1.3.32 Quantum Communication: efficiency thresholds, coding, and environment engineering

The study of how efficiently information can be preserved when transferring it via the use of quantum carriers, is central in quantum-information theory and represents a fundamental prerequisite to develop reliable quantum technologies. Our activity in the field covers a broad spectrum of different research lines which, among others, include the theoretical characterization of the optimal thresholds of the communication efficiency (capacities) attainable by several realistic quantum communication models (e.g. Bosonic quantum channels), the development of detection and coding schemes that allows one to reach such ultimate limits, the way in which partial engineering of the communication line environment can be used to in order to improve the overall quality of the signaling process, the study of non-Markovian effects.

Starting from previous results, in Refs. [1,2,8,10,12,14,20] generalizations of the longstanding Gaussian optimizer conjecture for Bosonic channels were proven. In particular in Ref. [8] an ordering between the quantum states emerging from a single mode gauge-covariant bosonic Gaussian channel was observed. Specifically it was shown that within the set of input density matrices with the same given spectrum, the element passive with respect to the Fock basis (i.e. diagonal with decreasing eigenvalues) produces an output which majorizes all the other outputs emerging from the same set. In Ref. [5] the set of linear maps sending the set of quantum Gaussian states into itself was explored: these transformations are in general not positive, a feature which can be exploited as a test to check whether a given quantum state belongs to the convex hull of Gaussian states. In Ref. [19] we derived several upper bounds on the quantum capacity of qubit and bosonic thermal attenuators.

In Ref. [4] an all-optical scheme for simulating non-Markovian evolution of a quantum system was proposed. It uses only linear optics elements and by controlling the system parameters allows one to control the presence or absence of information backflow from the environment.

In Ref. [3] a set of new functionals (called entanglement-breaking indices) has been introduced which characterize how many local iterations of a given (local) quantum channel are needed in order to completely destroy the entanglement between the system of interest over which the transformation is defined and an external ancilla. In Ref. [6] instead the set of Entanglement Saving quantum channels was characterized: these are completely positive, trace preserving transformations which when acting locally on a bipartite quantum system initially prepared into a maximally entangled configuration, preserve its entanglement even when applied an arbitrary number of times. In Ref. [22] a similar analysis was conducted for the case of dynamical semigroups, and in Ref. [23] a scheme was proposed to improve the entanglement survival via environment resetting.

In Ref. [18] reciprocal pairs of quantum channels were introduced as completely positive transformations which admit a rigid, distance-preserving, yet not completely-positive transformation that allows to reproduce the outcome of one from the corresponding outcome of the other, see Fig. 1. From a classical perspective these transmission lines should exhibit the same communication efficiency, interestingly enough however, it turns out that this is no longer the case in the quantum setting.

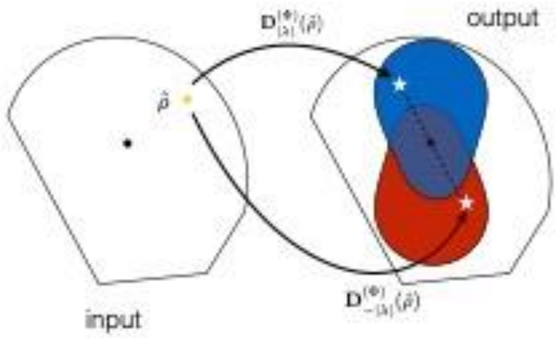

Figure 1. Graphical representation of output throughput of a quantum channel (blue region) of its reciprocal counterpart (red region) obtained by rigidly inverting the former (figure taken from [18]).

In Refs [7,15] we presented a new decoding protocol to realize transmission of classical information through a quantum channel at asymptotically maximum capacity, achieving the Holevo bound and thus the optimal communication rate. At variance with previous proposals, our scheme recovers the message bit by bit, making use of a series "yes-no" measurements, organized in bisection fashion, thus determining which codeword was sent in log(N) steps, N being the number of codewords. In Refs. [9,13,16] several schemes for the detection of low-intensity optical coherent signals ware studied which use probabilistic amplifier operated in the non-heralded version, improved applications of Hadamard receivers, and adaptive receivers. In Ref. [25] a dynamical model for Positive-Operator Valued Measures was presented. In Ref. [30] a perturbative to continuous-time quantum error correction was presented.

The distribution of entangled quantum systems among two or more nodes of a network is a key task at the basis of quantum communication, quantum computation and quantum cryptography. Unfortunately, the transmission lines used in this procedure can introduce so much perturbations and noise in the transmitted signal that prevent the possibility of restoring quantum correlations in the received messages either by means of encoding optimization or by exploiting local operations and classical communication. In Ref. [11] we presented a procedure which allows one to improve the performance of some of these channels. The mechanism underpinning this result is a protocol which we dub cut-and-paste, as it consists in extracting and reshuffling the sub-components of these communication lines, which finally succeed in "correcting each other". The proof of this counterintuitive phenomenon has a direct application in the realization of quantum information networks based on imperfect and highly noisy communication lines. In Ref. [17] instead we reported a bulk optics experiment demonstrating the possibility of restoring the entanglement distribution through noisy quantum channels by inserting a suitable unitary operation (filter) in the middle of the transmission process, see Fig. 2 below. We focus on two relevant classes of single-qubit channels consisting in repeated applications of rotated phase damping or rotated amplitude damping maps, both modeling the combined Hamiltonian and dissipative dynamics of the polarization state of single photons. Our results show that interposing a unitary filter between two noisy channels can significantly improve entanglement transmission.

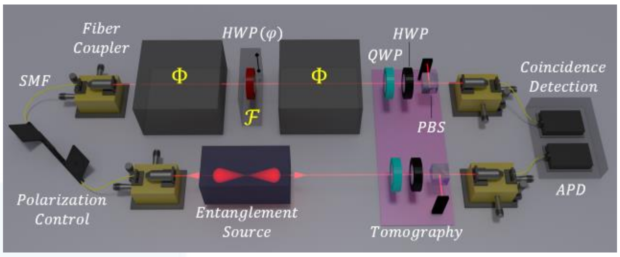

Figure 2. Scheme of the experimental setting used in Ref. [17]. The model uses a source of polarization entangled qubits which undergoes to noisy evolutions (grey boxes) and filtering operations (the F element of the figure). Figure taken from [17].

In Ref. [21] we considered the problem of correctly classifying a given quantum two-level system (qubit) which is known to be in one of two equally probable quantum states. We assumed that this task should be performed by a quantum machine which does not have at its disposal a complete classical description of the two template states, but can only have partial prior information about their level of purity and mutual overlap. Moreover, similarly to the classical supervised learning paradigm, we assumed that the machine can be trained by n qubits prepared in the first template state and by n more qubits prepared in the second template state. In this situation we were interested in the optimal process which correctly classifies the input qubit with the largest probability allowed by quantum mechanics. The problem was studied in its full generality for a number of different prior information scenarios and for an arbitrary size n of the training data. Finite size corrections around the asymptotic limit $n\rightarrow\infty$ were also derived. In Ref. [28] instead we derived the optimal performance of quantum state overlap estimation, a task which essential for at the decoding stage of any communication line.

In Ref. [24] the impossibility of undoing a mixing process was analyzed in the context of quantum information theory. The optimal machine to undo the mixing process was studied in the case of pure states, focusing on qubit systems. For simple but non-trivial cases we computed the analytical solution, comparing the performance of the optimal machine with other protocols. As a spin-off of this analysis in Ref. [29] we provided optimal bounds for the quantum capacity of the depolarizing channel.

In Ref. [27] we exploited an improved version of the Lieb-Robinson bound derived in [26], to estimate the quantum capacity of information transmission on spin-network communication lines.

In Refs. [31,32] quantum cascade networks where analyzed in which quantum systems are connected through unidirectional channels that can mutually interact giving rise to interference effects. In particular we showed how to compute master equations for cascade systems in an arbitrary interferometric configuration by means of a collisional model.

In Ref. [33] we studied the most efficient way to exploit a certain amount of entanglement to perform quantum teleportation protocols implemented using two-mode Gaussian states with a limited degree of entanglement and energy.

In Ref. [34] we showed how to recover complete positivity (and hence positivity) of the Redfield equation via a coarse grain average technique. We derived general bounds for the coarse graining time scale above which the positivity of the Redfield equation is guaranteed.

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