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Project-Team QUANTIC

QUANTum Information Circuits

IN COLLABORATION WITH: Laboratoire Pierre Aigrain

RESEARCH CENTER
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THEME
Optimization and control of dynamic systems

Table of contents

Project-Team QUANTIC

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

Keywords:

Computer Science and Digital Science:

1.1.11. - Quantum architectures
4.2. - Correcting codes
6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.1.4. - Multiscale modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.3. - Probabilistic methods
6.2.6. - Optimization
6.3.1. - Inverse problems
6.3.2. - Data assimilation
6.3.3. - Data processing
6.3.4. - Model reduction
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.2. - Stochastic control
6.4.3. - Observability and Controlability
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

5.3. - Nanotechnology
5.4. - Microelectronics
6.5. - Information systems
9.8. - Privacy

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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. Towards microwave quantum networks

The classical states of microwave radiation, are the so-called coherent states. They can be prepared by a commercial microwave generator (frequency $1\text{GHz} < f < 20\text{GHz}$) followed by thermalization to $k_B T \ll hf$ using a chain of attenuators anchored at various stages of a dilution refrigerator.

Owing to the strength of its coupling to superconducting circuits [53] or Rydberg atoms [70], microwave radiation can also be prepared in many possible non-classical states. Using a sequence of quanta exchanges between superconducting qubits and a microwave cavity, the direct preparation of an arbitrary superposition of Fock states has been demonstrated in 2009 [72] with about 90% fidelity up to 5 photons. Recently, the physicists at Yale university in collaboration with the theorists of QUANTIC team, demonstrated a superposition of classical states, or Schrödinger cat, with 100 photons on average, using the dispersive coupling to a transmon qubit [121].

An important class of states for quantum information processing with continuous variables is that of the Gaussian squeezed states [122]. These states can be seen as a coherent state for which the fluctuations on a quadrature are less than the zero point fluctuations. Of course, owing to Heisenberg uncertainty principle, this comes at the expense of larger fluctuations on the conjugated quadrature. In the optical domain, Gaussian light has been demonstrated and used with single and multimodes decades ago [122]. In the microwave domain, single mode squeezing of thermal noise had been demonstrated already in 1988 [127] but vacuum noise squeezing was only demonstrated in 2008 [50]. Since then, several groups have been able to generate single- and two-mode squeezing of microwave radiation, including us [57], [124], [88], [92], [59]. The two-mode squeezed states are of particular interest for quantum information processing, because they are maximally entangled for a given average number of quanta. In particular, the circuit developed by QUANTIC's experimentalists is able to directly generate two-mode squeezed states on separate transmission lines, at arbitrarily different frequencies [59].

In the perspective of a quantum network using microwave radiation, one needs a way to store and preserve microwave fields in nodes. Arguably, creating a memory for quantum systems able to preserve indefinitely a quantum state is the next big challenge on the road towards quantum computing [54], yet unrealized in any system. In a first step, we focus on a quantum node able to preserve a quantum state for a finite time.

In the optical domain, current implementations of quantum memories [112] rely mainly on two physical effects: the light deceleration due to electromagnetically induced transparency and the transfer of photonic quantum states onto collective atomic coherences (optical or spin). In the microwave domain, several quantum memories have emerged in the last years using spin ensembles [125], [78], [107], mechanical resonators [96], [97] or superconducting circuits [126], [123], such as our device described in [60].

All these microwave implementations have pros and cons. However, only two of them, the mechanical oscillator of the Lehnert group [97] and our device [60] have demonstrated entanglement between the memory and a propagating microwave mode. Specifically, our device consists in a 3D storage microwave cavity whose coupling to a transmission line is performed using an active superconducting circuit: the Josephson ring modulator. In the frequency conversion regime, it acts as a tunable coupler whose rate is solely controlled by the amplitude of a pump signal. In the parametric down-conversion regime, it acts as an entanglement generator, similarly to the mechanical version of the Boulder group. However, the inherently small coupling rate between the transmission line and the mechanical resonator in [97] makes our device [60] a much stronger candidate for a quantum node. Apart from this crucial possibility to generate entanglement, our device is similar to the implementation of Santa Barbara [126]. Both have demonstrated fast tuning (up to 30 MHz for Santa Barbara) with high catching efficiency and storage time of 4 μs. However we believe that two specificities make our route more promising. In their case it is a flux knob which allows tuning of the transparency of a 2D microwave cavity. The core of the device we propose is a 3D storage microwave, an architecture where there is plenty of room to improve the storage time and exceed this figure by orders of magnitude, even without quantum error correction [101]. Moreover the cavity transparency is controlled solely by the amplitude of a microwave tone, free of the complications of hysteresis inherent to fast flux tuning in a superconducting environment.

The quantum information protocols one can envision using the quantum node developed by QUANTIC's experimentalists gets a useful inspiration from what has been realized in the optical domain in the last 20 years. One of the most interesting protocols we would like to implement is the teleportation of a quantum state from the memory into a transmission line or another memory. In optics, this was performed already in 1998 for a coherent state [61], and more recently for a Schrödinger-cat-like state [79]. We could readily reproduce these experiments in the microwave regime. The deterministic teleportation of a superconducting quantum bit was realized only in 2013 [116] but no experiments have shown teleportation of a continuous variable state in the microwave domain up to now. Furthermore, none of the protocols needed for quantum information processing (entanglement distillation and dilution for instance) have ever been realized in the microwave domain with Gaussian states [122]. It is thus of great interest to investigate where the tools specific to superconducting circuits will allow us to go beyond what can be done in the optical domain. In particular, the microwave quantum limited amplifiers [104] developed by QUANTIC's experimentalists lead to unmatched heterodyne measurement efficiencies. Finally using a qubit as a Fock number resolved photocounter unleashes many scenarios in the preparation and manipulation by measurement of an entangled state [93].

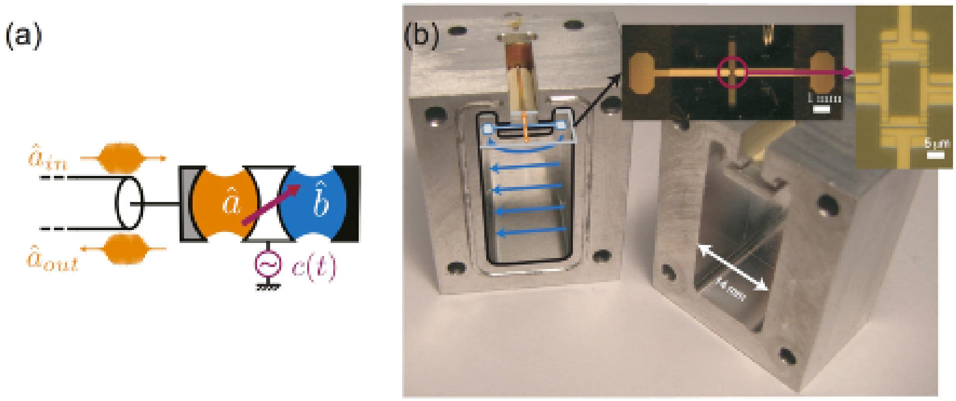

Figure 1. (a) Scheme of the quantum memory. A three-wave mixer is used as a controllable switch between a read/write cavity a and a long storage time cavity b *via the application of a control field c. (b) Picture of the first device. A 2D microstrip resonator on a Sapphire chip is dynamically coupled to a 3D aluminum cavity mode through antennas attached to a ring of 4 Josephson junctions.*

3.2. 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 [111], [115]. 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 [81]. 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 [76], [68] 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 [80]. Through a recent experimental work [121], 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 [117] 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 2, 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.

3.3. 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 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 [44]. In the context of cavity quantum electro-dynamics (cavity

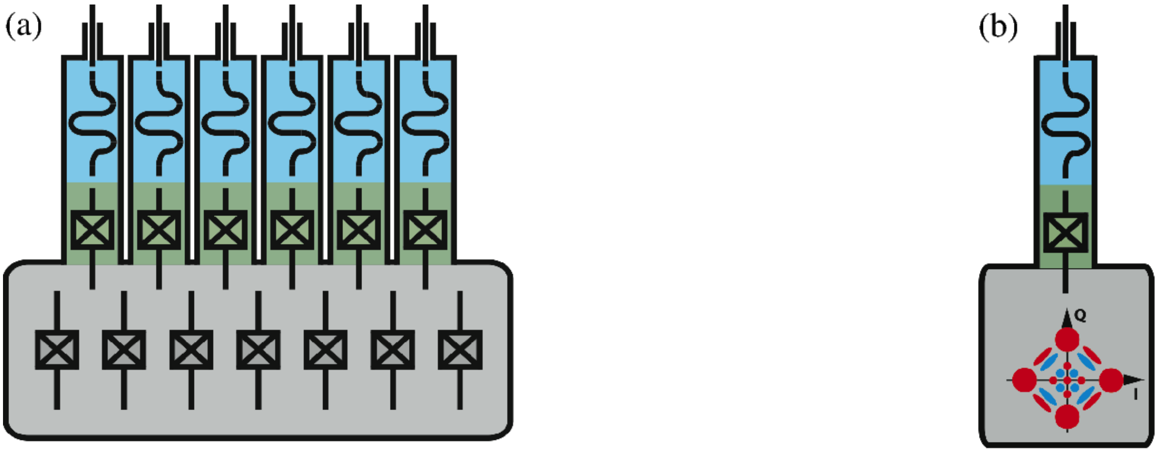

Figure 2. (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [115] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

QED) with Rydberg atoms [70], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [69]. 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 [56], [35], [114], [37]. 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) [55], recent advances in quantum-limited amplifiers [104], [119] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [71]. 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 [119], [103], [46]. 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 [89].

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 [100] and the closely related coherent feedback [86] 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 [67], single-qubit state stabilization [91], and the creation [39] and stabilization [77], [85][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 [67], [83], [51]. The experimental results based on these protocols have illustrated the efficiency of the approach [67][9]. Through these experiments, we exploit the strong dispersive interaction [109] 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 [90], [106], [73][5].

3.4. 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 [105], [35], [113], [108], [114], [37][7] resulting from collaborations with the cavity quantum electrodynamics group of Laboratoire Kastler Brossel.

3.4.1. 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 [37]: 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 [128]; 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 [98]. 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 [71], [46].

3.4.2. 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 [40] and is related to quantum trajectories [48], [52]. A modern and mathematical exposure of the diffusive models is given in [38]. In [129] 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 [105], [113]. This stability result is extended to a large class of continuous-time filters in [36]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [41]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [62], [94].

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 [45] that post-selection statistics and “past quantum” state analysis [63] enhance sensitivity to parameters and could be interesting towards increasing the precision of an estimation.

3.4.3. 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 [100], [86]. 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] [67], 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 [99]). 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., [34][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] [67], [90] 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 [66], [65]. We will start with [110] and [102] where, based on a theorem due to Birkhoff [42], 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 [118] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [87].

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 [95], 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 [120], [84] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [43], 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.

3.4.3.1. *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 [70], [64]. 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 2b. 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 [82].

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 [47] 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 [58] and invariant manifold techniques [49] 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 [74] 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 [67][9] [83].

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

- Pierre Rouchon was a plenary speaker at 55th IEEE Conference on Decision and Control.

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

- First demonstration of a quantum error correcting code extending the lifetime of a quantum bit: this experiment performed at Yale in collaboration with the team of Robert J. Schoelkopf realizes the hardware-efficient quantum error correction protocol that we had proposed a few years ago. This is the first experiment where a redundant encoding of quantum information, together with continuous measurements of an error syndrome and real-time closed-loop error corrections, extend the lifetime of the encoded information beyond the best physical part. This result was published in Nature [22].
- An experimental marriage of two central concepts of mechanics, the Schrödinger cat states and the entanglement, was realized in collaboration with the team of Robert J. Schoelkopf at Yale. Following our earlier theoretical proposals, an entangled Schrödinger cat state of light shared between two boxes (two high-Q cavities) were successfully achieved and measured. Experimental realization of such states of light were proposed more than 20 years ago and have important applications in quantum information processing. This result was published in Science [28] and has attracted important press converge around the world.
- First experimental demonstration of the quantum-state diffusion associated with spontaneous emission that triggered the field of quantum trajectories in the 1990s. This result was published in Phys. Rev. X [16]. This also led us to implement a first experimental demonstration of multi-input multi-output (MIMO) feedback in the quantum regime. This result was published in Phys. Rev. Lett. [15].

6. New Results

6.1. Observing Quantum State Diffusion by Heterodyne Detection of Fluorescence

Participants: Benjamin Huard, Mazyar Mirrahimi, Pierre Rouchon, Alain Sarlette, Pierre Six.

The results of this section were published in [16] and in [17].

Light emitted via fluorescence is associated with matter decaying in energy, and this light can be viewed as a probe that carries information about the state of its emitter. When this information is lost, the fragile quantum properties of the emitter are destroyed, a process known as decoherence. Using a superconducting qubit, we demonstrate how the sole measurement of fluorescence makes it possible to accurately track the quantum state in time. The observed evolution is erratic, which is expected based on the random backaction of measurements in quantum mechanics.

We continuously measure the amplitude of the fluorescence field emitted by a superconducting qubit using an amplifier close to the quantum limit; our measurements are obtained at cryogenic temperatures. From each fluorescence record, we can reconstruct a quantum trajectory, which is the succession of states the qubit occupies on a single relaxation event. We collect independent measurements of the qubit state at an arbitrary time during relaxation. These measurements follow the statistics that are expected from the quantum trajectories, thereby verifying the reconstructed quantum states. By repeating the experiment millions of times, we are able to determine the distribution of quantum trajectories. Strikingly, monitoring fluorescence can generate a superposition of states and counterintuitively lead to a temporary increase in the qubit excitation probability.

Our work provides an experimental demonstration of the quantum-state diffusion associated with spontaneous emission that triggered the field of quantum trajectories in the 1990s. We expect that our findings, which enlighten the correspondence between decoherence and measurement by the environment, will contribute to the progress of quantum error correction.

In a parallel work, we theoretically investigate statistical properties of the diffusion. In particular, we use a path integral formulation to determine the most likely trajectory during an evolution.

This work was made in collaboration with the team of Andrew Jordan at University of Rochester.

6.2. Using Spontaneous Emission of a Qubit as a Resource for Feedback Control

Participants: Nathanael Cottet, Benjamin Huard, Sebastien Jezouin, François Mallet, Pierre Rouchon, Alain Sarlette, Pierre Six.

The results of this section were published in [15].

We performed an experiment that demonstrates the permanent stabilization of any state of a superconducting qubit despite decoherence using a feedback scheme based on the information leaking out by the relaxation channel itself when the qubit spontaneously emits a photon.

At first sight, it may seem that using the detection of the photon that a qubit emits during a relaxation event cannot allow to protect an arbitrary quantum state from decoherence. First, it is very hard to collect efficiently the photons emitted by a two-level system. Second, the information contained in the emitted photon alone does not seem to be sufficient to correct the effect of relaxation and stabilize an arbitrary qubit state.

However, as we recently showed experimentally (see previous paragraph), it is now possible to measure the spontaneously emitted field using heterodyne detection, and reconstruct the quantum trajectory of a qubit. The information is therefore indeed useful and accessible!

Here, we go well beyond this previous work by not only decoding but also using the information contained in the spontaneously emitted field in real time. Specifically, we use the information contained in fluorescence to stabilize permanently any chosen state of the qubit by measurement feedback.

Stabilizing qubits by a feedback protocol based on the measurement of their relaxation channel had been proposed about 20 years ago by Hofmann and coworkers. They had claimed that it is possible to stabilize any state in the Southern hemisphere of the Bloch sphere. Wang and Wiseman revisited this problem 15 years ago and proposed a scheme that stabilizes any state of the Bloch sphere except the equator. In our work, we devise a new scheme that stabilizes any state, even on the equator! We are also the first ones to implement any such scheme experimentally.

The experiment itself covers several premieres, which are of wider interest to the quantum information and quantum control communities. First, we reach an unprecedented 35% of measurement efficiency for the spontaneously emitted photons out of a qubit (crucial parameter for feedback control). Second, this is the first multiple-input multiple-output feedback in the quantum regime. Finally, we devise a new feedback controller based on the ac-Stark effect to tune the qubit frequency as a function of one input analog signal.

6.3. Well-posedness and convergence of the Lindblad master equation for a quantum harmonic oscillator with multi-photon drive and damping

Participants: Remi Azouit, Pierre Rouchon, Alain Sarlette

The main motivation for this result was to finally treat in a rigorous way the convergence of a non-trivial infinite-dimensional system (harmonic oscillator Hilbert space) that is of relevance to physicists. The essential tools for this proof are the choice of an appropriate metric leading to contraction, and the Hille-Yosida theorem ensuring well-posedness of the problem. This could be a valuable basis towards a more general, yet easily invocable argument to treat the many other infinite-dimensional quantum dynamics which intuitively "should never escape towards infinite energies."

This result has been published in [13].

6.4. Quantum state tomography with non-instantaneous measurements, imperfections, and decoherence

Participants: Pierre Six, Alain Sarlette, Benjamin Huard, Pierre Rouchon

Tomography of a quantum state is usually based on positive operator-valued measure (POVM) and on their experimental statistics. Among the available reconstructions, the maximum-likelihood (MaxLike) technique is an efficient one. We propose an extension of this technique when the measurement process cannot be simply described by an instantaneous POVM. Instead, the tomography relies on a set of quantum trajectories and their measurement records. This model includes the fact that, in practice, each measurement could be corrupted by imperfections and decoherence, and could also be associated with the record of continuous-time signals over a finite amount of time. The goal is then to retrieve the quantum state that was present at the start of this measurement process. The proposed extension relies on an explicit expression of the likelihood function via the effective matrices appearing in quantum smoothing and solutions of the adjoint quantum filter. It allows to retrieve the initial quantum state as in standard MaxLike tomography, but where the traditional POVM operators are replaced by more general ones that depend on the measurement record of each trajectory. It also provides, aside the MaxLike estimate of the quantum state, confidence intervals for any observable. Such confidence intervals are derived, as the MaxLike estimate, from an asymptotic expansion of multi-dimensional Laplace integrals appearing in Bayesian Mean estimation. This work should allow much more accurate inference of the state achieved by some quantum experiment, before a non-instantaneous measurement process is performed to check its results – distinguishing the loss in fidelity truly incurred by the preparation process, from the loss in fidelity induced only by the benchmarking measurement process which would not be present in the final application. A validation is performed on two sets of experimental data: photon(s) trapped in a microwave cavity subject to quantum non-demolition measurements relying on Rydberg atoms, where we have collaborated with the group of Igor Dotsenko at the LKB, College de France; and the heterodyne fluorescence measurements of a superconducting qubit, with the experimentalists of the QUANTIC team.

This result has been published in [27].

6.5. Adiabatic elimination for open quantum systems with effective Lindblad master equations

Participants: Remi Azouit, Pierre Rouchon, Alain Sarlette

We consider an open quantum system described by a Lindblad-type master equation with two times-scales. The fast time-scale is strongly dissipative and drives the system towards a low-dimensional decoherence-free space. To perform the adiabatic elimination of this fast relaxation, we propose a geometric asymptotic expansion based on the small positive parameter describing the time-scale separation. This expansion exploits geometric singular perturbation theory and center-manifold techniques. We conjecture that, at any order, it provides an effective slow Lindblad master equation and a completely positive parameterization of the slow invariant sub-manifold associated to the low-dimensional decoherence-free space. By preserving complete positivity and trace, two important structural properties attached to open quantum dynamics, we obtain a reduced-order model that directly conveys a physical interpretation since it relies on effective Lindbladian descriptions of the slow evolution. At the first order, we derive simple formulae for the effective Lindblad master equation. For a specific type of fast dissipation, we show how any Hamiltonian perturbation yields Lindbladian second-order corrections to the first-order slow evolution governed by the Zeno-Hamiltonian. These results are illustrated on a composite system made of a strongly dissipative harmonic oscillator, the ancilla, weakly coupled to another quantum system.

This result has been published in [30].

6.6. Loss-tolerant parity measurement for distant quantum bits

Participants: Mazyar Mirrahimi, Alain Sarlette

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 last property is a new and essential feature towards using repeated parity measurements in realistic physical conditions. It is achieved thanks to the use of cat states for the probe field that interacts with the two remote qubits. We show how this allows to stabilize highly entangled states between distant qubits, with the current state-of-the-art circuit QED capabilities. Highly entangled states are envisioned as a fundamental building block of the so-called modular quantum computing architecture, so their stabilization, i.e rapid availability, can be viewed as a major step towards enabling such technology.

This result has been submitted as a journal paper [23].

6.7. Holonomic quantum control with continuous variable systems

Participants: Mazyar Mirrahimi

In a collaboration with the team of Liang Jiang at Yale University we propose a scheme to realize a set of universal gates on protected cat-qubits. Universal computation of a quantum system consisting of superpositions of well-separated coherent states of multiple harmonic oscillators can be achieved by three families of adiabatic holonomic gates. The first gate consists of moving a coherent state around a closed path in phase space, resulting in a relative Berry phase between that state and the other states. The second gate consists of “colliding” two coherent states of the same oscillator, resulting in coherent population transfer between them. The third gate is an effective controlled-phase gate on coherent states of two different oscillators. Such gates should be realizable via reservoir engineering of systems that support tunable nonlinearities, such as trapped ions and circuit QED.

This result has been published in [11].

6.8. A Schrodinger cat living in two boxes

Participants: Mazyar Mirrahimi

Quantum superpositions of distinct coherent states in a single-mode harmonic oscillator, known as cat states, have been an elegant demonstration of Schrodinger’s famous cat paradox. Here, in a collaboration with the team of Robert Schoelkopf at Yale university, we realize a two-mode cat state of electromagnetic fields in two microwave cavities bridged by a superconducting artificial atom, which can also be viewed as an entangled pair of single-cavity cat states. We present full quantum state tomography of this complex cat state over a Hilbert space exceeding 100 dimensions via quantum nondemolition measurements of the joint photon number parity. The ability to manipulate such multicavity quantum states paves the way for logical operations between redundantly encoded qubits for fault-tolerant quantum computation and communication.

This result has been published in [28].

6.9. Extending the lifetime of a quantum bit with error correction in superconducting circuits

Participants: Zaki Leghtas, Mazyar Mirrahimi

Quantum error correction (QEC) can overcome the errors experienced by qubits and is therefore an essential component of a future quantum computer. To implement QEC, a qubit is redundantly encoded in a higher-dimensional space using quantum states with carefully tailored symmetry properties. Projective measurements of these parity-type observables provide error syndrome information, with which errors can be corrected via simple operations. The break-even point of QEC at which the lifetime of a qubit exceeds the lifetime of the constituents of the system has so far remained out of reach. Although previous works have demonstrated elements of QEC, they primarily illustrate the signatures or scaling properties of QEC codes rather than test the capacity of the system to preserve a qubit over time. Here, in a collaboration with the team of Robert Schoelkopf at Yale University, we demonstrate a QEC system that reaches the break-even point by suppressing the natural errors due to energy loss for a qubit logically encoded in superpositions of Schrodinger-cat states of a superconducting resonator. We implement a full QEC protocol by using real-time feedback to encode, monitor naturally occurring errors, decode and correct. As measured by full process tomography, without any post-selection, the corrected qubit lifetime is 320 microseconds, which is longer than the lifetime of any of the parts of the system: 20 times longer than the lifetime of the transmon, about 2.2 times longer than the lifetime of an uncorrected logical encoding and about 1.1 longer than the lifetime of the best physical qubit (Fock states of the resonator). Our results illustrate the benefit of using hardware-efficient qubit encodings rather than traditional QEC schemes. Furthermore, they advance the field of experimental error correction from confirming basic concepts to exploring the metrics that drive system performance and the challenges in realizing a fault-tolerant system.

This result has been published in [22].

6.10. Robust Concurrent Remote Entanglement Between Two Superconducting Qubits

Participants: Zaki Leghtas

Entangling two remote quantum systems that never interact directly is an essential primitive in quantum information science and forms the basis for the modular architecture of quantum computing. When protocols to generate these remote entangled pairs rely on using traveling single-photon states as carriers of quantum information, they can be made robust to photon losses, unlike schemes that rely on continuous variable states. However, efficiently detecting single photons is challenging in the domain of superconducting quantum circuits because of the low energy of microwave quanta. Here, in a collaboration with the team of Michel Devoret at Yale University, we report the realization of a robust form of concurrent remote entanglement based on a novel microwave photon detector implemented in the superconducting circuit quantum electrodynamics platform of quantum information. Remote entangled pairs with a fidelity of 0.57 are generated at 200 Hz. Our experiment opens the way for the implementation of the modular architecture of quantum computation with superconducting qubits.

This work was published in [21].

6.11. Planar Multilayer Circuit Quantum Electrodynamics

Participants: Zaki Leghtas

Experimental quantum information processing with superconducting circuits is rapidly advancing, driven by innovation in two classes of devices, one involving planar microfabricated (2D) resonators, and the other involving machined three-dimensional (3D) cavities. In a collaboration with the team of Michel Devoret at Yale University, we demonstrate that circuit quantum electrodynamics can be implemented in a multilayer superconducting structure that combines 2D and 3D advantages. We employ standard microfabrication techniques to pattern each layer, and rely on a vacuum gap between the layers to store the electromagnetic energy. Planar qubits are lithographically defined as an aperture in a conducting boundary of the resonators. We demonstrate the aperture concept by implementing an integrated, two-cavity-mode, one-transmon-qubit system.

This work was published in [19].

6.12. Theory of remote entanglement via quantum-limited phase-preserving amplification

Participants: Zaki Leghtas

In a collaboration with the teams of Steven Girvin and Michel Devoret at Yale University, we show that a quantum-limited phase-preserving amplifier can act as a which-path information eraser when followed by heterodyne detection. This “beam splitter with gain” implements a continuous joint measurement on the signal sources. As an application, we propose heralded concurrent remote entanglement generation between two qubits coupled dispersively to separate cavities. Dissimilar qubit-cavity pairs can be made indistinguishable by simple engineering of the cavity driving fields providing further experimental flexibility and the prospect for scalability. Additionally, we find an analytic solution for the stochastic master equation, a quantum filter, yielding a thorough physical understanding of the nonlinear measurement process leading to an entangled state of the qubits. We determine the concurrence of the entangled states and analyze its dependence on losses and measurement inefficiencies.

This work was published in [26].

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Emergences-Ville de Paris program, QuMotel project

This project, entitled “Quantum memory for microwaves: towards quantum error correction and quantum state teleportation” and led by François Mallet, started on september 2013 and ran till september 2016. It was composed of the members of the QUANTIC project-team. In this project we worked on the development of a decoherence free quantum memory with the tools of circuit quantum electrodynamics. This crucial device is still missing in any implementations of quantum information processing. It aims at capturing, in an efficient manner, the quantum information encoded by flying photons, protect this information over long times, and release it on demand towards a desired channel. The realization of this memory is based on a high quality factor cavity connected to a superconducting circuit performing three-wave mixing. We will entangle the memory state with a propagating microwave signal, then use it to perform quantum teleportation from one memory to another, generate Schrödinger cat states in the memory and realize quantum error correction protocols in order to stabilize a cat state in the memory for an arbitrary time.

7.2. National Initiatives

7.2.1. ANR project GEARED

This three-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 and Benjamin Huard (QUANTIC project-team), 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 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: University of Padova

Alain Sarlette has been pursued a fruitful collaboration with the group of Francesco Ticozzi on “dynamical systems aspects of quantum systems”. A novel line of work in the direction of quantum thermalization and quantum random walks has been explored, in the framework of the PhD of S. Apers (Ghent University) supervised by A. Sarlette. Further joint work for the future is planned about among others generalized Markovian feedback and, reservoir engineering, and linear Lyapunov functions for quantum systems. F. Ticozzi has visited us for one week.

Partner 2: Ghent University.

A. Sarlette is collaborating with applied mathematicians interested in quantum control at UGent (Dirk Aeyels, Lode Wylleman, Gert De Cooman) in the framework of thesis co-supervisions. One PhD student is co-supervised with Dirk Aeyels in the framework of Belgian Inter-University Attraction Poles “Dynamical Systems, Control and Optimization” network 2013-2017. A second PhD student is also co-supervised with Dirk Aeyels in the framework of Chinese Scholarship Council and Flanders Research Fund grant “Developing control mechanisms to counter biases and drifts in coordination”, 2013-2016. Finally, benefiting from a UGent starting grant on “Coordination control algorithms inspired from nonlinear PDEs and lattices”, 2013-2017, Alain Sarlette also supervises a third PhD student at Ghent University.

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 we had many exchanges between Inria and Yale in 2016. Shantanu Mundhada from Yale visited Inria for 2 months. Nicolas Didier and Lucas Verney visited Yale for 3 months, and Joachim Cohen for 3 weeks.

Pierre Rouchon is a participant to the Inria associate Team CDSS with principal Inria investigator, François Dufour of the Inria Team Project CQFD on the topic "Control of dynamic systems subject to stochastic jumps".

7.4.2. Inria International Partners

7.4.2.1. Informal International Partners

Partner 1: University of Yale

The long-term collaborations with the teams of Michel H. Devoret, Robert J. Schoelkopf, Liang Jiang and Steven M. Girvin, enforced through a two year sabbatical visit of Mazyar Mirrahimi at Yale university, have led to a set of contributions ranging from the theoretical analysis and performance optimization of ongoing experiments on weak quantum measurements [71] and preparation of non-classical field states through single photon Kerr effect [75] to the design of new experiments on single qubit cooling [67] and stabilization of maximally entangled states of superconducting qubits [9] by reservoir engineering techniques. Through these collaborations, Zaki Leghtas and Mazyar Mirrahimi have introduced a new direction for hardware-efficient universal quantum computation [81], [90]. These theoretical proposals have already led to groundbreaking experiments [5], [6], [10]. This collaboration is partially formalized through the Taquilla associate team.

Partner 2: University of SaoPaulo and Federal University of Santa Catarina

Pierre Rouchon is collaborating with P. S. Pereira da Silva (Escola Politecnica, PTC, University of SaoPaulo, Brazil) and H. B. Silveira Federal (University of Santa Catarina (UFSC), Florianopolis, Brazil) on the system theory problems behind the experiment on the feedback stabilization of the photon box.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

Francesca Chittaro from Université de Toulon made a 6-month sabbatical visit (February-July 2016) working on adiabatic elimination for composite quantum systems. Preliminary results have been submitted to the IFAC World Congress 2017 [32].

P. S. Pereira da Silva (Escola Politécnica, PTC, University of SaoPaulo, Brazil) made a 3-week visit (June 27 to July 15) to investigate with Mazyar Mirrahimi and Pierre Rouchon controllability issues on composite quantum systems.

7.5.1.1. Internships

In the framework of the Inria-MITACS program, Pantita Palittapongarnpim, student in the group of Barry Sanders at University of Calgary, visited QUANTIC for a period of 4 months working on optimal control methods for photon-number parity measurements.

In the framework of TAQUILLA associate team, Shantanu Mundhada, student in the group of Michel Devoret at Yale University, visited QUANTIC for a period of 2 months working on circuit designs for high-order non-linear quantum dissipation.

Partner: University of Calgary

In the framework of the Inria-MITACS program, Pantita Palittapongarnpim, student in the group of Barry Sanders visited QUANTIC for a period of 4 months working on optimal control methods for photon-number parity measurements.

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 Nicolas Didier and Lucas Verney spent three months and Joachim Cohen three weeks in the same group.

Pierre Rouchon was invited to give a one-week visit and several lectures on modelling and control of open-quantum systems at Zhejiang University (Hangzhou, China), College of control and Engineering (28 May – 7 June 2016).

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Journal

8.1.1.1. Member of the Editorial Boards

Mazyar Mirrahimi is an associate editor of System and Control Letters.

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

8.1.1.2. Reviewer - Reviewing Activities

Benjamin Huard served as a referee for Nature, Science, Physical Review Letters and other physics journals.

Zaki Leghtas served as a referee for Physical Review Letters and Physical Review X.

Mazyar Mirrahimi served as a referee for Nature and 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

Benjamin Huard, Aug 2016 Formulating and Finding Higher-Order Interference Workshop, Perimeter Institute, Canada.

Benjamin Huard, Jun 2016 4th International Workshop on Frontiers in Quantum Optics and Quantum Information, Beijing Computational Research Center, Beijing, China.

Benjamin Huard, May 2016 Physics department seminar, Chalmers University, Sweden.

Benjamin Huard, May 2016 Statistical Mechanics of Quantum Dynamics, Mariehamn, Finland.

Benjamin Huard, May 2016 Workshop Non-equilibrium thermodynamic phenomena and problems of mesoscopic physics, Aalto University, Finland.

Benjamin Huard, Mar 2016 Mini-Colloque “Rencontre du Non Linéaire” 2016, Paris, France.

Benjamin Huard, Jan 2016 Conference SCALEQIT 2016, Delft, Netherlands.

Zaki Leghtas, Oct 2016, Karlsruhe Institute of Technology, Germany.

Mazyar Mirrahimi, Dec 2016, Yale University, USA.

Mazyar Mirrahimi, Dec 2016, Tutorial at Conference GDR Physique Mesoscopique, Aussois, France.

Mazyar Mirrahimi, Nov 2016, UC Berkeley, USA.

Mazyar Mirrahimi, Oct 2016, University of Pennsylvania, USA.

Mazyar Mirrahimi, June 2016, Journées Scientifiques Inria, Inria Rennes, France.

Mazyar Mirrahimi, July 2016, Tutorial in summer school "Stochastic Methods in Quantum Mechanics", Autrans, France.

Mazyar Mirrahimi, April 2016, "Quantum and Nano Control" workshop, Institute of Mathematics and its Applications of Minneapolis, USA.

Mazyar Mirrahimi, Feb 2016, Institut Néel, Grenoble, France.

Mazyar Mirrahimi, Jan 2016, Conference SCALEQIT 2016, Delft, Netherlands.

Pierre Rouchon, Dec 2016, IEEE Conference on Decision and Control, Las Vegas, USA.

Pierre Rouchon, April 2016, "Quantum and Nano Control" workshop, Institute of Mathematics and its Applications of Minneapolis, USA.

Pierre Rouchon, June 2016, Conference "Nonlinear Partial Differential Equations and Applications" in the honor of Jean-Michel Coron for his 60th birthday, IHP, Paris.

Alain Sarlette, May 2016, workshop on quantum dynamics and control, IHP, Paris.

Alain Sarlette, July 2016, summer school "Stochastic Methods in Quantum Mechanics", Autrans, France.

8.1.3. Scientific Expertise

Benjamin Huard was a member of the ANR CES30 committee in 2016.

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

Pierre Rouchon was "president du comité d’experts" for the HCERES evaluation in January 2016 of the "Laboratoire des Sciences du numériques de Nantes (LS2N)" .

Pierre Rouchon acts as panel member for the panel PE1-Mathematics in the ERC Advanced Grant 2016 evaluation.

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

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Benjamin Huard has given a course (20 hours) entitled "Quantum fluctuations and measurement" in the Master ICFP (International Centre for Fundamental Physics) of ENS Paris, UPMC, Paris 7 and Orsay.

Benjamin Huard has coordinated an experimental project (40 hours) entitled "Measuring the quantum of conductance across an atom" at ENS Paris for Physics students in L3.

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 has given a graduate-level course (15 hours) entitled "Quantum Control" at Yale University.

Mazyar Mirrahimi has given a 4-hour tutorial on "Quantum measurement and feedback" at the summer school "Stochastic Methods in Quantum Mechanics", Autrans, France.

Pierre Rouchon and Alain Sarlette gave a one week half-time course (15hours) on feedback control of quantum systems at the Elgersburg schools for Mathematical System Theory, 29/2/2016 - 4/3/2016, Germany.

Alain Sarlette has given a master course on "Probabilistic robotics" at Ghent University (30 hours).

8.2.2. Supervision

PhD in progress: Danijela Markovic, ENS. “Quantum information protocols with microwave quantum optics”. Sept 2014. (advisors: Benjamin Huard and François Mallet).

PhD in progress: Nathanaël Cottet. ENS. “Quantum heat engines based on superconducting circuits”. Sept 2015. (advisor: Benjamin Huard).

PhD in progress: Quentin Ficheux. ENS. “Thermodynamics of quantum information”. Sept 2015. (advisors: Benjamin Huard and Zaki Leghtas).

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 in progress: Rémi Azouit. Mines Paristech. “Quantum circuits, Input/Output theory and adiabatic elimination”. Sept 2014. (advisor: Pierre Rouchon).

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”. Nov 2013 (advisor: Mazyar Mirrahimi), His defense is programmed for Feb 2017.

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

PhD: Noad Hamze El Badaoui. He has defended his PhD thesis on December 2, 2016. His thesis entitled "Dynamique et estimation paramétrique pour les gyroscopes laser à milieu amplificateur gazeux" was under the supervision of Philippe Martin and Pierre Rouchon.

PhD: Pierre Six. He has defended his PhD thesis on November 22, 2016. His thesis entitled "Estimation d’état et de paramètres pour les systèmes quantiques ouverts" was under the supervision of Pierre Rouchon.

8.2.3. Juries

Benjamin Huard was a member of the PhD defense committees of Katrina Sliwa (Yale University, USA), Antoine Tilloy (ENS Paris, France), Philip Krantz (Chalmers, Sweden), Kristinn Juliusson (CEA Saclay, France), Yehan Liu (Yale University, USA), Pierre Six (Mines ParisTech, France) and of the HdR committee of Caglar Girit (Collège de France, France).

Mazyar Mirrahimi was a member the PhD defense committees of Zhan Shi (Reviewer, University of New South Wales, Australia), Shakib Daryanoush (Reviewer, University of Griffith, Australia), Ying Fu (Reviewer, Université Paris Dauphine), Kristinn Juliusson (CEA Saclay, France).

Alain Sarlette was a member of the PhD defense committee of Bram Vervisch (Ghent University, Belgium).

8.3. Popularization

Mazyar Mirrahimi gave interviews for radios, newspapers, magazines and websites (France Culture, Le Monde, La Recherche, Silicon, Industrie and Technologies).

Pierre Rouchon was invited by the "Département de Mathématiques Appliquées de l'Ecole Polytechnique" to give a talk entilted "Dynamique et contrôle des systèmes: du classique au quantique' for the students of Ecole Polytechnique (April 21, 2016).

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.

9. Bibliography

Major publications by the team in recent years

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