after the classical information about Alice's BSM has arrived. Second, the protocol suffers from decorrelation or decoherence in the entangled channel used as a communication resource, and thus any environmental influence could impact the teleportation fidelity.

In the ultimate quantum network configuration, the quantum teleportation or entanglement swapping will need to make use of quantum memories with ultra-long storage times. Several proposals showed the viability and approach for placing quantum memories into space (Gündoğan2021A, Gündoğan2021B) as this is recognized as a priority development. For instance, a spacecraft could carry a memory of stored, entangled quantum bits (qubit), and gradually use them up for quantum communication tasks such as quantum networking, secure communications, quantum computing, or super-dense-coding (Mattle1996).

Quantum teleportation was first achieved outside a single laboratory in 2002, between two stations separated by 55 m using optical fiber (Marcikic2003). In 2003, the first long-baseline teleportation with an active unitary operation at the receiver was demonstrated over 500m (Ursin2004). In subsequent years, quantum teleportation was demonstrated over increasing distances including 100 km (Yin2012), then 143 km (Ma2012A). The 2017 *Micius* mission (Ren2017) demonstrated the teleportation of single-photons from ground to a low-Earth-orbit satellite through an uplink channel over distances of up to 1,400 km. While these demonstrations represent major advances, all involved photons were generated by the same laser pulse, and only after their creation was the receiver photon transmitted over a large distance. This implies that the actual entangling BSM operation occurred while all the photons were technically still in, or very close to, the original laboratory, which largely defeats the main purpose of a scalable quantum networking application.

Moreover, in *passive* teleportation (Pirandola2015), Bob's unitary transformation according to the classical signal from Alice is performed not physically, but virtually via data analysis (Ren2017) to obtain the fidelity of quantum teleportation. In this approach Bob does not keep and maintain the quantum coherence of his photon until he receives Alice's classical signal. Instead, Bob performs the measurement immediately after he receives the photons [M_B in gray in Figure 1(b)] in a randomly chosen basis. Bob can even perform the measurement before Alice's joint measurement on A and C in the bookkeeper coordinates. Thus, this passive scheme is very far from the *complete* quantum teleportation protocol.

Entanglement swapping is the generalization of teleportation, and more difficult to achieve than a Bell test or teleportation because two entangled photon pairs are involved, and all operations must achieve high fidelity in order to reach a useful quality of entanglement (Jennewein et al, 2002). In particular, for Deep-space scenarios, both Alice and Bob may store part of their states [carried by A (B) of the entangled *Aa*-pair (*Bb*-pair) in Figure I(c)] in a local quantum memory until they are instructed to perform their local measurements. In each run a joint measurement on two photons [a and b in Figure 1(c)], each belonging to an entangled photon pair produced by Alice or Bob, may be performed by Diana, even at a later time. Just as for the *passive* quantum teleportation, the time order of the measurements by Alice, Bob, and Diana in different bookkeeper's coordinates can be different once they are spacelike separated. In particular, the decision of performing joint measurement - or not - can be made by Diana later than both local measurements by Alice and Bob in bookkeeper's coordinates, so that quantum entanglement of the photons of Alice and Bob appears to be determined after the fact by Diana's delayed choice, as seen in that reference frame [Figure 1(c)]. This delay feature is a basic requirement for future quantum networks, and was first studied as fundamental experiments (Peres2000, Ma2012B) on delayed choice entanglement swapping.

II. Key technical issues for a *complete* quantum teleportation with long baseline

In implementations of quantum teleportation, as well as entanglement swapping – both used for quantum repeaters (Briegel1998) – the photons should be generated by ***independent*** **emitters**. This is experimentally much more challenging compared to the early implementations (Bouwmeester 1997, Jennewein2002), because the different photons must be spectrally and temporally indistinguishable in order to achieve a high-quality BSM operation, based on two-photon interference (Weinfurter1994, Casmaglia2001). Typically, entangled photons have a temporal coherence of about 200-500 fs, which is at the technical limit for synchronizing separate pulsed lasers. The first demonstration of two-photon interference using two synchronized femtosecond lasers was reported in 2006 (Kaltenbaek2006), and entanglement swapping in 2009 (Kaltenbaek2009). Another approach to realize truly independent optical sources uses two entangled photon sources operated with continuous wave lasers, and **very narrow-band filtered** photons (Halder2007), with photon coherence times of several hundred picoseconds, longer than the timing resolution of detectors, however at the cost of photon rates. A particularly promising approach is to generate entangled photon using high-finesse optical resonators; such sources are intrinsically narrow-band, rather than frequency filtering. For example, photon pairs generated in lithium niobate whispering gallery resonators have coherence lengths tunable around 10-20 ns (Fortsch2013), and could be engineered to match the spectrum of atomic memory transitions (Schunk2015), which could be a critical tool for implementing teleportation. However, when using such narrow-band sources, the spectral **Doppler shifts** caused by relative motion of the platforms need to be compensated; e.g., a relative velocity of 10,000 km/s leads to a frequency shift of 3.3×10^{-5}, or ~ 6.4 GHz; which is comparable to the bandwidth of the light. This shift must be corrected before coupling the photon to a quantum memory, or interfering it with another photon. Therefore, for Earth-Moon teleportation, specific emphasis will be on the **synchronization and frequency alignment** of the sources and the photon-interference.

Another issue in photon-based quantum teleportation is the fidelity reduction due to the **photon emission statistics** of typical **realistic photon sources**. Most early demonstrations of teleportation based on entangled photon sources used spontaneous parametric down conversion (SPDC) (Kwiat1995, Zhang2021) or four-wave mixing (Chen2005, Camacho2012). These sources exhibit thermal emission statistics, which constrain the probability of creating exactly one photon pair in a pulse, where the vacuum emissions lead to inefficiency while two or more pair emissions lead to noise. Multiplexing of multiple SPDC sources (Meyer-Scott2020) is a promising technical solution. Alternatively, as was proposed by the team of the lead author of this White Paper (Bourgoin2013), quantum teleportation in space will benefit from **deterministic photon emitters**, e.g. quantum dots. While technically challenging, recent demonstrations of high-efficiency coupling of photons from quantum dot emitters into optical fibers (Zhai2021), and the generation (though not yet efficient extraction) of high-quality polarization-entangled photon pairs (Huber2018, Schimpf2021) are very promising developments.

III. Towards achieving the Earth-Moon distance

The gravitational effects on photons in the quantum optical experiments at the Earth-Moon scale are mainly those for electromagnetic fields in a fixed spacetime background: *a.* the gravitational Doppler shift ($\Delta\lambda/\lambda_0 \sim 10^{-9}$) and *b.* the Wigner rotation of photon polarization (Schleich & Scully 1982, Brodutch &Terno 2011, Lin & Hu 2021). These can be negligible compared to similar effects due to the relative motion (Lin et al. 2015) – the radial Doppler shift $\Delta\lambda/\lambda_0 \sim 10^{-5}$ and the transverse Doppler shift $\Delta\lambda/\lambda_0 \sim 10^{-10}$ at the Earth-Moon scale – which could be suppressed by executing the experiments during periods of minimal relative radial motion, and by dynamically correcting the shift according to reference laser beams from the photon sources (Ren2017).

The pico-second synchronization between the photon sources located at the different locations, Alice and Charlie (Fig 1 (b)), or Alice, Bob and Diane (Fig. 1 (c)), is a critical challenge. However, synchronization at that level has been achieved with high-speed optical communication. Furthermore, quantum memories could provide another means to synchronize the different photons, as the memories could release the photons based on local trigger events. A full quantum teleportation from Alice (Earth or ISS) to Bob (Lunar Gateway) assisted by quantum memories, requires these to have coherence times of around 1.3 seconds, which may be achievable by emerging technology (Rančić2018) within the coming decade.

Long range entanglement swapping could also lead into the next step for long-distance tests of Bell's inequality. In the conventional ground-based Bell-test experiments (Figure 1 (a)) requiring transmission of multiple entangled photons, the late events in each agent's worldline would be inside the future lightcones of the early events of the other agent's worldline, potentially opening up a "memory loophole" (Barrett2002). The O(1)-second travel time of light signals along the Earth-Moon baseline offers the possibility to perform sufficiently many resolvable runs within this travel time, so that a whole set of outcomes by one agent for ensemble averaging can each be spacelike-separated from the measurement events in the same period by the other agent. In the Bell tests this will eliminate the two-sided memory of the early measurements by the other agent (Gill 2001, Larsson 2014). To achieve this, however, the photon emission rate of the source of entangled photon pairs has to be very large because the expected photon losses due to diffraction of optical beams for such a long distance.

With a photon source (Charlie in Figure 1) or a measurement agent (Diana) placed around the mid-point of the Earth and the Moon, if the agent takes a transfer vehicle traveling between the ISS and the Gateway, the speed of the vehicle would be ~ 10^3 m/s around the mid-point. This would lead to a radial Doppler shift of the order of $\Delta\lambda/\lambda_0 \sim 5 \times 10^{-6}$ even if Alice and Bob have negligible relative radial motion, and has to be corrected. Alternatively, suppose Charlie or Diana is carried by a satellite in a high earth orbit, the radial Doppler shift of the emitted or received photons may be suppressed in those time windows of negligible relative radial motions between the agents.

With potentially all parties (Alice, Bob, Charlie/Diana) in high relative motion with respect to each other, it is important to consider the *frame dependence*, which is innate with canonical quantization, where one first chooses a coordinate system and specifies the time coordinate, and assigns the quantum state evolution accordingly. Note that simultaneity in a reference frame is a different concept from synchronization of the experimental stations. Simultaneity is relative, and quantum states in different reference frames are in general incommensurate when their associated time slices are different.

IV. Link performance estimates

For simplicity and as a nominal worst-case, we consider four-photon entanglement swapping scheme using two entangled photon pairs (Jennewein2002) generated by SPDC, at 810 nm. Clocked at F_{clock} = 1 GHz, this source emits entangled pairs with probability P(1)=1% per pulse.

Assuming the link uses a 0.22 m transmitter aperture and a 1.0 m receiver aperture across the baseline of Earth's diameter (around 13,000 km), with 10 dB of additional losses, the net link efficiency is about η_L~ -43 dB. In this configuration, roughly 500 entangled photon events (2-fold) per second are expected, which yields 5 teleportation events (4-folds) per second. This necessitates around 350 seconds of integration to obtain the desired counting statistics (ca. 1700 events). The required noise count rate is about N_{noise} = 0.25 noise events per clock pulse per second, and a photon-time-of-arrival resolution and timing synchronization error less than 1 nano-second, achievable with state-of-the-art detector systems.

For a teleportation between Moon - Earth (384,000 km), it will be necessary to increase the apertures. Assuming a 0.5 m transmitter (Gateway) and a 3.5 m receiver (Ground or ISS) respectively, with parameters as above, the link is estimated at η_{EM} ~ -55 dB. The expected 2-photon rate is around 30 per second, yielding successful 4-fold teleportation events of around 0.3 per second, requiring an accumulation time of around 5,600 seconds (ca. 1.5 hr), which is still in the realm of feasible. More favorable rates (and margins) could be expected if the ground-based receiver could be as large as 10 m, with the 2-fold photon pair rate of 250 per second, the teleportation rate (4 folds) is about 2.5 per second, and a total measurement time of ca. 700 seconds is sufficient to achieve the required counting statistics.

Even more dramatic improvements of these long-distance teleportation rates are expected with enhanced quantum photonic devices. With the use of deterministic photon pair emitters, the 4-fold rates would readily increase by 4 orders of magnitudes. Furthermore, space suitable quantum memories, have already been identified and technical developments are planned, and long-baseline quantum networking becomes conceivable, and even ground based quantum memory systems which are quite mature, could reach our requirements in the coming decade.

In summary, it is interesting that the performance estimates for long-baseline teleportation over the Earth-Moon distance indicate a demonstration is already (albeit borderline) achievable with today’s technology, and will be dramatically improved with emerging quantum technologies. Thus, implementing a *complete* quantum teleportation link between a ground station and satellite is a viable objective for the DSQL mission.

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