A Roadmap Towards Entanglement Distribution Over Useful Telecom Distances

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Abstract: I review progress on the distribution of photonic entanglement under extreme conditions of noise and loss, enabled by high-dimensionally entangled quantum states of light. © 2024 The Author(s)

The distribution of quantum entanglement over practical distances unlocks many applications in quantum technologies, ranging from device-independent quantum communications to distributed quantum computing. However, entanglement is susceptible to noise and loss, which are present in any real-world communication link. For example, the distribution of entanglement over existing classical telecommunication links or over dedicated free-space channels exposed to sunlight introduces noise in the form of spurious detection events. Similarly, propagation through optical fibres or the atmosphere necessarily introduces loss. Losing one photon from an entangled pair can lead to false detection events when the lost photon is replaced by an uncorrelated background or dark detection event. Thus, there are limits to how far entanglement can be distributed, which depend on the assumptions under which the distribution is performed. In the device-dependent case, where all the measurement devices are trusted, entanglement can be certified by the violation of a suitable entanglement witness. In the fully device-independent scenario, entanglement is normally certified through the violation of a Bell inequality. The intermediate one-sided device-independent scenario, where only one party is trusted, requires the violation of a so-called steering inequality. These three different scenarios impose increasingly stricter demands on the amounts of loss and noise that can be tolerated before entanglement is lost. For example, loophole-free Bell tests simultaneously require a very high quality entangled state as well as a high threshold detection efficiency. Consequently, device-independent quantum communication has only recently been demonstrated over distances up to 400m and at very low data rates [1].

High-dimensional entanglement involves the entanglement of inherently high-dimensional photonic degrees of freedom such as position-momentum [2] or time-frequency. High-dimensional or "qudit" entanglement offers several advantages over qubit-entangled systems such as stronger quantum correlations [3] and more practical tests of nonlocality [4]. Notably, the large dimensionality of photonic platforms has enabled device-dependent entanglement distribution with greater noise resistance [5, 6] and higher information encoding capacities [7] than qubits. Qudits were even recently used to demonstrate entanglement distribution over 10.2km in the presence of daylight [8]. In the quantum steering scenario, the use of qudits has enabled demonstrations of genuine high-dimensional steering as well as increased noise-robustness [9]. In recent work, we introduced a test of quantum steering that harnesses the advantages of high-dimensional entanglement to be simultaneously noise-robust and loss-tolerant [10]. Despite being constructed for qudits, our steering inequalities require only a single detector at each party and are able to close the fair-sampling loophole in a time-efficient manner. We showcase the improvements over qubit-based systems by experimentally demonstrating quantum steering in up to 53 dimensions, free of the fair-sampling loophole, through simultaneous loss and noise conditions corresponding to 14.2 dB loss equivalent to 79 km of telecommunication fibre, and 36% of white noise. Our work conclusively demonstrates the significant resource advantages that high-dimensional entanglement provides for entanglement distribution, and opens the door towards practical quantum networks with the ultimate form of security.

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