Characterizing quantum dynamics with initial system-environment correlations

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Perfect isolation of a quantum system is rarely achievable and the system might thus be correlated to the environment even before it is prepared in the initial state for the experiment. As a consequence, different preparations of the system might lead to vastly different dynamics, which can appear unphysical when initial correlations are unnoticed. First results showed that partial information about the environment can be obtained from measurements on the system alone. However, the scope and operational significance of these results was limited. We present a full experimental reconstruction of an operationally derived quantum super-channel. It can be obtained from measurements on the system alone and captures both initial system-environment correlations and the dynamical influence from the environment. We show how to extract and use this information for achieving optimal performance of a quantum optical in the presence of an environment.

Harnessing the power of quantum systems for information processing, quantum computation and quantum communication is one of the great challenges today. In particular, every experiment suffers from the omnipresent environment, which tends to deteriorate fragile properties such as entanglement and coherence. Isolation of quantum information processing systems has thus become a primary objective in any of their applications. Such isolation, however, can typically not be achieved perfectly in any practical situation. Remaining correlations with the environment and coupling to it in the course of the evolution must therefore be taken into account.

Under the assumption that system and environment are initially uncorrelated, the theory of open quantum systems allows to describe the evolution of a system within an inaccessible environment [1]. In this case well-established tools like quantum process tomography (QPT) [2] are routinely used to reconstruct a description of the system evolution, see Fig. 1a). In the presence of experimental fluctuations these methods might nevertheless reproduce unphysical results. Techniques such as maximum likelihood estimation [3, 4] overcome this problem by enforcing complete-positivity of the reconstructed map, which ensures that every physical state is transformed to another physical state by the evolution.

The success of all these methods, however, relies crucially on the separability assumption, which cannot be guaranteed to hold in practice, see Fig. 1b). In particular, complete positivity of the reduced evolution of the system is naturally lost in the presence of initial system-environment correlations *before* the experiment [5–10]. In this case the very act of state preparation of the system leaves the environment in different states and thus modifies the subsequent coupling and leads to conditional dynamics of the system [11]. As a consequence the observed dynamics might appear non-completely positive and naive application of QPT without appropriately taking these effects into account would correspond to the attempt of partially characterising different evolutions [8, 12, 13].

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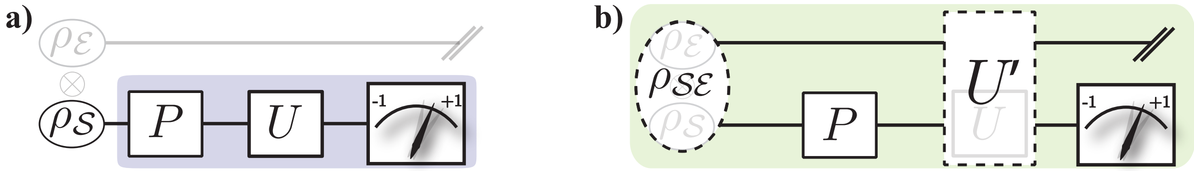

FIG. 1. **a) Quantum Process Tomography.** An isolated quantum system undergoes a preparation procedure $\mathcal{P}$, then evolves unitarily (U) and is finally measured. Quantum process tomography can be used to reconstruct a full description of the evolution from a tomographically complete set of input states $\{\rho_i\}$ and measurements $\{M_j\}$. **b) The complete picture.** The situation depicted in a) is only an approximation of the real state of affairs. In any realistic scenario the system is initially correlated with the environment—even before the state preparation procedure $\mathcal{P}$. Furthermore, the evolution U is in general also affected by the environment. While QPT is not suitable here, quantum super-channel tomography can still be used to reconstruct a full description of the system evolution without requiring any measurements on the environment.

Remarkably. recent developments showed that at least partial information about the joint system-environment state before the experiment can be extracted from measurements on the system alone and that initial correlations can be witnessed [14–21]. Here we extend these results and demonstrate a more complete characterisation of a quantum experiment that fully describes the evolution of the system in the presence of an environment [8]. This method uses established tomographic techniques to reconstruct a quantum super-channel $\mathcal{M}$, which explicitly takes the preparation procedure applied to the system as an input—instead of the prepared state as in the case of QPT—and can be used to predict the output of the experiment for arbitrary preparation procedures.

In contrast to previous, more theoretical investigations into initial system-environment correlations [7, 10, 22, 23], the super-channel $\mathcal{M}$ is operationally derived and can be fully reconstructed from measurements on the system alone. It takes into account the full system-environment state to describe the evolution of the system and is therefore always completely positive, up to experimental fluctuations. In our work we also develop maximum likelihood methods for reconstructing $\mathcal{M}$ in a fashion that is robust against finite counting statistics and real-world experimental fluctuations.

We demonstrate the experimental application of the method to a typical scenario in linear optical quantum computing. The environment is simulated in a controllable way as a separate photonic system. We define novel measures to extract the strength of initial correlations from the reconstructed $\mathcal{M}$ and to use it for optimizing the experiment to achieve minimal influence of the environment and maximal fidelity with the intended unitary evolution of the system.

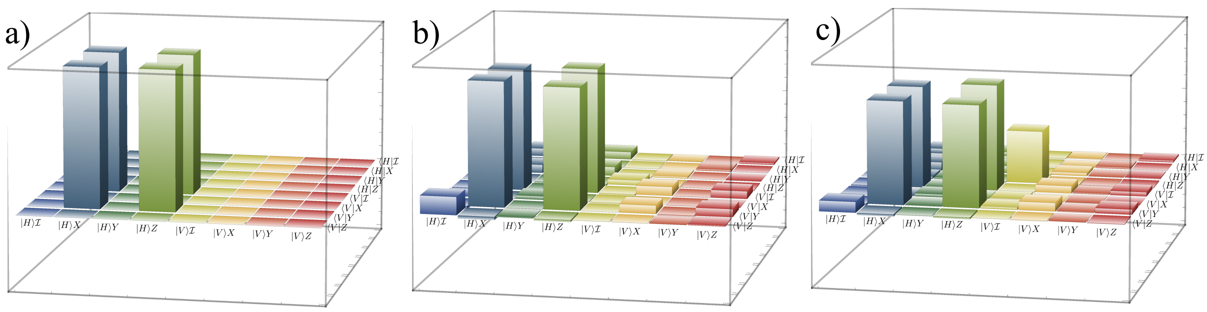

FIG. 2. **Quantum super-channels $\mathcal{M}$ for a single-qubit system undergoing a Hadamard evolution**. The operators are visualized in a compound polarization-Pauli basis for easy interpretation. Shown are **a)** the ideal map for an uncorrelated system-environment state, and the experimentally reconstructed $\mathcal{M}$ for **b)** weak and **c)** strong initial system-environment correlations.

The quantum super-channel approach, together with the operational metrics introduced in our work offers a sophisticated characterisation technique for quantum systems evolving within an environment. The method is applicable to any architecture and can be used to optimize the system in various aspects, such as minimizing the effect of the environment on certain evolutions of the system. It can on the other hand also be helpful in determining the optimal way of exploiting present system-environment correlations for tasks such as state-engineering [24].

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