Short Roadmap to Quantum Networking by Light-Matter Interfacing

(milestones, technologies & timeline)

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The coherent interconnection of small quantum units to larger networks is a key procedure enabling numerous applications of quantum technology, such as distributed quantum processing, quantum simulation, quantum-enhanced sensing, and quantum communication. Faithful state mapping or remote entanglement of qubits are the basic requirements to be met. In turn, these call for the efficient and reliable interfacing of matter and light to couple the states of stationary and flying qubits. Whilst the direct approach of collecting a fraction of the scattered photons has been good for a proof of principle, high photon losses diminish its success rate. This makes scaling difficult if not impossible, and underpins the need for a refined strategy.

One popular remedy is cavity-enhanced light-matter coupling and single-photon emission, used to eventually demonstrate, realise or implement quantum network links. For a successful implementation of such a quantum interface, an indicative series of steps has to be taken which are largely based on one another:

(1a) Cavity mirror manufacturing and high-finesse dielectric coating.
(1b) Cavity mounting, alignment and vibrational isolation.
(1c) High-bandwidth cavity frequency locking far off resonance with the emitter.
(1d) Efficient coupling of photons from the emitter via the cavity into the output field mode.
(1e) Preparation and sufficient localisation of the emitter within the cavity mode.

(2a) Demonstration of the Purcell effect with a single emitter coupled to a cavity.
(2b) Demonstration of the singleness of emitted photons (Hanbury-Brown Twiss).
(2c) Coherent quantum control of amplitude and phase in triggered photon emissions.
(2d) Efficient and fast initialisation of the emitter.
(2e) Proof of photon indistinguishability (Hong-Ou-Mandel type two-photon interference).

(3a) Efficient emission scheme, taking the entire level structure into account.
(3b) Full polarisation, amplitude and phase control of the photons.
(3c) Optimum birefringence or polarisation-mode splitting, mode volume and cooperativity.

(4a) Deterministic emitter-photon entanglement (spin and polarisation).
(4b) Quantum networking and photonic quantum processing with multiple cavity photons.
(4c) Entanglement swapping by projective measurements to entangle remote emitters.
(4d) Going beyond pairwise entanglement to prepare non-local cluster states.

(5a) Non-demolition measurement of the intra-cavity emitter state.
(5b) Cavity-mediated quantum gates and entanglement distillation acting on the emitters.
(5c) Cavity-mediated quantum gates acting on reflected photons.
(5d) Hybrid gate operations combining (5b) and (5c).

(6) Cavity-based quantum memory or EIT for photon storage and quantum repeaters.

(7) Intra-cavity one and two qubit quantum gates.

(8a) Reproducible cavities for multiple systems in a quantum network.
(8b) Multiple operational cavities working simultaneously on the same chip.

(9) Real-world compliance (wavelength, distance, scale)

Technical progress has reached different stages, depending on the chosen pathway. Groups implementing new cavities are often at level (1), whereas established ion-cavity systems reach level (2). This is different for neutral atoms, with the state-of-the-art at level (3-7). Solid-state implementations are equally successful, but suffer from additional challenges related to inhomogeneity and yield. Typically it takes four years to move by one level, and past experience suggests any new development needs 12 years to reach a mature stage.

This might seem long at first glance but is well worth the effort. Light-matter interfacing in cavities is the best known technique to seriously tackle most limitations to scalability in any networked implementation of a quantum-technological application. For the most advanced forerunners in the field, very few steps remain to be taken to demonstrate and eventually implement faithful quantum-network links on a larger scale.

Roadmap to Quantum Networking - Glossary

(1a) Cavity mirror manufacturing and high-finesse dielectric coating.

This entails the machining by super-polishing, laser ablation or FIB milling of the mirror surfaces on substrates of reasonable dimensions, commensurate with the chosen emitter, at a radius of curvature and ellipticity optimised for the desired light-matter coupling scheme. In case of fibre tip-cavities it has to allow for perfect mode matching into a single-mode fibre core. Dielectric coatings to achieve high finesse and low losses, as required for strong coupling, and for directed output coupling of the photons through only one of the two cavity mirrors.

(1b) Cavity mounting, alignment and vibrational isolation.

Mirror alignment procedure and mechanical design of the cavity mount, compatible with the desired coupling scheme, e.g. an atom or ion trap. Sufficient passive stability of the entire setup to eventually operate in the quantum regime.

(1c) High-bandwidth cavity frequency locking far off resonance with the emitter.

Frequency-stable reference for locking the cavity to the desired transition. Typically this reference laser has to be on a different mode, a couple of nanometers away, to allow for its separation from single photons emitted into the cavity. Required extinction ratio 1E-8.

(1d) Efficient coupling of photons from the emitter via the cavity into the output field mode.

Various different efficient schemes for emitting a photon into a cavity. Coupling it with negligible losses into one single free-running mode outside is challenging. Requires at least an asymmetric cavity of low losses with a dedicated output coupler, with one well-defined transverse cavity mode perfectly mode-matched with an output mode of defined polarisation. Most of this is straight forward when coupling into free space, but much harder than anticipated when using fibre-tip mirrors.

(1e) Preparation and sufficient localisation of the emitter within the cavity mode.

Large variety of schemes. The only systems providing permanent coupling are solid-state colour centres or quantum dots. Atoms or ions can be considered quasi-permanently coupled, with the emitter-cavity interaction time ranging from 0.1 ms to several hours, which outweighs the repetition period of any experiment by at least two orders of magnitude. Localisation in solid state systems or with atoms in free flight is done by pre- or post-selection, whereas trapped ions or atoms can be positioned within the Lamb-Dicke regime.

(2a) Demonstration of the Purcell effect with a single emitter coupled to a cavity.

Enhanced spontaneous emission into the cavity or observation of normal-mode splitting upon the presence of a single emitter in the cavity.

(2b) Demonstration of the singleness of emitted photons (Hanbury-Brown Twiss).

Analyze the photon statistics of the emitted light to prove the singleness of the photons. Both for a continuously driven emitter and when using a pulsed driving scheme.

(2c) Coherent quantum control of amplitude and phase in triggered photon emissions.

Implement a highly efficient driving scheme for the triggered emission of single photons that allows to control their temporal mode profile, i.e. the phase coherent evolution of amplitude and phase within time, all identical from photon to photon. Needs verification, see (2e).

(2d) Efficient and fast initialisation of the emitter.

Resetting the emitter to the initial state after each emission. This can be rather involved the richer the level structure. Methods include optical pumping, STIRAP, rf-pulses and self-initialisation, where the final state after one photon emission is the initial state for the following one.

(2e) Proof of photon indistinguishability (Hong-Ou-Mandel type two-photon interference).

The title says it all. Two-photon interference, typically as a function of detection-time difference with the photons arriving simultaneously at the beam splitter.

(3a) Efficient emission scheme, taking the entire level structure into account.

First step towards considering a real emitter, which normally goes beyond the simple 2 or 3 level system considered to proof the principle. For instance, this is taking into account that magnetic sublevels couple to different polarisation modes of the cavity, and therefore calls for a more complex model. Also with the emitter subject to external fields, e.g. due to the surrounding trap, or even deliberately, Stark- and non-linear Zeeman effects need to be factored in. Some of the very simple Jaynes-Cummings or V-STIRAP like coupling schemes change substantially when doing so.

(3b) Full polarisation, amplitude and phase control of the photons.

Devise a driving scheme that is factoring in (3a) and takes also into account that any cavity is supporting different polarisation modes. Using the full physical picture, the photon emission scheme must still allow to control all parameters of the emitted photon, including its polarisation.

(3c) Optimum birefringence or polarisation-mode splitting, mode volume and cooperativity.

Factoring in (3a) and (3b), with any cavity supporting two polarisation modes near the desired resonance, an optimum cavity design has to be found which is tweaking the above-named parameters to achieve the maximum efficiency, and least perturbs the operation of the trap holding the emitter. Astonishingly, minimizing birefringence, which is often adopted to eventually achieve degeneracy of polarisation modes, is often compromising the system and negatively affects the overall performance. A more sophisticated approach is mandatory to optimise the design. Back to square (1a) if the mirror ellipticity is too far from being ideal.

(4a) Deterministic emitter-photon entanglement (spin and polarisation).

Identify a suitable level scheme within the emitter and devise a preparation + diving scheme that eventually entangles the polarisation of an emitted photon with the spin state (magnetic substate) of the emitter. A priori deterministic in case the photon is not lost, and pre-condition for effective and scalable entanglement swapping across larger networks.

(4b) Quantum networking and photonic quantum processing with multiple cavity photons.

Proof the feasibility of elementary quantum networking arrangements with more than one photon travelling simultaneously through the network. The latter can be as simple as a single beam splitter, or as complex as LOQC multiple-qubit gates or other multi-path interferometric settings. Typically this is calling for large-scale correlation measurements between various network output ports, and must show a similarity of 98% or better with the expected quantum behaviour to eventually allow for any scaling.

(4c) Entanglement swapping by projective measurements to entangle remote emitters.

Bell-state measurement on a pair of photons coming from different emitters to eventually entangle their spins.

(4d) Going beyond pairwise entanglement to prepare non-local cluster states.

Proof the feasibility of using multi-mode interferometry to effectuate joint measurements on photons send into multiple inputs of an interferometer, with the correlation pattern in the output being used to both entangle the emitters into a joint cluster state, and to eventually probe the degree of entanglement.

(5a) Non-demolition measurement of the intra-cavity emitter state.

Similar to the Purcell effect, off-resonant light reflected of the cavity experiences a pi-shift in phase if the emitter is in a state that couples to the cavity. This can be done using weak coherent pulses and the state-detection fidelity may exceed 98%. The quantum state of the emitter remains unchanged, apart from the systematic phase shift of the combined system. In contrast to this, many direct detection schemes that involve electron shelving and resonant fluorescence collection normally destroy the phase information, whilst being slightly more reliable.

(5b) Cavity-mediated quantum gates and entanglement distillation acting on the emitters.

Based on (5a), the reflective scattering of single photons from the cavity combined with the associated phase shifts can be used to implement quantum gate operations acting on one or two emitters.

(5c) Cavity-mediated quantum gates acting on reflected photons.

Based on (5a), the reflective scattering of single photons from the cavity combined with the associated phase shifts can be used to implement quantum gate operations acting on one or two successively reflected photons. All shown by G. Rempe at the MPQ.

(5d) Hybrid gate operations combining (5b) and (5c).

This complements the above, including quantum-state mapping between atom and photon.

(6) Cavity-based quantum memory or EIT for photon storage and quantum repeaters.

This basically constitutes a time-reversal of the photon generation process, with an arriving photon coupled into the cavity and then being mapped to an atomic state. Whilst this can be shown to work nicely on paper, all experimental implementation lack substantially behind expectations. Dynamic impedance matching with the cavity being the major issue, simply because the photon bounces off the HR mirror without penetrating into the cavity if this is not perfect.

(7) Intra-cavity one and two qubit gates.

Establish gate operations mediated by a common cavity mode, like e.g. those demonstrated by S. Haroche with Rydberg atoms in microwave cavities.

(8a) Reproducible cavities for multiple systems in a quantum network.

Basically a manufacturing challenge for doing distributed quantum networking, to simply provide a large number of nearly identical systems, with parameters being so well defined that emitted photons can be considered being identical.

(8b) Multiple operational cavities working simultaneously on the same chip.

Another manufacturing and alignment challenge, with the aim to have a tightly spaced array of cavities coupled to an array of emitters. Frequency locking all cavities at the same time will be rather demanding, and also positioning one emitter in strong coupling within each cavity is far from trivial.

(9) Real-world compliance (wavelength, distance, scale)

Compliance of the network architecture, including distances, complexity and detector properties, with the characteristics of the photons and the emitter/cavity systems used to produce them. This forcibly imposes numerous boundaries and limitations, and compromise is inevitable. Some modern techniques, like single-photon frequency conversion and super-conductive nanowire detectors, can be used to circumvent certain constraints.