Characterization of classical fluctuating fields by quantum probes

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We consider qubit systems coupled to classical stochastic fields and address both the decoherence and the non-Markovianity induced by the external fields, as well as their characterization by quantum-limited measurements on the qubits.

Decoherence may be induced by classical or quantum noise, i.e. by the interaction with an environment described classically or quantum-mechanically. The classical description is often more realistic to describes environments with a very large number of degrees of freedom, and it has also been shown that even certain quantum environments may be described with equivalent classical models. We thus analyze in details the dynamics of quantum correlations, for two-qubit systems interacting with classical stochastic field, focusing on relevant examples of non-Gaussian process, e.g. random telegraph noise and colored noise with $1/f^{\alpha}$ spectra. We also evaluate quantitatively the non-Markovianity of the induced dynamical map by analyzing the dynamics of both the trace distance and the quantum capacity, and show that the behaviour of non-Markovianity based on both measures is qualitatively similar. Our results show that environments with a spectrum that contains a relevant low-frequency contribution are generally non-Markovian. We also find that non-Markovianity of colored environments decreases when the number of fluctuators realizing the envinroment increases. Besides, we discuss how reliable transmission of information through a quantum channel subjected to random classical noise may be achieved by tailoring the channel length and properly engineering the structured environments.

Stochastic modelling is often the most effective tool available in order to describe complex systems in physical, biological and social networks and a question arises on how to characterize the underlying stochastic process with minimal resources. To this aim we also address the characterization of classical random fields by quantum probes. This means that we consider a microscopic system, say a qubit encoded onto a particle, subject to classical noise, and assume that some classical degree of freedom, e.g. its motion, is coupled to a quantum degree of freedom of the same system, e.g. its spin. We then ignore the noisy classical part and exploit quantum limited measurements on the spin (qubit) part to extract information about the classical stochastic noise, e.g. its noise spectrum or the damping and the memory parameters.

At first, we address single-qubit estimation strategies for the spectral parameters of two relevant kinds of non-Gaussian noise: random telegraph noise with Lorentzian spectrum and colored noise with $1/f^{\alpha}$ spectrum. We analyze in details the estimation precision achievable by quantum probes and prove that population measurement on the qubit is optimal for noise estimation in both cases. We also evaluate the optimal interaction times for the quantum probe, i.e. the values maximizing the quantum Fisher information and the quantum signal-to-noise ratio. We also address estimation and discrimination problems for classical fractional random noise via quantum probes.

Finally, we address the use of entangled qubits as quantum probes to characterize the dynamical noise induced by complex environments. In particular, we show that entangled probes improve estimation of the correlation time for a broad class of environmental noises compared to any sequential strategy involving single qubit preparation. The effect is present when the noise is faster than a threshold value, a regime which may always be achieved by tuning the coupling between the quantum probe and the environment inducing the noise. Our scheme exploits time-dependent sensitivity of quantum systems to decoherence and does not require dynamical control on the probes. We derive the optimal interaction time and the optimal probe preparation, showing that it corresponds to multiqubit GHZ states when entanglement is useful. We also show robustness of the scheme against depolarization or dephasing of the probe, and discuss simple measurements approaching optimal precision.