QCrypt2015 Tutorial

Quantum Repeaters

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The distribution of entangled quantum states over large distances plays a key role in quantum information science. For example, it enables the implementation of long distance quantum key distribution, quantum teleportation, and large scale quantum networks. The task is however very challenging as the direct transmission of quantum bits in optical fibers is limited to a few hundred km, due to unavoidable photon absorption.

A potential solution to this problem was proposed in 1998 by Briegel, Dür, Cirac and Zoller[1], and named quantum repeater. This solution combines entanglement swapping and quantum memories. The main idea (see Fig 1) is to divide the total distance into several segments, to distribute entanglement independently within each segment, and then to extend the entanglement distance via entanglement swapping. For this scheme to be scalable, it is essential that the various segments be independent from each other. This implies that (1) the entanglement distribution within each is segment must be heralded, i.e. there must be a signal telling us when the entanglement is successful. (2) The entanglement must be stored in quantum memories, such that the entanglement within each segment must not necessarily happen at the same time.

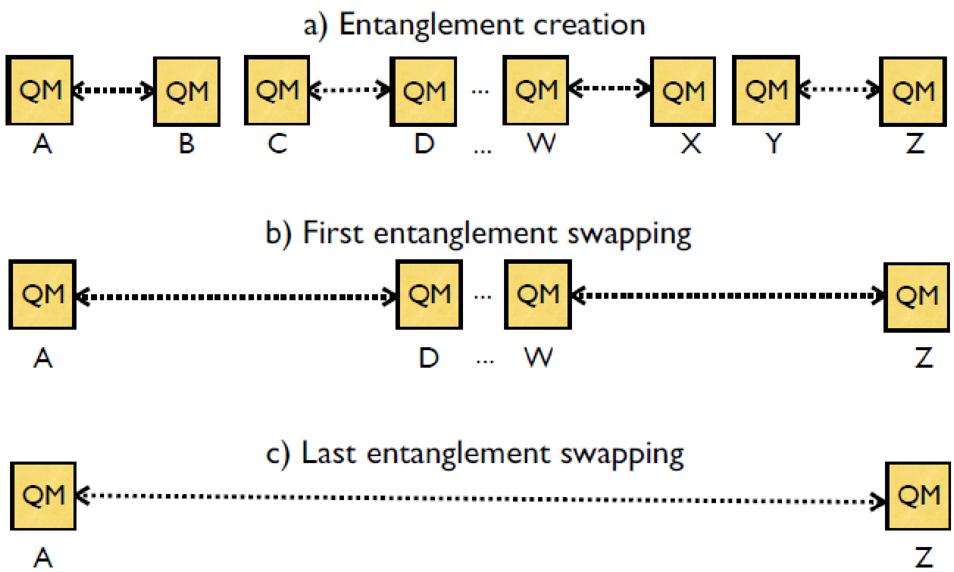

Figure 1: schematic of a quantum repeater (taken from ref. [5])

In this tutorial, I will explain the challenges to distribute entanglement experimentally over continental scale. I will review the main protocols based on heralded entanglement that have been proposed as quantum repeaters, explaining their advantages and drawbacks. I will also review the progress and state of the art about the main building blocks, quantum memories and compatible photon pair sources.

The first proposal practical quantum repeater architecture was proposed in 2001 by Duan, Lukin, Cirac and Zoller (DLCZ), using atomic ensembles and linear optics[2]. The proposal is based on the creation, storage and transfer to light of single collective spin excitation in atomic ensembles. Entanglement between remote atomic ensembles is then created by quantum interference in the detection of photons emitted by the atomic ensembles. The entanglement is then heralded by the detection of photon after a beam splitter located at a central station between the two ensembles. This pioneering proposal triggered an intense experimental effort to realize the main building blocks of the protocol, including the demonstration of elementary segment of quantum repeaters[3,4].

The DLCZ protocol has the great advantage that is relies only on atomic ensembles, linear optics and single photon detection and is therefore in principle realizable with current and near future technology. However, it was soon realized that, despite an exponential gain over direct transmission, the DLCZ scheme alone would lead to very low entanglement distribution rates over very long distances (> 1000 km), which in turn would require extremely long memory storage times. Since then, various protocols using the same resources have been proposed, that significantly increase the repeater count rate[5]. Other protocols based on heralded entanglement have been proposed with different resources, such as single ions[6], single atoms in cavities[7] or Rydberg atoms[8,9]. Architectures based on quantum error correction have also been proposed recently, leading to potentially higher count rates[10,11], but significantly more demanding in terms of resources (number of qubits) and required capabilities (fast high fidelity quantum gates).

Several limitations were identified that limit the available count rate of the original DLCZ proposal. I now summarize these limitations, together with potential solutions. The first one is that, due to the probabilistic nature of the spin-wave creation, there is an intrinsic trade-off between the probability to generate a pair per trial and the fidelity achievable. This means that in practice, the excitation probability has to remain low in order to achieve a sufficient fidelity for the repeater protocol. In order to overcome this limitation, novel protocols have been proposed, that use single photons sources[12] or that can generate light-matter entanglement almost deterministically, using combinations of DLCZ quantum memories, albeit with more resources needed[13]. Another possibility is to use single ions or single atoms in cavity, where deterministic light-matter entanglement can in principle be achieved.

The second limitation, which is common to all protocols based on heralded entanglement, is that the need for heralding imposes a latency corresponding to the communication time between two remote quantum memories. For large distances between the nodes, this severely limits the repetition rate of the experiment, and in turn the entanglement distribution rate. This limitation can be partly overcome if quantum memories able to store multiple qubits are used (multimode memories)[14]. In that case, the repetition rate is not limited by the communication time, and the entanglement creation rate of the repeater can be increased by several orders of magnitude. Different types of multiplexing can be used, e.g. temporal[12,15], spectral[16] or spatial[17].

Another limitation of protocols based on linear optics is that the efficiency of each swapping is at most ½, which strongly decreases the available count rate for large number of segments. In order to overcome this problem and reach deterministic entanglement swapping, it is mandatory to achieve strong non-linear interactions between the stored qubits. This is difficult to achieve using atomic ensembles, but proposal have been done to realize this using collective Rydberg excitations[8,9]. Alternatively, it can be realized using single systems, e.g. single ions[18], single atoms in cavities or single nitrogen-vacancy (NV) centers in diamond.

Finally, all realizations of elementary segments of quantum repeater to date, including those using the DLCZ approach with cold atomic ensembles, but also others based on single emitters such as single ions[18], single atoms[19,20] and NV-centers in diamond[21], have been performed with quantum memories emitting photons in the visible or near infrared, where absorption in optical fibers is very high (between 2 and > 10 dB/km). In order to obtain quantum memories compatible with photons at telecom wavelengths, techniques based on non-degenerate photon pair sources (with one atom resonant photon and one telecom photon)[22,23,24] or on quantum frequency conversion[25,26] are being developed. Research on quantum memories based on Erbium doped solids absorbing light at telecom wavelength is also being pursued[27.28].

The distribution of entangled states over continental scale is a formidable challenge in quantum physics. Although first enabling steps have been taken, there is still a long way before a practical quantum repeater can be built. In particular, quantum memories, light sources and interfaces need to be considerably improved and simplified in order to enable scaling up to repeaters with several links. This will require a concerted effort between various fields, including quantum information, quantum optics, non-linear optics, atomic physics and solid state physics. A successful realization of a quantum repeater able to beat direct transmission would be a huge step forward for our ability to deploy quantum information over large scales and would open new opportunities for quantum cryptography. At the same time, research in this field offers unique opportunities to demonstrate fascinating quantum effects over large distances and to increase our level of control of the interaction between quantum light and matter, which may find application in other light-based quantum technologies.

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