SEVENTH FRAMEWORK PROGRAMME

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Project acronym: **Q-ESSENCE**

Project title: **Quantum Interfaces, Sensors, and Communication based on Entanglement**

Funding Scheme: **Collaborative Project (Large-Scale Integrating Project)**

DELIVERABLE REPORT

Deliverable no.:	**D2.4.3**
Deliverable name:	**Report on the optimisation of architectures for quantum repeaters to maximise throughput**
Workpackage no.	**WP2.4**
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Nature	**R = Report**
Dissemination level	**PU = Public**
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Actual / forecast delivery date	**30/04/2013**
Status	**Submitted**

The high level goals of this deliverable are reports on architectures for quantum repeaters and their optimisation to maximise throughput, along with reports on advancements made during the project for entanglement distribution architectures and protocols, and their potential for application in quantum networks. A significant range of published reports comprise the results that constitute this deliverable, performed over the complete duration of the project. New proposals have been put forward and researched, providing detailed studies of architectures, new enabling technologies and strategies/protocols for long distance entanglement distribution and networking. All these deliverable report contributions are outlined below, but with emphasis placed on the work not reported in detail in previous reports.

New enabling technologies:

Loss-resistant state teleportation and entanglement swapping using a quantum-dot spin in an optical microcavity has been proposed, studied and reported. The proposed schemes could be realised with current technologies. Unit fidelity and >10% efficiency should be achievable with weak coupling, and near unit fidelity and >35% efficiency with strong coupling. (See publication report [HR1-11].)

Quantum repeater systems utilising atomic ensemble and linear optics technologies have been comprehensively studied, reviewed, analysed in detail and reported. (See publication report [SSR2-11].)

Strategies/protocols:

A strategy for device-independent quantum key distribution (DIQKD) using heralded qubit amplifier technology has been proposed, studied and reported. A key feature of this approach is the use of a Bell test to verify long distance entanglement. (See publication report [GPS1-10].) A very significant extension of this work has been made and reported in [MRS1-12]. Here heralded qubit amplifier technology is applied in a quantum repeater scheme. The scheme relies on an on-demand entangled-photon pair source, which is built upon on-demand single-photon sources, linear optical elements and atomic ensembles. Very conveniently, the imperfections affecting the states created from this source (caused e.g. by detectors with non-unit efficiencies) are systematically purified through an entanglement swapping operation based on a two-photon detection. This feature allows the distribution of entanglement over very long distances with a high fidelity, i.e. without vacuum components and multiphoton errors. As a consequence of this, the resultant quantum repeater architecture does not necessitate final post-selections and is thus able to achieve very high entanglement distribution rates. This work also provides unique opportunities for device-independent quantum key distribution over long distances with linear optics and atomic ensembles.

The key on-demand entangled source is described in figure 3 below reproduced from [MRS1-12]. A schematic of the whole repeater system is shown in figure 4 below reproduced from [MRS1-12]. A benchmarking distance of 1000 km is often used to illustrate quantum repeater performance (a useful long distance that cannot be reached without repetition). Table 1 reproduced from [MRS1-12] demonstrates that high fidelity states can be distributed over this distance with the scheme.

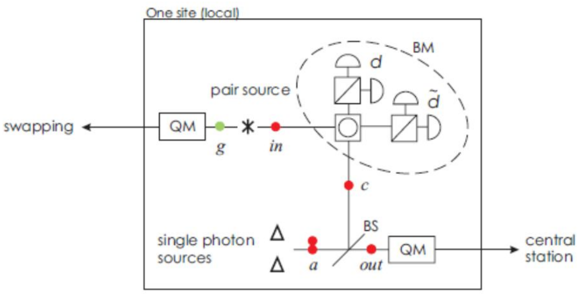

Figure 3: (Color online) Heralded source of entangled pairs, QM - quantum memories, BM - Bell measurement. A pair source (star) produces a polarization entangled state in a probabilistic way in modes *in* and g. Two single-photon sources (triangles) produce a product state of two photons with orthogonal polarizations in the same spatial mode a. The mode a is sent through a the beam splitter (BS) with tunable reflectivity R (in intensity) and the two photon coincidence detection d-$\tilde{d}$ teleports the mode *in* to the mode *out* (up to a unitary transformation). This leads to the entanglement between the modes g and *out* which are then stored in the memories. The BM here is inspired by [7] and consists of one PBS in the $\pm 45^o$ basis followed by a PBS in H/V basis at each output.

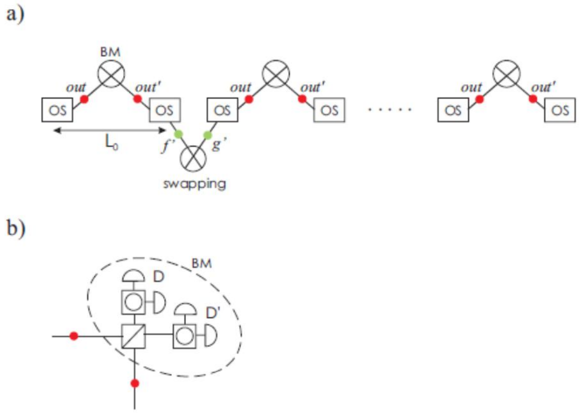

Figure 4: (Color online) a) A scheme of the whole repeater consisting of 2^n elementary links of length L_0. Blocks labeled OS represent the *on site* blocks presented in Fig. 3. The entanglement in each elementary link is created by converting the *out* atomic excitations into optical modes and by performing subsequently a Bell measurement (BM). The BM is represented here by the $\otimes$ symbol. When the entanglement is succesfully created in neighboring elementary links, they are then swapped using the same BM (swapping between modes f' and g' is shown; see the text for the details). b) Detail of the BM used in the elementary link and for the swappings. The BM consists of one PBS in the H/V basis followed by a PBS in $\pm 45^o$ at each output.

T_{tot} [s]	p	q	R	F	γ_{rep} [MHz]
7.4	$6 \cdot 10^{-4}$	1	0.12	0.96	60
7.8	$3.6 \cdot 10^{-3}$	1	0.23	0.9	6
19.2	$6 \cdot 10^{-4}$	0.66	0.17	0.96	60

TABLE I: Performance of the proposed quantum repeater based on qubit amplifiers. The results correspond to the distribution of entangled pairs over $L = 1000$ km, with memory and detector efficiencies $\eta_M = \eta_D = 0.9$ using 16 links ($n = 4$). T_{tot} is the average time for the distribution of one entangled pair, p (q) is the probability with which the pair source (single-photon sources) used within the qubit amplifier emits a photon-pair (emit a single photon). R is the beam splitter reflectivity. F is the fidelity of the distributed state and γ_{rep} is the basic repetition rate of sources.

Architectures:

An architecture for establishing long distance entanglement through a quantum repeater network based on the rapid firing of repeater nodes has been proposed, studied and reported (see publication report [MHS1-10]). This architecture requires a number of qubits at each node that scales only polylogarithmically with the communication distance. This “transmitter redundancy” at each repeater node is illustrated in Figure 1 below reproduced from [MHS1-10]. For the benchmark 1000 km overall distance, this repeater architecture could achieve ~2500 entangled pairs per second using a node separation of 40 km, a figure that compares very favourably with other schemes. Another appealing feature of the proposed scheme is that it only requires memory coherence over the round-trip communication time between adjacent nodes, rather than the full network. For detailed comparisons, see the discussion section of [MHS1-10].

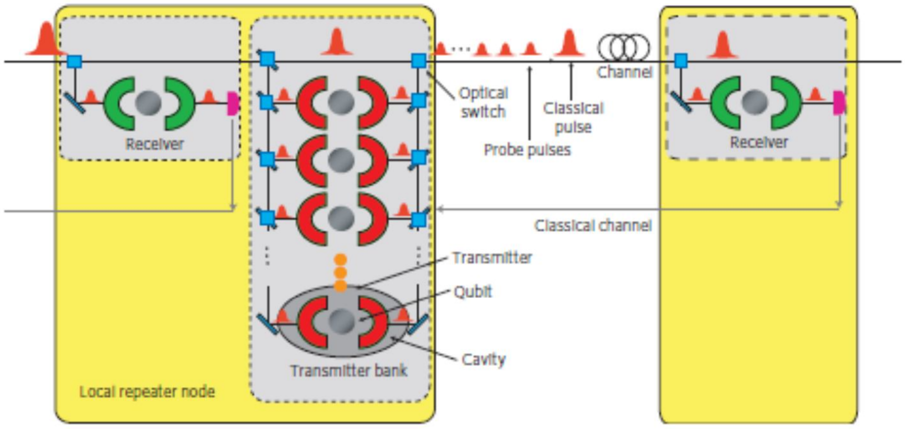

Figure 1 | Schematic of a quantum repeater node and its link to its nearest neighbour. The repeater node is composed of two fundamental components: a bank of transmitters (cavities each with a qubit within them) and a bank of recievers (receiving cavity with a qubit within it and a signal detector). There are generally more transmitters than receivers, but here we consider only a single receiver. The situation where we have a single transmitter and a single receiver in each node is equivalent to existing entanglement-distribution schemes. Two channels are required: a quantum channel to connect the adjacent nodes, which carries a heralding pulse and the quantum-optical signals in the forward direction, and a classical channel to return information about which transmitter was successful.

Finally, a review of quantum communication technology, including perspective on the aspects of such communications that rely on long distant entanglement has also been reported (see publication report [GT1-10]).

References:

[HR1-11] C. Y. Hu, J. G. Rarity, *Loss-resistant state teleportation and entanglement swapping using a quantum-dot spin in an optical microcavity*, Phys. Rev. B **83**, 115303 (2011), arXiv:1005.5545.

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[GT1-10] N. Gisin, R. Thew, *Quantum communication technology*, Electronics Letters **46**, 965 (2010), arXiv:1007.4128.