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Correlated Noise Errors in Quantum Information Processing

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Project summary (months: 25-43)

In WP1 general properties of noisy transmission channel were analyzed. It was shown that memory effects may enhance the transmission capacity of a channel. Models for this were found in the quantum optically interesting class of Gaussian channels. The study of long-term correlations was centered about the notion of forgetfulness of a memory channel, which ensures that a well-defined transformation on signal strings is implemented by the channel, for which no extrinsic information about the remote past of the memory is required. The memory channel can then be reconstructed from the signal transformation, and its exact memory requirement can be determined. On the other hand, a failure of forgetfulness can manifest itself by a failure of the "strong converse" property of channel capacity.

WP2 in the third period aimed at optimizing coding and decoding procedures developed to counteract correlated noise errors. Beside the problem of finding codes that are optimal for correlated noise, the problem of decoding such codes efficiently should also have been addressed.

To establish what are good codes in the presence of correlated noise, several codes (including those already developed by project partners) have been analyzed quantifying their performance with both entanglement fidelity and code entropy. For efficient decoding, the informational power of a quantum measurement has been introduced as the maximum amount of classical information that the measurement can extract from any ensemble of quantum states.

Furthermore, in the case of channels with memory it is natural to also think at encoding and decoding processes that run in a continuous fashion, as a stream encoding (opposed to pure block coding). Along this line, a family of efficiently realizable (streaming like) transformations, which can be used to partially remove correlations among errors, has been introduced for bosonic Gaussian memory channels and the reduction of the gap with memoryless channels quantified.

Another goal was to establish the conditions for coherence recovery by feedback actions. Actually it has been found the optimal measurement on the environment to perform the best possible correction also in case of non-unital channels, and it has shown the possibility of correcting errors occurring on a multipartite system through a feedback mechanism that acquires information on one or few qubits and exploit errors correlations to decide what kind of global recovery perform.

By considering the possibility of logical operations while the noise is affecting the data, the objective was the determination of fault-tolerant thresholds. Regarding this objective a modified notion of entanglement (resp. separability) has been introduced to develop alternative methods of classical simulation. This approach provides new regimes of noisy quantum evolution (including correlations occurring in error-propagation) that can be efficiently simulated classically, and it leads to new upper bounds to fault tolerance thresholds.

A more visionary objective was the development of a universal encoding and decoding method to be used if the exact model of the channel is not known. Along this line a universal coding theorem (not depending on specific structure of the channel) has been proved regarding transmission of private information over a classical-quantum channel from Alice to Bob and Eve.

Finally, on the experimental ground, it has been shown that the average key rate for the distillation-based protocol is inferior compared to that of direct key generation from a noisy entangled state. Furthermore, practical systems to accomplish high information transmission by the use of short pulses of light have been realized.

In WP3 we have developed several quantum state and process estimation techniques, which are optimized for the efficient characterization of practical experimental systems in the presence of correlated noise and correlated degrees of freedoms within the signal carrier fields. More specifically we approached this topic from two different angles:

One emphasis was put on broadband pulsed parametric downconversion states, which typically exhibit a complex spectral entanglement structure. This can be interpreted as a highly multi-mode characteristic. By studying correlation functions in combination with quantum interference experiments efficient quantum state and channel estimation becomes possible for practical systems. For analysing the photon number characteristics we employed photon counting as well as state characterization in phase space by probing single points of a Wigner functions with parity measurements.

Our second main research direction was devoted towards optimized quantum state and channel reconstruction for noisy qubit states including the investigation of efficient quantum information transfer over optical fiber with correlated noise. By analysing four qubit-states and introducing a partition into two sub-systems, where part of the qubits are transmitted over correlated-noise channels, different methods for the full characterization of noisy channels were compared to each other and were found to be consistent when using an appropriate measure. These results have important consequences for secure quantum communication over noisy channels.

WP4 focused on the efficient description of the dynamics of a few qubits systems subject to noisy environments. It involved a main body of theory work supplement by experimental activities using superconducting flux qubits. From the theory side, a powerful technique for the efficient simulation of open system dynamics has been developed: TEDOPA (Time Evolving Density Matrix with Orthogonal Polynomials Algorithm). We have shown how a standard open quantum system Hamiltonians can be mapped analytically onto representations in which the environments appear as one dimensional harmonic chains with nearest neighbour interactions. This mapping, carried out rigorously using orthogonal polynomial theory, then allows the full evolution of the system and environment to be simulated using time-adaptive density matrix renormalisation group (DMRG) methods. With the combination of these two techniques, numerically-exact results can be obtained for dissipative quantum systems in the presence of arbitrarily complex environmental spectral functions, and the correlations and processes in the environment which drive the effectively irreversible dynamics of the reduced state of the quantum system can be explored in real time. We have applied TEDOPA to a number of physical systems, including the description of exciton dynamics in types of biomolecular, photosynthetic systems and the quantum phase transition at zero temperature between a localised and delocalised phase in the sub-ohmic spin-boson model.

We have also developed a novel method for efficient and certifiable quantum state tomography. We showed that one can do exponentially better than direct state tomography for a wide range of quantum states, in particular those that are well approximated by a matrix product state ansatz. One scheme requires unitary operations on a constant number of subsystems, while the other requires only local measurements together with more elaborate post-processing. Both schemes rely only on a linear number of experimental operations and classical postprocessing that is polynomial in the system size. Moreover, the accuracy of the reconstructed states can be rigorously certified without any a priori assumptions.

Experimental activity in solid state systems focused on the development of novel schemes for the initialization, coupling and detection of superconducting flux qubits. For these qubits the coherence is limited by several independent factors. The electronic circuitry for biasing, driving and readout leads to an electromagnetic environment that may induce relaxation when energy can be transferred at the frequency of the qubit splitting and may lead to dephasing by low-frequency noise. In addition, relaxation occurs when the physical neighbourhood of the qubit contains electronic two-level systems (microscopic defects) with an energy splitting close to the qubit frequency. Low frequency flux noise induced by fluctuating trapped spins on the sample surface induces dephasing when the qubit is biased at a magnetic bias away from the symmetry point. Experimentally a study was made of the interaction between a flux qubit and an accidental two-level fluctuator. That latter system turned out to be quite coherent, and quantum states could be transferred.

Particular attention was paid to a system of two permanently coupled flux qubits that could be read out independently and simultaneously. A method for dynamical coupling was developed with each qubit in its optimal bias point. For the coupled qubits it could be observed that some transitions were less sensitive to flux noise than others due to correlations. A method was designed to locate specific strong two-level fluctuators on the chip by dynamic driving of the two qubits with controlled amplitudes and phases.

The interplay between theory and experiments focused on the study of superconducting architectures and in particular the analysis of qubit arrays that have been manufactured. This type of spin chains is well suited for the exploration of coherent effects in open quantum systems and, in particular, for the simulation of non equilibrium physics. We have proposed a coherence test based upon population measurements that exploits dynamical localization effects and can witness the quantum behaviour of realistic qubit arrays of moderate size. To further understand the nature of the quantum correlations that can build up in these systems, we have also studied the entanglement properties of the chain when subject to a sudden quench and analysed the conditions required for both bipartite quantum correlations and true multiparticle entanglement to persist in the steady state. Our results indicate that the demonstration of persistent entanglement and the existence of a noise threshold for having long lived quantum correlations are within the realm of current technology.

All these results are in a direct relation with the main objectives of CORNER project which, when achieved, will have brought closer the quantum breakthrough in information and communication technologies (ICT) paving the way for the implementation of quantum protocols leading to computational speed-up and communication security. Since the key obstacle on the way is decoherence and noise, which in realistic quantum systems quite commonly exhibits both temporal and spatial correlations, understanding the methods for dealing with and, for certain tasks, even exploiting the presence of noise, is a base for any further progress in the field. The variety of physical platforms being investigated within the CORNER project (photonic, superconducting, spin-systems) creates strong prospects that the results obtained will find their application in real life prototype devices and, eventually, large-scale implementations.