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Activity Report 2017

Project-Team QUANTIC

QUANTum Information Circuits

IN COLLABORATION WITH: Centre Automatique et Systèmes, Laboratoire Pierre Aigrain

RESEARCH CENTER
Paris

THEME
Optimization and control of dynamic systems

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Project-Team QUANTIC

Creation of the Team: 2013 September 12, updated into Project-Team: 2015 April 01

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1. Personnel

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2. Overall Objectives

2.1. Overall objectives

The research activities of QUANTIC team lie at the border between theoretical and experimental efforts in the emerging field of quantum systems engineering. Our research topics are in direct continuation of a historic research theme of Inria, classical automatic control, while opening completely new perspectives toward quantum control: by developing a new mathematical system theory for quantum circuits, we will realize the components of a future quantum information processing unit.

One of the unique features of our team concerns the large spectrum of our subjects going from the mathematical analysis of the physical systems (development of systematic mathematical methods for control and estimation of quantum systems), and the numerical analysis of the proposed solutions, to the experimental implementation of the quantum circuits based on these solutions. This is made possible by the constant and profound interaction between the applied mathematicians and the physicists in the group. Indeed, this close collaboration has already brought a significant acceleration in our research efforts. In a long run, this synergy should lead to a deeper understanding of the physical phenomena behind these emerging technologies and the development of new research directions within the field of quantum information processing.

Towards this ultimate task of practical quantum digital systems, the approach of the QUANTIC team is complementary to the one taken by teams with expertise in quantum algorithms. Indeed, we start from the specific controls that can be realistically applied on physical systems, to propose designs which combine them into *hardware shortcuts* implementing *robust* behaviors useful for quantum information processing. Whenever a significant new element of quantum engineering architecture is developed, the initial motivation is to prove an enabling technology with major impact for the groups working one abstraction layer higher: on quantum algorithms but also on e.g. secure communication and metrology applications.

3. Research Program

3.1. Hardware-efficient quantum information processing

In this scientific program, we will explore various theoretical and experimental issues concerning protection and manipulation of quantum information. Indeed, the next, critical stage in the development of Quantum Information Processing (QIP) is most certainly the active quantum error correction (QEC). Through this stage one designs, possibly using many physical qubits, an encoded logical qubit which is protected against major decoherence channels and hence admits a significantly longer effective coherence time than a physical qubit.

Reliable (fault-tolerant) computation with protected logical qubits usually comes at the expense of a significant overhead in the hardware (up to thousands of physical qubits per logical qubit). Each of the involved physical qubits still needs to satisfy the best achievable properties (coherence times, coupling strengths and tunability). More remarkably, one needs to avoid undesired interactions between various subsystems. This is going to be a major difficulty for qubits on a single chip.

The usual approach for the realization of QEC is to use many qubits to obtain a larger Hilbert space of the qubit register [89], [93]. By redundantly encoding quantum information in this Hilbert space of larger dimension one make the QEC tractable: different error channels lead to distinguishable error syndromes. There are two major drawbacks in using multi-qubit registers. The first, fundamental, drawback is that with each added physical qubit, several new decoherence channels are added. Because of the exponential increase of the Hilbert's space dimension versus the linear increase in the number of decay channels, using enough qubits, one is able to eventually protect quantum information against decoherence. However, multiplying the number of possible errors, this requires measuring more error syndromes. Note furthermore that, in general, some of these new decoherence channels can lead to correlated action on many qubits and this needs to be taken into account with extra care: in particular, such kind of non-local error channels are problematic for surface codes. The second, more practical, drawback is that it is still extremely challenging to build a register of more than on the order of 10 qubits where each of the qubits is required to satisfy near the best achieved properties: these properties include the coherence time, the coupling strengths and the tunability. Indeed, building such a register is not merely only a fabrication task but rather, one requirers to look for architectures such that, each individual qubit can be addressed and controlled independently from the others. One is also required to make sure that all the noise channels are well-controlled and uncorrelated for the QEC to be effective.

We have recently introduced a new paradigm for encoding and protecting quantum information in a quantum harmonic oscillator (e.g. a high-Q mode of a 3D superconducting cavity) instead of a multi-qubit register [66]. The infinite dimensional Hilbert space of such a system can be used to redundantly encode quantum information. The power of this idea lies in the fact that the dominant decoherence channel in a cavity is photon damping, and no more decay channels are added if we increase the number of photons we insert in the cavity. Hence, only a single error syndrome needs to be measured to identify if an error has occurred or not. Indeed, we are convinced that most early proposals on continuous variable QIP [63], [57] could be revisited taking into account the design flexibilities of Quantum Superconducting Circuits (QSC) and the new coupling regimes that are provided by these systems. In particular, we have illustrated that coupling a qubit to the cavity mode in the strong dispersive regime provides an important controllability over the Hilbert space of the cavity mode [65]. Through a recent experimental work [98], we benefit from this controllability to prepare superpositions of quasi-orthogonal coherent states, also known as Schrödinger cat states.

In this Scheme, the logical qubit is encoded in a four-component Schrödinger cat state. Continuous quantum non-demolition (QND) monitoring of a single physical observable, consisting of photon number parity, enables then the tractability of single photon jumps. We obtain therefore a first-order quantum error correcting code using only a single high-Q cavity mode (for the storage of quantum information), a single qubit (providing the non-linearity needed for controllability) and a single low-Q cavity mode (for reading out the error syndrome). An earlier experiment on such QND photon-number parity measurements [94] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [6]. As shown in Figure 1, this leads to a significant hardware economy for realization of a protected logical qubit. Our goal here is to push these ideas towards a reliable and hardware-efficient paradigm for universal quantum computation.

3.2. Reservoir (dissipation) engineering and autonomous stabilization of quantum systems

Being at the heart of any QEC protocol, the concept of feedback is central for the protection of the quantum information enabling many-qubit quantum computation or long-distance quantum communication. However, such a closed-loop control which requires a real-time and continuous measurement of the quantum system has been for long considered as counter-intuitive or even impossible. This thought was mainly caused by

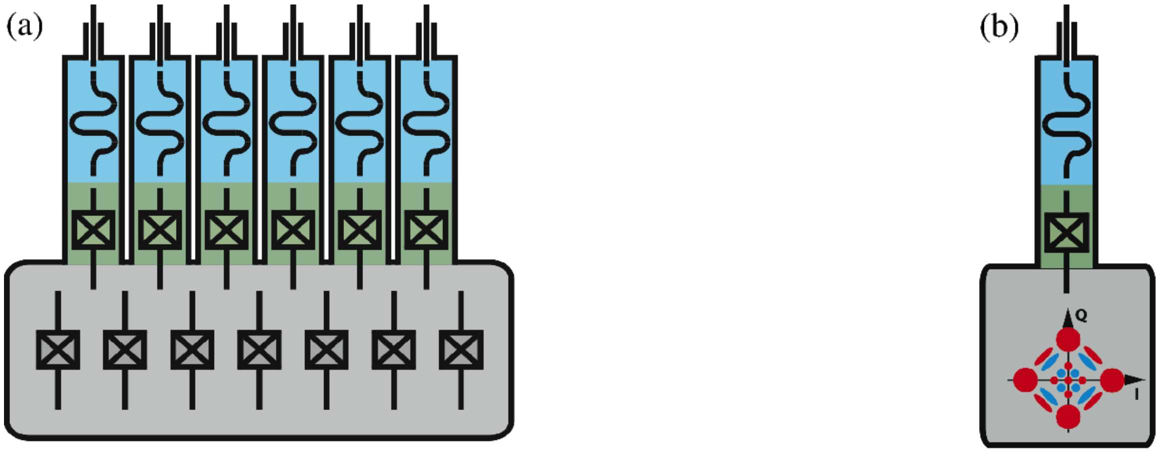

Figure 1. (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [93] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error syndromes is ensured through 6 additional ancillary qubits with the possibility of individual readout of the ancillary qubits via independent low-Q resonators. (b) Minimal architecture for a protected logical qubit, adapted to circuit quantum electrodynamics experiments. Quantum information is encoded in a Schrödinger cat state of a single high-Q resonator mode and a single error syndrome is measured, using a single ancillary transmon qubit and the associated readout low-Q resonator.

properties of quantum measurements: any measurement implies an instantaneous strong perturbation to the system's state. The concept of *quantum non-demolotion* (QND) measurement has played a crucial role in understanding and resolving this difficulty [40]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [59], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [58]. Later on, this ability of performing continuous measurements allowed the same group to realize the first continuous quantum feedback protocol stabilizing highly non-classical states of the microwave field in the cavity, the so-called photon number states [8] (this ground-breaking work was mentioned in the Nobel prize attributed to Serge Haroche). The QUANTIC team contributed to the theoretical work behind this experiment [49], [31], [92], [33]. These contributions include the development and optimization of the quantum filters taking into account the quantum measurement back-action and various measurement noises and uncertainties, the development of a feedback law based on control Lyapunov techniques, and the compensation of the feedback delay.

In the context of circuit quantum electrodynamics (circuit QED) [48], recent advances in quantum-limited amplifiers [83], [96] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [60]. This ability to perform high-fidelity non-demolition measurements of a quantum signal has very recently led to quantum feedback experiments with quantum superconducting circuits [96], [82], [42]. Here again, the QUANTIC team has participated to one of the first experiments in the field where the control objective is to track a dynamical trajectory of a single qubit rather than stabilizing a stationary state. Such quantum trajectory tracking could be further explored to achieve metrological goals such as the stabilization of the amplitude of a microwave drive [73].

While all this progress has led to a strong optimism about the possibility to perform active protection of quantum information against decoherence, the rather short dynamical time scales of these systems limit, to a great amount, the complexity of the feedback strategies that could be employed. Indeed, in such measurement-based feedback protocols, the time-consuming data acquisition and post-treatment of the output signal leads to an important latency in the feedback procedure.

The reservoir (dissipation) engineering [80] and the closely related coherent feedback [71] are considered as alternative approaches circumventing the necessity of a real-time data acquisition, signal processing and feedback calculations. In the context of quantum information, the decoherence, caused by the coupling of a system to uncontrolled external degrees of freedom, is generally considered as the main obstacle to synthesize quantum states and to observe quantum effects. Paradoxically, it is possible to intentionally engineer a particular coupling to a reservoir in the aim of maintaining the coherence of some particular quantum states. In a general viewpoint, these approaches could be understood in the following manner: by coupling the quantum system to be stabilized to a strongly dissipative ancillary quantum system, one evacuates the entropy of the main system through the dissipation of the ancillary one. By building the feedback loop into the Hamiltonian, this type of autonomous feedback obviates the need for a complicated external control loop to correct errors. On the experimental side, such autonomous feedback techniques have been used for qubit reset [56], single-qubit state stabilization [75], and the creation [35] and stabilization [64], [70][9] of states of multipartite quantum systems.

Such reservoir engineering techniques could be widely revisited exploring the flexibility in the Hamiltonian design for QSC. We have recently developed theoretical proposals leading to extremely efficient, and simple to implement, stabilization schemes for systems consisting of a single, two or three qubits [56], [68], [46]. The experimental results based on these protocols have illustrated the efficiency of the approach [56][9]. Through these experiments, we exploit the strong dispersive interaction [87] between superconducting qubits and a single low-Q cavity mode playing the role of a dissipative reservoir. Applying some continuous-wave (cw) microwave drives with well-chosen fixed frequencies, amplitudes, and phases, we engineer an effective interaction Hamiltonian which evacuates entropy from the qubits when an eventual perturbation occurs: by driving the qubits and cavity with continuous-wave drives, we induce an autonomous feedback loop which corrects the state of the qubits every time it decays out of the desired target state. The schemes are robust against small variations of the control parameters (drives amplitudes and phase) and require only some basic calibration. Finally, by avoiding resonant interactions between the qubits and the low-Q cavity mode, the qubits remain protected against the Purcell effect, which would reduce the coherence times. We have also investigated both theoretically and experimentally the autonomous stabilization of non-classical states (such as Schrodinger cat states and Fock states) of microwave field confined in a high-Q cavity mode [74], [85], [61][5].

3.3. System theory for quantum information processing

In parallel and in strong interactions with the above experimental goals, we develop systematic mathematical methods for dynamical analysis, control and estimation of composite and open quantum systems. These systems are built with several quantum subsystems whose irreversible dynamics results from measurements and/or decoherence. A special attention is given to spin/spring systems made with qubits and harmonic oscillators. These developments are done in the spirit of our recent contributions [84], [31], [91], [86], [92], [33][7] resulting from collaborations with the cavity quantum electrodynamics group of Laboratoire Kastler Brossel.

3.3.1. Stabilization by measurement-based feedback

The protection of quantum information via efficient QEC is a combination of (i) tailored dynamics of a quantum system in order to protect an informational qubit from certain decoherence channels, and (ii) controlled reaction to measurements that efficiently detect and correct the dominating disturbances that are not rejected by the tailored quantum dynamics.

In such feedback scheme, the system and its measurement are quantum objects whereas the controller and the control input are classical. The stabilizing control law is based on the past values of the measurement outcomes. During our work on the LKB photon box, we have developed, for single input systems subject to quantum non-demolition measurement, a systematic stabilization method [33]: it is based on a discrete-time formulation of the dynamics, on the construction of a strict control Lyapunov function and on an explicit compensation of the feedback-loop delay. Keeping the QND measurement assumptions, extensions of such stabilization schemes will be investigated in the following directions: finite set of values for the control input with application to the convergence analysis of the atomic feedback scheme experimentally tested in [99]; multi-input case where the construction by inversion of a Metzler matrix of the strict Lyapunov function is not straightforward; continuous-time systems governed by diffusive master equations; stabilization towards a set of density operators included in a target subspace; adaptive measurement by feedback to accelerate the convergence towards a stationary state as experimentally tested in [78]. Without the QND measurement assumptions, we will also address the stabilization of non-stationary states and trajectory tracking, with applications to systems similar to those considered in [60], [42].

3.3.2. Filtering, quantum state and parameter estimations

The performance of every feedback controller crucially depends on its online estimation of the current situation. This becomes even more important for quantum systems, where full state measurements are physically impossible. Therefore the ultimate performance of feedback correction depends on fast, efficient and optimally accurate state and parameter estimations.

A quantum filter takes into account imperfection and decoherence and provides the quantum state at time $t \geq 0$ from an initial value at $t = 0$ and the measurement outcomes between 0 and t. Quantum filtering goes back to the work of Belavkin [36] and is related to quantum trajectories [44], [47]. A modern and mathematical exposure of the diffusive models is given in [34]. In [100] a first convergence analysis of diffusive filters is proposed. Nevertheless the convergence characterization and estimation of convergence rate remain open and difficult problems. For discrete time filters, a general stability result based on fidelity is proven in [84], [91]. This stability result is extended to a large class of continuous-time filters in [32]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [37]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [51], [76].

We will continue to investigate stability and convergence of quantum filtering. We will also exploit our fidelity-based stability result to justify maximum likelihood estimation and to propose, for open quantum system, parameter estimation algorithms inspired of existing estimation algorithms for classical systems. We will also investigate a more specific quantum approach: it is noticed in [41] that post-selection statistics and "past quantum" state analysis [52] enhance sensitivity to parameters and could be interesting towards increasing the precision of an estimation.

3.3.3. Stabilization by interconnections

In such stabilization schemes, the controller is also a quantum object: it is coupled to the system of interest and is subject to decoherence and thus admits an irreversible evolution. These stabilization schemes are closely related to reservoir engineering and coherent feedback [80], [71]. The closed-loop system is then a composite system built with the original system and its controller. In fact, and given our particular recent expertise in this domain [7], [9] [56], this subsection is dedicated to further developing such stabilization techniques, both experimentally and theoretically.

The main analysis issues are to prove the closed-loop convergence and to estimate the convergence rates. Since these systems are governed by Lindblad differential equations (continuous-time case) or Kraus maps (discrete-time case), their stability is automatically guaranteed: such dynamics are contractions for a large set of metrics (see [79]). Convergence and asymptotic stability is less well understood. In particular most of the convergence results consider the case where the target steady-state is a density operator of maximum rank (see, e.g., [30][chapter 4, section 6]). When the goal steady-state is not full rank very few convergence results are available.

We will focus on this geometric situation where the goal steady-state is on the boundary of the cone of positive Hermitian operators of finite trace. A specific attention will be given to adapt standard tools (Lyapunov function, passivity, contraction and Lasalle's invariance principle) for infinite dimensional systems to spin/spring structures inspired of [7], [9] [56], [74] and their associated Fokker-Planck equations for the Wigner functions.

We will also explore the Heisenberg point of view in connection with recent results of the Inria project-team MAXPLUS (algorithms and applications of algebras of max-plus type) relative to Perron-Frobenius theory [55], [54]. We will start with [88] and [81] where, based on a theorem due to Birkhoff [38], dual Lindblad equations and dual Kraus maps governing the Heisenberg evolution of any operator are shown to be contractions on the cone of Hermitian operators equipped with Hilbert's projective metric. As the Heisenberg picture is characterized by convergence of all operators to a multiple of the identity, it might provide a mean to circumvent the rank issues. We hope that such contraction tools will be especially well adapted to analyzing quantum systems composed of multiple components, motivated by the facts that the same geometry describes the contraction of classical systems undergoing synchronizing interactions [95] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [72].

Besides these analysis tasks, the major challenge in stabilization by interconnections is to provide systematic methods for the design, from typical building blocks, of control systems that stabilize a specific quantum goal (state, set of states, operation) when coupled to the target system. While constructions exist for so-called linear quantum systems [77], this does not cover the states that are more interesting for quantum applications. Various strategies have been proposed that concatenate iterative control steps for open-loop steering [97], [69] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [39], but without considering experimental implementations. A viable stabilization by interaction has to combine the capabilities of these various approaches, and this is a missing piece that we want to address.

3.3.3.1. Perturbation methods

With this subsection we turn towards more fundamental developments that are necessary in order to address the complexity of quantum networks with efficient reduction techniques. This should yield both efficient mathematical methods, as well as insights towards unravelling dominant physical phenomena/mechanisms in multipartite quantum dynamical systems.

In the Schrödinger point of view, the dynamics of open quantum systems are governed by master equations, either deterministic or stochastic [59], [53]. Dynamical models of composite systems are based on tensor products of Hilbert spaces and operators attached to the constitutive subsystems. Generally, a hierarchy of different timescales is present. Perturbation techniques can be very useful to construct reliable models adapted to the timescale of interest.

To eliminate high frequency oscillations possibly induced by quasi-resonant classical drives, averaging techniques are used (rotating wave approximation). These techniques are well established for closed systems without any dissipation nor irreversible effect due to measurement or decoherence. We will consider in a first step the adaptation of these averaging techniques to deterministic Lindblad master equations governing the quantum state, i.e. the system density operator. Emphasis will be put on first order and higher order corrections based on non-commutative computations with the different operators appearing in the Lindblad equations. Higher order terms could be of some interest for the protected logical qubit of figure 1b. In future steps, we intend to explore the possibility to explicitly exploit averaging or singular perturbation properties in the design of coherent quantum feedback systems; this should be an open-systems counterpart of works like [67].

To eliminate subsystems subject to fast convergence induced by decoherence, singular perturbation techniques can be used. They provide reduced models of smaller dimension via the adiabatic elimination of the rapidly converging subsystems. The derivation of the slow dynamics is far from being obvious (see, e.g., the computations of page 142 in [43] for the adiabatic elimination of low-Q cavity). Contrarily to the classical composite systems where we have to eliminate one component in a Cartesian product, we here have to eliminate one component in a tensor product. We will adapt geometric singular perturbations [50] and invariant manifold techniques [45] to such tensor product computations to derive reduced slow approximations of any order. Such adaptations will be very useful in the context of quantum Zeno dynamics to obtain approximations of the slow dynamics on the decoherence-free subspace corresponding to the slow attractive manifold.

Perturbation methods are also precious to analyze convergence rates. Deriving the spectrum attached to the Lindblad differential equation is not obvious. We will focus on the situation where the decoherence terms of the form $L\rho L^\dagger - (L^\dagger L\rho + \rho L^\dagger L)/2$ are small compared to the conservative terms $-i[H/\hbar, \rho]$. The difficulty to overcome here is the degeneracy of the unperturbed spectrum attached to the conservative evolution $\frac{d}{dt}\rho = -i[H/\hbar, \rho]$. The degree of degeneracy of the zero eigenvalue always exceeds the dimension of the Hilbert space. Adaptations of usual perturbation techniques [62] will be investigated. They will provide estimates of convergence rates for slightly open quantum systems. We expect that such estimates will help to understand the dependence on the experimental parameters of the convergence rates observed in [56][9] [68].

As particular outcomes for the other subsections, we expect that these developments towards simpler dominant dynamics will guide the search for optimal control strategies, both in open-loop microwave networks and in autonomous stabilization schemes such as reservoir engineering. It will further help to efficiently compute explicit convergence rates and quantitative performances for all the intended experiments.

4. Application Domains

4.1. Quantum engineering

A new field of quantum systems engineering has emerged during the last few decades. This field englobes a wide range of applications including nano-electromechanical devices, nuclear magnetic resonance applications, quantum chemical synthesis, high resolution measurement devices and finally quantum information processing devices for implementing quantum computation and quantum communication. Recent theoretical and experimental achievements have shown that the quantum dynamics can be studied within the framework of estimation and control theory, but give rise to new models that have not been fully explored yet.

The QUANTIC team's activities are defined at the border between theoretical and experimental efforts of this emerging field with an emphasis on the applications in quantum information, computation and communication. The main objective of this interdisciplinary team is to develop quantum devices ensuring a robust processing of quantum information.

On the theory side, this is done by following a system theory approach: we develop estimation and control tools adapted to particular features of quantum systems. The most important features, requiring the development of new engineering methods, are related to the concept of measurement and feedback for composite quantum systems. The destructive and partial [1] nature of measurements for quantum systems lead to major difficulties in extending classical control theory tools. Indeed, design of appropriate measurement protocols and, in the sequel, the corresponding quantum filters estimating the state of the system from the partial measurement record, are themselves building blocks of the quantum system theory to be developed.

On the experimental side, we develop new quantum information processing devices based on quantum superconducting circuits. Indeed, by realizing superconducting circuits at low temperatures and using microwave measurement techniques, the macroscopic and collective degrees of freedom such as the voltage and the current are forced to behave according to the laws of quantum mechanics. Our quantum devices are aimed to protect and process quantum information through these integrated circuits.

5. Highlights of the Year

5.1. Highlights of the Year

[1] Here the partiality means that no single quantum measurement is capable of providing the complete information on the state of the system.

- Rémi Azouit (supervisor: Pierre Rouchon; co-supervisor: Alain Sarlette) has successfully defended his PhD thesis on October 27th and is now moving as a postdoc to Sherbrooke University. This thesis provides a systematic approach towards model reduction through adiabatic elimination for open quantum systems.
- Joachim Cohen (supervisor: Mazyar Mirrahimi) has successfully defended his PhD thesis on February 2nd. This thesis provides a roadmap for future experiments on autonomous hardware efficient quantum error correction with superconducting circuits.

5.1.1. Awards

- Mazyar Mirrahimi has received the “Inria-Academie des Sciences young researcher award 2017”.
- Pierre Rouchon has received the “Grand Prix IMT-Academie ses Sciences 2017”.

6. New Results

6.1. Quantum Walks and accelerated mixing algorithms

Participants: A. Sarlette

This major line of work has been pursued together with S.Apers (UGent) and F.Ticozzi (U.Padova), in an attempt to distinguish what is "necessarily" quantum in such models, and what could be explained by memory effects which we could mimic with just classical dynamic controllers. We hence have a series of papers on both sides (quantum and non-quantum): the conference papers are published, the journal papers will be for 2018.

In [19], we investigate under which conditions a higher-order Markov chain, or more generally a Markov chain on an extended state space, can mix faster than a standard Markov chain on a graph of interest. We find that, depending on the constraints on the dynamics, two very different scenarios can emerge: under strict invariance of the target marginal and for general initialization of the lifted chain no speedup is possible; on the other hand, if these requirements are both relaxed, the lifted dynamics can achieve mixing in a time that corresponds to the diameter of the graph, which is optimal.

In [20], we establish a discrete-geometric bound on the convergence speed of mixing with *any* local stochastic process, under the key assumption that it leaves the target distribution invariant at each time. These processes include classical algorithms, any quantum algorithms, as well as possibly other strategies that obey the non-signalling criterion of probability transmission. We explicitly give the bound in terms of isoperimetric inequalities. We illustrate how this general result leads to new bounds on convergence times beyond the explicit Markovian setting. Mixing is essentially concerned with the discrete-time spreading of a distribution along the edges of a graph. In essence we establish that even by exploiting global information about the graph and allowing a very general use of this information, this spreading can still not be accelerated beyond the so-called *conductance bound*. An upcoming journal paper will discuss which assumption changes do lead to faster algorithms, and argue how relevant they are for practical applciations.

In [26], we give a preview on our specific results about Quantum walks. Quantum walks have been linked to acceleration in various information processing tasks, and proposed as a possible model for quantum-enhanced behavior in biological systems. These links and acceleration claims have been made with various levels of detail. Here we consider discrete-time quantum walks, and focus on the task of mixing, i.e., distributing the state over a graph. Previous papers have observed that the so-called coined quantum walks can accelerate mixing on certain graphs with respect to the optimal classical Markov chain. We here show that the same speedup can be attained with a classical process, if a similar classical coin is added. We establish a precise correspondence between the mixing performance of quantum walks and such " lifted walks " for all (finite) graphs, and thereby improve known bounds on quantum walk mixing time. We conclude that the advantage of quantum walks with respect to classical processes is not in the mixing speed of the optimal design. However, a notable quantum advantage might reside in the fact that the mixing speed obtained with suboptimal designs, due to for instance limited graph knowledge, appears to be generically faster. The journal version is being finalized and will be sumbitted before the end of 2017.

6.2. String Stability towards Leader thanks to Asymmetric Bidirectional Controller

Participants: A. Sarlette

This result published in [21] is the result of an investigation of classical (non-quantum) distributed and coupled systems and their fundamental limitations – a sequel of A.Sarlette's previous line of work. It deals with the problem of string stability of interconnected systems with double-integrator open loop dynamics (e.g. acceleration-controlled vehicles). We analyze an asymmetric bidirectional linear controller, where each vehicle is coupled solely to its immediate predecessor and to its immediate follower with different gains in these two directions. We show that in this setting, unlike with unidirectional or symmetric bidirectional controllers, string stability can be recovered when disturbances act only on a small (N-independent) set of leading vehicles. This improves existing results from the literature with this assumption. We also indicate that string stability with respect to arbitrarily distributed disturbances cannot be achieved with this controller.

A journal version is in preparation where we essentially close the subject, on a discrete-controller version:
- we will show that no local digital controller whatsoever (including nonlinearity, local communication,...) can achieve the academic property of string stability for infinite length chains and with bounded noise/disturbance on *each* member of the chain, and this implies serious consequences for practical behaviors of finite-length chains.
- conversely, we give the equivalent of the above result to show that if one is concerned mainly about the noise/disturbance acting on the leader (boundary condition of the chain), then indeed our above result achieves all existing variants of the string stability definitions.

6.3. Towards generic adiabatic elimination for bipartite open quantum systems

Participants: R. Azouit, A. Sarlette, P. Rouchon (and F. Chittaro, visitor in 2016)

The paper [12] is the main paper summarizing the results of the PhD thesis of R.Azouit. We give a theoretical method, with a directly applicable recipe for the physicists who would want to use it, and with examples worked out on applications that experimentalists (e.g. in the partner group at Yale U.) are actually considering nowadays.

We consider a composite open quantum system consisting of a fast subsystem coupled to a slow one. Using the timescale separation, we develop an adiabatic elimination technique to derive at any order the reduced model describing the slow subsystem. The method, based on an asymptotic expansion and geometric singular perturbation theory, ensures the physical interpretation of the reduced second-order model by giving the reduced dynamics in a Lindblad form and the state reduction in Kraus map form. We give explicit second-order formulas for Hamiltonian or cascade coupling between the two subsystems. These formulas can be used to engineer, via a careful choice of the fast subsystem, the Hamiltonian and Lindbald operators governing the dissipative dynamics of the slow subsystem.

6.4. Deterministic submanifolds and analytic solution of the quantum stochastic differential master equation describing a monitored qubit

Participants: A. Sarlette, P. Rouchon

In the paper [18], we study the stochastic differential equation (SDE) associated with a two-level quantum system (qubit) subject to Hamiltonian evolution as well as unmonitored and monitored decoherence channels. The latter imply a stochastic evolution of the quantum state (density operator), whose associated probability distribution we characterize. We first show that for two sets of typical experimental settings, corresponding either to weak quantum non demolition measurements or to weak fluorescence measurements, the three Bloch coordinates of the qubit remain confined to a deterministically evolving surface or curve inside the Bloch sphere. We explicitly solve the deterministic evolution, and we provide a closed-form expression for the probability distribution on this surface or curve. Then we relate the existence in general of such deterministically evolving submanifolds to an accessibility question of control theory, which can be answered with an explicit algebraic criterion on the SDE. This allows us to show that, for a qubit, the above two sets of weak measurements are essentially the only ones featuring deterministic surfaces or curves.

This paper was motivated by a striking experimental observation of Ph.Campagne-Ibarcq (group of Benjamin Huard - now at ENS Lyon and still collaborator). It appears to be actually quite general, and to generalize to higher-dimensional systems than the qubit. We are working on this extension, time permitting (as we have no student support currently), to publish a complete story about relevant experimental systems where the QSDE can be modeled in a very low-dimensional manifold.

6.5. Loss-tolerant parity measurement for distant quantum bits

Participants: A. Sarlette, M. Mirrahimi

This work, published in [17], [24], is part of the major line of work led by M.Mirrahimi about stabilizing distant entangled states. The latter are a major building block in quantum information technology, thanks to their ability to enable quantum teleportation. They are supposed to play a major 'quantum-bus-type' role in some of the most promising quantum computing architectures.

In this paper, we propose a scheme to measure the parity of two distant qubits, while ensuring that losses on the quantum channel between them does not destroy coherences within the parity subspaces. This capability enables deterministic preparation of highly entangled qubit states whose fidelity is not limited by the transmission loss. The key observation is that for a probe electromagnetic field in a particular quantum state, namely a superposition of two coherent states of opposite phases, the transmission loss stochastically applies a near-unitary back-action on the probe state. This leads to a parity measurement protocol where the main effect of the transmission losses is a decrease in the measurement strength. By repeating the non-destructive (weak) parity measurement, one achieves a high-fidelity entanglement in spite of a significant transmission loss.

6.6. Discrete-time reservoir engineering with entangled bath and stabilizing squeezed states

Participants: Z. Miao and A. Sarlette

The paper [15] is the first result of a line of work that we try to establish about the possible use of "time-structured reservoirs" towards stabilizing more complicated states of quantum systems. In particular, we here analyze a setting where reservoir items (qubits) are entangled over discrete time, and we show how it stabilizes squeezed states of a quantum harmonic oscillator. The parameters of the stabilized state can be tuned at will, in tradeoff with the convergence speed. The squeezing direction is determined by the phase of entanglement, thus allowing to distinguish genuine entanglement from mere classical correlations.

This work has allowed to identify the following lines for future research:
- first check time-varying, non-entangled reservoir inputs: from the same mathematical model, it appears that they can also stabilize squeezed states.
- provide a proof, on a non-trivial setting, of the specific benefit of entangled inputs: i.e. show how they achieve stabilization of some interesting states which are not accessible with any non-entangled inputs.
- laying the premises of possible approaches to studying continuous-time reservoir inputs which are entangled over time. This is currently an open question even from the modeling perspective.

6.7. Observing a quantum Maxwell demon at work

Participants: R. Azouit, B. Huard and P. Rouchon

The results of this section were published [14]

In apparent contradiction to the laws of thermodynamics, Maxwell's demon is able to cyclically extract work from a system in contact with a thermal bath exploiting the information about its microstate. The resolution of this paradox required the insight that an intimate relationship exists between information and thermodynamics. Here, this Maxwell demon experiment tracks the state of each constituent both in the classical and quantum regimes. The demon is a microwave cavity that encodes quantum information about a superconducting qubit and converts information into work by powering up a propagating microwave pulse by stimulated emission. Thanks to the high level of control of superconducting circuits, direct measurements (combined with maximum-likelihood estimation techniques inspired by [90]) give the extracted work and entropy remaining in the demon's memory. This experiment provides an enlightening illustration of the interplay of thermodynamics with quantum information.

6.8. Asymptotic expansions of Laplace integrals for quantum state tomography

Participant: P. Rouchon (with his former PhD student P. Six)

The results of this section were published in [25].

Bayesian estimation of a mixed quantum state can be approximated via maximum likelihood (MaxLike) estimation when the likelihood function is sharp around its maximum. Such approximations rely on asymptotic expansions of multi-dimensional Laplace integrals. When this maximum is on the boundary of the integration domain, as it is the case when the MaxLike quantum state is not full rank, such expansions are not standard. We provide here such expansions, even when this maximum does not belong to the smooth part of the boundary, as it is the case when the rank deficiency exceeds two. These expansions provide, aside the MaxLike estimate of the quantum state, confidence intervals for any observable. They confirm the formula proposed and used without precise mathematical justifications by the authors in an article published in Physical Review A in 2016 [90].

6.9. Generating higher order quantum dissipation from lower order parametric processes

Participant: M. Mirrahimi (and S. Mundhada, visitor from Yale in 2016)

The results of this section were published in [16].

Stabilization of quantum manifolds is at the heart of error-protected quantum information storage and manipulation. Nonlinear driven-dissipative processes achieve such stabilization in a hardware efficient manner. Josephson circuits with parametric pump drives implement these nonlinear interactions. In this work, we propose a scheme to engineer a four-photon drive and dissipation on a harmonic oscillator by cascading experimentally demonstrated two-photon processes. This would stabilize a four-dimensional degenerate manifold in a superconducting resonator. We analyze the performance of the scheme using numerical simulations of a realizable system with experimentally achievable parameters. This theoretical work, initiated by Shantanu Mundhada during his visit to Inria in 2016, is currently investigated experimentally at Yale.

6.10. Degeneracy-preserving quantum nondemolition measurement of parity-type observables for cat qubits

Participant: J. Cohen, M. Mirrahimi

The results of this section were published in [13] and correspond to an important chapter of J. Cohen's thesis [11].

A central requirement for any quantum error correction scheme is the ability to perform quantum nondemolition measurements of an error syndrome, corresponding to a special symmetry property of the encoding scheme. It is in particular important that such a measurement does not introduce extra error mechanisms, not included in the error model of the correction scheme. In this work, we ensure such a robustness by designing an interaction with a measurement device that preserves the degeneracy of the measured observable. More precisely, we propose a scheme to perform continuous and quantum nondemolition measurement of photon-number parity in a microwave cavity. This corresponds to the error syndrome in a class of error correcting codes called the cat codes, which have recently proven to be efficient and versatile for quantum information processing. In our design, we exploit the strongly nonlinear Hamiltonian of a high-impedance Josephson circuit, coupling a high-Q storage cavity mode to a low-Q readout one. By driving the readout resonator at its resonance, the phase of the reflected or transmitted signal carries directly exploitable information on parity-type observables for encoded cat qubits of the high-Q mode. This important result has defined a new line of experimental research persued by the experimentalists of the Quantic team and Yale university.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Emergences-Ville de Paris program, ENDURANCE project

In the framework of the Ville de Paris program “EMERGENCES”, Zaki Leghtas has received a funding for his research program "Multi-photon processes in superconducting circuits for quantum error correction". This grant of 232k euros over 4 years will complement the ANR project of the same name obtained last year. Using this funding, we will purchase all the microwave and nano-fabrication equipment and consumables for the experiment based at ENS.

7.1.2. DIM SIRTEQ, PhD fellowship

In the framework of the project “DIM SIRTEQ Domaine d’intérêt Majeur: Science et Ingénierie Quantique” of Ile de France Region, we have received 18 months of PhD fellowship. This completes the funding from ANR GEARED of the PhD thesis of J. Guillaud, who has started his PhD under the supervision of M. Mirrahimi and P. Rouchon in September 2017.

7.1.3. Programme Math-PSL, Postdoctoral fellowship

In the framework of the programme Math-PSL of PSL Research University, we have resceived a 12 month postdoctoral fellowship. Paolo Forni has been hired as a postdoc on this funding.

7.2. National Initiatives

7.2.1. ANR project GEARED

This four-year collaborative ANR project, entitled “Reservoir engineering quantum entanglement in the microwave domain” and coordinated by Mazyar Mirrahimi, started on October 2014. The participants of the project are Mazyar Mirrahimi, François Mallet (QUANTIC project-team), Benjamin Huard (ENS Lyon), Daniel Esteve and Fabien Portier (Quantronics group, CEA Saclay), Nicolas Roch and Olivier Buisson (Institut Neel, Grenoble). This project deals with robust generation of entanglement as a key resource for quantum information processing (quantum simulation, computation and communication). The entangled states are difficult to generate and sustain as interaction with a noisy environment leads to rapid loss of their unique quantum properties. Through Geared we intend to investigate different complementary approaches to master the entanglement of microwave photons coupled to quantum superconducting circuits.

7.2.2. ANR project ENDURANCE

In the framework of the ANR program “Accueil de chercheur de haut niveau”, Zaki Leghtas has received a funding for his research program "Multi-photon processes in superconducting circuits for quantum error correction". This grant of 400k euros has allowed us to purchase the experimental equipment to build a new experiment based at ENS.

7.3. European Initiatives

7.3.1. Collaborations with Major European Organizations

Partner 1: ENS Lyon

We are pursuing our interdisciplinary work about quantum control from theoretical aspects in direct collaboration with existing experiments (ENS Lyon) with the group of Benjamin Huard, former member of the QUANTIC team. Joint papers are published and underway. We are in particular working on the proper combination of two model reduction techniques in their experimental context: adiabatic elimination and Rotating-Wave Approximation. An ANR-JCJC project has been deposited by Alain Sarlette on this subject, with Benjamin Huard as external supporting collaborator.

Partner 2: University of Padova

Alain Sarlette has been pursuing a fruitful collaboration with the group of Francesco Ticozzi on dynamical systems aspects of quantum systems. Common work on the theory of quantum random walks is being finalized and we are working out a concrete plan about next possible steps.

Partner 3: Ghent University.

A. Sarlette is collaborating with applied mathematicians interested in quantum control at his former institution UGent (Dirk Aeyels, Lode Wylleman, Gert De Cooman) in the framework of thesis co-supervisions. Two students are in their last year PhD, in particular Simon Apers is finalizing a thesis centered around Quantum Walks, also in collaboration with Partner 2. A master student in applied physics has started an internship in 2017.

7.4. International Initiatives

7.4.1. Inria Associate Teams Not Involved in an Inria International Labs

TAQUILLA is an Inria associate team (between Quantic team and Yale university) with principal Inria investigator, Mazyar Mirrahimi, and principal Yale investigator Michel Devoret. In this framework, L. Verney, J. Guillaud and M. Mirrahimi visited Yale for respectively, 2, 3 and 4 months.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

P. S. Pereira da Silva (Escola Politécnica, PTC, University of SaoPaulo, Brazil) made a 2-week visit (July 3 to July 14) to investigate with Pierre Rouchon motion planning issues based on Lyapunov tracking for quantum gate generations.

7.5.2. Visits to International Teams

7.5.2.1. Research Stays Abroad

In the framework of TAQUILLA associate team, Mazyar Mirrahimi spent four months in the Quantronics Laboratory of Michel H. Devoret and in the Rob Schoelkopf Lab at Yale University. Also, in this same framework Jérémie Guillaud and Lucas Verney spent respectively three months and two months in the same group.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Journal

8.1.1.1. Member of the Editorial Boards

Pierre Rouchon is member of the editorial board of Annual Reviews in Control (since 2016).

Mazyar Mirrahimi was a guest editor for the journal "Quantum Science and Technology" (Institute Of Physics, 2016-2017), Special issue on “Quantum coherent feedback and quantum reservoir engineering”.

8.1.1.2. Reviewer - Reviewing Activities

Zaki Leghtas served as a referee for Physical Review Journals.

Mazyar Mirrahimi served as a referee for Physical Review Journals.

Pierre Rouchon has been a reviewer for several automatic control and dynamical systems journals and conferences.

Alain Sarlette has been a reviewer for several automatic control and dynamical systems journals and conferences.

8.1.2. Invited Talks

Mazyar Mirrahimi, July 2017, ICTS (Workshop Open Quantum Systems), Bangalore, India.

Mazyar Mirrahimi, June 2017, 22ème conférence Claude Itzykson, CEA Saclay, France.

Mazyar Mirrahimi, June 2017, CIFAR Workshop on Quantum Cavities, Jouvence, Quebec, Canada.

Mazyar Mirrahimi, May 2017, L2S, Supelec, France.

Mazyar Mirrahimi, April 2017, Conference of Optical Society of America, Quantum Information and Measurement, Paris, France.

Mazyar Mirrahimi, March 2017, CMAP, Ecole Polytechnique, France.

Mazyar Mirrahimi, February 2017, UVSQ, France.

Pierre Rouchon, November 2017, Control and Optimization Conference on the occasion of Frédéric Bonnans 60th birthday, Palaiseau, France.

Pierre Rouchon, June 2017, 22ème conférence Claude Itzykson, CEA Saclay, France.

Pierre Rouchon, April 2017, workshop on Quantum Control Theory: Mathematical Aspects and Physical Applications, TUM-IAS, Garching, Germany.

Pierre Rouchon, April 2017, 4th Workshop on Quantum Non-Equilibrium Dynamics, University of Nottingham, UK.

Alain Sarlette, July 2017, Praqcsys: Principles and Applications of Control in Quantum Systems, Seattle, USA.

Alain Sarlette, June 2017, L2S, Supelec, France.

Rémi Azouit, February 2017, Sherebrooke University, Canada.

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8.1.3. Scientific Expertise

Mazyar Mirrahimi is a member of the Technical Committee on "Distributed Parameter Systems" in IFAC (International Federation of Automatic Control).

Pierre Rouchon is a member of the scientific committee of LAGEP (Laboratoire d'Automatique et de Génie des Procédés) since 2017

Pierre Rouchon is a membre of the "Conseil Scientifique du DIM Math Innov" since 2017.

Pierre Rouchon is a member of the "Conseil de la recherche de PSL " since 2016.

Pierre Rouchon is a member of the "Conseil Scientifique du Conservatoire National des Arts et Metiers" since 2014.

Pierre Rouchon was a member of the scientific committee of PRACQSYS 2017

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Zaki Leghtas taught a course on Quantum Mechanics at Paris Sciences et Lettres (40 hours).

Zaki Leghtas taught a course on Quantum Mechanics and Statistical Physics at Mines ParisTech (12 hours).

Zaki Leghtas taught a course on Complex Analysis at Mines ParisTech (10 hours).

Mazyar Mirrahimi and Pierre Rouchon have given a course (20 hours) entitled "UE : Analyse et contrôle de systèmes quantiques " in the "Master de sciences et technologies, mention mathématiques et applications, Université Pierre et Marie Curie".

Mazyar Mirrahimi is hired as a professeur chargé de cours à temps partiel of Applied Mathematics at Ecole Polytechnique. His teaching will start during winter 2018.

Mazyar Mirrahimi has given TDs of the courses on Probabilities and on Stochastic Processes at Ecole des Mines de Paris.

Pierre Rouchon gave a course on "Cryptographie, théorie des nombres et information quantique" at Mines ParisTech (24 hours).

Pierre Rouchon gave a course on "Modelling, simulation and feedback of open quantum systems" in the PSL-Master, PSL-IT, IQ Ingénierie Quantique (12 hours).

Alain Sarlette has given a master course on “Probabilistic robotics” at Ghent University (30 hours) and has given TDs of the courses on Probabilities and on Stochastic Processes at Ecole des Mines de Paris.

Alain Sarlette has given a quantum-related lecture in the course on Stochastic Processes (5 hours), Ecole des Mines de Paris.

8.2.2. Supervision

PhD in progress: Raphael Lescanne. ENS. “Engineering Multi-Photon Dissipation In Superconducting Circuits For Quantum Error Correction”. September 2016. (advisors: Zaki Leghtas and Benjamin Huard).

PhD: Rémi Azouit. Mines Paristech. “Adiabatic elimination for open quantum systems”. 2014-2017. (advisors: Pierre Rouchon and Alain Sarlette), Defended on Oct 2017.

PhD in progress: Gerardo Cardona. Mines ParisTech. "Beyond static gains in analog quantum feedback control". Nov 2016 (advisors: Pierre Rouchon and Alain Sarlette).

PhD in progress: Alain Sarlette is co-supervising 3 PhD students with his former institution UGent (Simon Apers, Zhifei Zhang, Arash Farnam). Simon Apers is working on (quantum) network algorithms accelerations and intends to address other quantum control questions.

PhD: Joachim Cohen. ENS. “Autonomous quantum error correction with superconducting circuits”. 2013-2017 (advisor: Mazyar Mirrahimi), Defended on Feb 2017.

PhD in progress: Lucas Verney. ENS. “Robust quantum information processing with superconducting circuits”. Sept 2016. (advisors: Zaki Leghtas and Mazyar Mirrahimi).

PhD in progress: Jérémie Guillaud. ENS. “Modular architecture for quantum information processing”. Sept 2017. (advisors: Mazyar Mirrahimi and Pierre Rouchon).

8.2.3. Juries

Mazyar Mirrahimi was a member the PhD defense committees of Serguei Fedortchenko (Jury president, University Paris Diderot).

Pierre Rouchon was a referee for the PhD thesis of Muhammad Emzi, Australian National University, and for the Habilitation thesis of Marco Caponigro, UMPC.

Alain Sarlette was a jury member for the PhD of Stavros Lopatatzidis (UGent, Belgium) and of Bram Vervisch (UGent, Belgium).

8.3. Popularization

Mazyar Mirrahimi has been interviewed by Le Monde for a dossier on quantum information.

Mazyar Mirrahimi gave an invited talk on “Quantum computing” at the CRiP’s ITES Innovation Summit at Deauville, France in Mars 2017.

Mazyar Mirrahimi gave an invited talk on “Quantum computing” at X-Creation (X-Drahi) in May 2017.

Pierre Rouchon was invited to give a talk "Contrôle des systèmes: du classique au quantique", Journée d’inauguration du programme PSL-maths, 19 October 2017 at ENS-Paris.

Alain Sarlette has been speaking at inria-organized dissemination events:
- 03/07 "fresh from the labs" talk about quantum technology hardware (at Boston Consulting Group, Paris – team gamma)
- 06-08/06 Keynote speech at Journées DGDT
- 10/07 presentation at inria-Paris-labs visit by high-level managers and stakeholders

Alain Sarlette is answering questions about quantum control and quantum computing on the website "ik-heb-een-vraag.be" where Flemish layman can ask questions to scientific experts.

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