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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

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- A6. - Modeling, simulation and control
 - A6.1. - Methods in mathematical modeling
 - A6.1.1. - Continuous Modeling (PDE, ODE)
 - A6.1.2. - Stochastic Modeling
 - A6.1.3. - Discrete Modeling (multi-agent, people centered)
 - A6.1.4. - Multiscale modeling
 - A6.2. - Scientific computing, Numerical Analysis & Optimization
 - A6.2.1. - Numerical analysis of PDE and ODE
 - A6.2.3. - Probabilistic methods
 - A6.2.6. - Optimization
 - A6.3.1. - Inverse problems
 - A6.3.2. - Data assimilation
 - A6.3.3. - Data processing
 - A6.3.4. - Model reduction
- A6.4. - Automatic control
 - A6.4.1. - Deterministic control
 - A6.4.2. - Stochastic control
 - A6.4.3. - Observability and Controlability
 - A6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

- B5.3. - Nanotechnology
- B5.4. - Microelectronics
- B6.5. - Information systems
- B9.10. - Privacy

1. Team, Visitors, External Collaborators

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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 [85], [88]. By redundantly encoding quantum information in this Hilbert space of larger dimension one makes 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 requires 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 [62]. 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 [59], [53] 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 [61]. Through a recent experimental work [93], 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 [89] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [5]. 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.

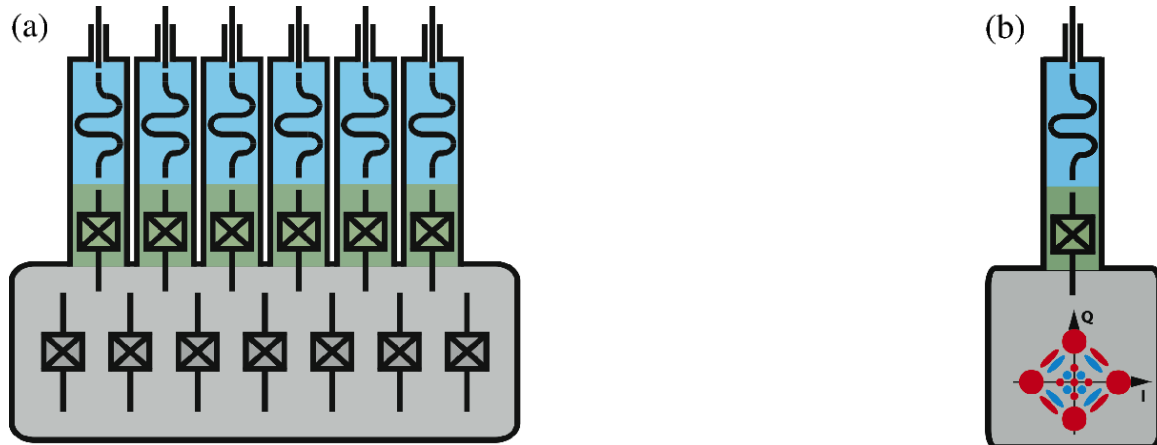


Figure 1. (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [88] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high- Q resonator and the measurement of the 6 error 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.

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 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-demolition* (QND) measurement has played a crucial role in understanding and resolving this difficulty [36]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [55], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [54]. 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 [45], [27], [87], [29]. 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) [44], recent advances in quantum-limited amplifiers [79], [91] have opened doors to high-fidelity non-demolition measurements and real-time feedback

for superconducting qubits [56]. 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 [91], [78], [38]. 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 [69].

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 [76] and the closely related coherent feedback [67] 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 [52], single-qubit state stabilization [71], and the creation [31] and stabilization [60], [66][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 [52], [64], [42][12]. The experimental results based on these protocols have illustrated the efficiency of the approach [52][9]. Through these experiments, we exploit the strong dispersive interaction [83] between superconducting qubits and a single low-Q cavity mode playing the role of a dissipative reservoir. Applying continuous-wave (cw) microwave drives with well-chosen fixed frequencies, amplitudes, and phases, we engineer an effective interaction Hamiltonian which evacuates the entropy of the system interacting with a noisy environment: 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 [70], [81], [57][4].

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 [80], [27], [86], [82], [87], [29][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 [29]: 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 [94]; 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 [74]. 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 [56], [38].

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 [32] and is related to quantum trajectories [40], [43]. A modern and mathematical exposure of the diffusive models is given in [30]. In [95] 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 [80], [86]. This stability result is extended to a large class of continuous-time filters in [28]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [33]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [47], [72].

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 [37] that post-selection statistics and “past quantum” state analysis [48] 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 [76], [67]. 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] [52], 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 [75]). 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., [26][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] [52], [70] 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 [51], [50]. We will start with [84] and [77] where, based on a theorem due to Birkhoff [34], 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 [90] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [68].

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 [73], 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 [92], [65] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [35], 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 [55], [49]. 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 [63].

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 [39] for the adiabatic elimination of low-Q cavity). Conversely 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 [46] and invariant manifold techniques [41] 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 [58] 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 [52][9][64].

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 partial¹ 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.

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

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 the main organizer of the spring thematic quarter at Institut Henri Poincaré entitled "Measurement and control of quantum systems: theory and experiments" (16 April – 13 July 2018). This thematic quarter included courses, lectures and conferences. In particular, a research school of one week at CIRM, two 3-day workshops in May and June and the 2018 issue of PRACQSYS conference in July were organized throughout the quarter. This thematic quarter involved several hundred of participants. See IHP web page (<http://www.ihp.fr/en/CEB/T2-2018>), CIRM web page (<https://conferences.cirm-math.fr/1732.html>) and the specific quarter web site (<https://sites.google.com/view/mcqs2018/home>).
- QUANTIC has received a sub-award from Yale university for pursuing the collaborations of Mazyar Mirrahimi and his students/postdocs. In the framework of a new ARO (Army Research Office) grant received by our collaborators at Yale, QUANTIC receives 500k dollars over 4 years to fund the hiring of PhD students/ postdocs working on the collaborative subjects with Yale and also to cover the travels between Inria and Yale.
- Alain Sarlette has received a JCJC ANR grant entitled HAMROQS "High-accuracy model reduction for open quantum systems". This grant of 212k euros over 4 years will fund the activities of Alain Sarlette and his students/postdocs on systematic methods for quantum systems model reduction.
- PhD students of Alain Sarlette, Arash Farnam and Simon Apers, defended their PhD at his previous institution (Ghent university, Belgium).
- Mazyar Mirrahimi was an invited speaker at the American Physical Society March Meeting in Los Angeles.
- Mazyar Mirrahimi was a semi-plenary speaker at MTNS in Hong Kong (Mathematical Theory of Networks and Systems).

6. New Results

6.1. Simulation of quantum walks and fast mixing with classical processes

Participants: A. Sarlette

This is the final result of a line of work where we show that the mixing behavior of quantum walks on graphs can always be simulated by a classical "lifted Markov chain". This implies that quantum walks must satisfy a conductance bound on mixing speed, like classical Markov chains. Also current efficient quantum walk constructions are linked to classical processes that provide the same convergence speed. This excludes a simple characterization of quantum walk advantages in terms of bare mixing speed, as has been done by some previous authors comparing just to simple Markov chains. The question of efficient design of walks on graphs, on the basis of local graph queries and for specific applications, is thus brought back to the center of the focus for quantum walks. This collaborative work with F. Ticozzi (U. of Padova) has been published in [11].

As a follow-up on this work, we have developed algorithms in the latter sense: quantum walks on the basis of local design and which do speed up some applications. These last results have been presented as posters at conferences and will hopefully be part of next year's publications.

6.2. Adiabatic elimination for multi-partite open quantum systems with non-trivial zero-order dynamics

Participants: Paolo Forni, Alain Sarlette, Pierre Rouchon

We pursue the work initiated in our group during the thesis of Rémi Azouit, where we apply center manifold theory in order to reduce the model of a quantum system to its slowly contracting dynamics. Such model reduction is ubiquitous in models of coupled quantum systems where part of the system relaxes quickly towards an equilibrium situation, and acts as an environment for a system of interest. The extension presented in this work is the answer to a question by experimental physicists at Laboratoire Kastler Brossel (LKB), where they apply a strong drive which, in an 'intuitive model', would saturate so-called two-level-system impurities and thereby imply a particular behavior of frequency shift and dissipation on the target system (slow dynamics) as a function of drive characteristics. A good model for this situation involves, beyond a strongly dissipative environment, also a fast non-dissipative dynamics on the slowly contracting subsystem. Adding the latter into the model reduction was the purpose of this result. We analyze the experimental results and show that the model reduction allows us to explain the observed trends. This result led to a publication in collaboration with physicists Thibault Capelle, Emmanuel Flurin and Samule Deleglise from LKB [20].

Further extensions of adiabatic elimination formulas have been worked out during this year and will hopefully be part of next year's publications.

6.3. Exponential stochastic stabilization of a two-level quantum system via strict Lyapunov control

Participants: Gerardo Cardona, Alain Sarlette, Pierre Rouchon

In this result, we address the fundamental task of stabilizing the state of a quantum system towards a target eigenstate of a continuous-time quantum nondemolition measurement. The starting point is that a static output feedback does not allow us to stabilize this system, while more complicated procedures were not able to provide a convergence rate. Our main idea is to introduce a dynamic feedback controller of moderate complexity, where (i) feedback gains depend on estimated state and progressively go to zero as one approaches the target; and (ii) the feedback involves noise (in this paper from the measurement back-action but in further extensions possibly just independent noise). With this controller we show, providing a Lyapunov function close to the Bures distance measure, that the system converges exponentially towards the target eigenstate. This result, restricted to a proof-of-principle on the qubit, was published in [19].

This has laid the basis for further work, presented on posters and to be published next year, where we have shown that:

- the optimal convergence rate, equal to information gain, can be achieved with this feedback;
- the procedure extends to N-level systems, with noise just independent instead of coming from the measurement backaction;
- the procedure can be exploited towards continuous-time measurement-based quantum error correction

6.4. Structural instability of driven Josephson circuits prevented by an inductive shunt

Participants: Lucas Verney, Raphaël Lescanne, Zaki Leghtas, Mazyar Mirrahimi.

Superconducting circuits are a versatile platform to implement a multitude of Hamiltonians which perform quantum computation, simulation and sensing tasks. A key ingredient for realizing a desired Hamiltonian is the irradiation of the circuit by a strong drive. These strong drives provide an insitu control of couplings, which cannot be obtained by near-equilibrium Hamiltonians. However, as shown in our result, out-of-equilibrium systems are easily plagued by complex dynamics leading to instabilities. Predicting and preventing these instabilities is crucial, both from a fundamental and application perspective. We propose an inductively shunted transmon as the elementary circuit optimized for strong parametric drives. Developing a novel numerical approach that avoids the built-in limitations of perturbative analysis, we demonstrate that adding the inductive shunt significantly extends the range of pump powers over which the circuit behaves in a stable manner. This collaborative work between the Quantic team and Michel Devoret at Yale has been recently submitted for publication [25].

6.5. Observing the escape of a driven quantum Josephson circuit into unconfined states

Participants: Raphaël Lescanne, Lucas Verney, Mazyar Mirrahimi, Zaki Leghtas.

Josephson circuits have been ideal systems to study complex non-linear dynamics which can lead to chaotic behavior and instabilities. More recently, Josephson circuits in the quantum regime, particularly in the presence of microwave drives, have demonstrated their ability to emulate a variety of Hamiltonians that are useful for the processing of quantum information. In this experimental work, we show that these drives lead to an instability which results in the escape of the circuit mode into states that are not confined by the Josephson cosine potential. We observe this escape in a ubiquitous circuit: a transmon embedded in a 3D cavity. When the transmon occupies these free-particle-like states, the circuit behaves as though the junction had been removed, and all non-linearities are lost. This work deepens our understanding of strongly driven Josephson circuits, which is important for fundamental and application perspectives, such as the engineering of Hamiltonians by parametric pumping. This collaborative work between Quantic team, Benjamin Huard's team at ENS Lyon and Michel Devoret at Yale, has been recently submitted for publication [21].

6.6. Dynamics of a qubit while simultaneously monitoring its relaxation and dephasing

Participants: Zaki Leghtas.

Decoherence originates from the leakage of quantum information into external degrees of freedom. For a qubit, the two main decoherence channels are relaxation and dephasing. Here, we report an experiment on a superconducting qubit where we retrieve part of the lost information in both of these channels. We demonstrate that raw averaging of the corresponding measurement records provides a full quantum tomography of the qubit state where all three components of the effective spin-1/2 are simultaneously measured. From single realizations of the experiment, it is possible to infer the quantum trajectories followed by the qubit state conditioned on relaxation and/or dephasing channels. The incompatibility between these quantum measurements of the qubit leads to observable consequences in the statistics of quantum states. The high level of controllability of superconducting circuits enables us to explore many regimes from the Zeno effect to underdamped Rabi oscillations depending on the relative strengths of driving, dephasing, and relaxation. This work is a collaboration between the Quantic team and the group of Benjamin Huard at ENS Lyon and was published in [13].

6.7. Demonstration of an effective ultrastrong coupling between two oscillators

Participants: Zaki Leghtas

When the coupling rate between two quantum systems becomes as large as their characteristic frequencies, it induces dramatic effects on their dynamics and even on the nature of their ground state. The case of a qubit coupled to a harmonic oscillator in this ultrastrong coupling regime has been investigated theoretically and experimentally. Here, we explore the case of two harmonic oscillators in the ultrastrong coupling regime. Probing the properties of their ground state remains out of reach in natural implementations. Therefore, we have realized an analog quantum simulation of this coupled system by dual frequency pumping a nonlinear superconducting circuit. The pump amplitudes directly tune the effective coupling rate. We observe spectroscopic signature of a mode hybridization that is characteristic of the ultrastrong coupling. We experimentally demonstrate a key property of the ground state of this simulated ultrastrong coupling between modes by observing simultaneous single- and two-mode squeezing of the radiated field below vacuum fluctuations. This work is a collaboration between the Quantic team and the group of Benjamin Huard at ENS Lyon and was published in [14].

6.8. Fault-tolerant detection of a quantum error

Participants: Mazyar Mirrahimi

A critical component of any quantum error-correcting scheme is detection of errors by using an ancilla system. However, errors occurring in the ancilla can propagate onto the logical qubit, irreversibly corrupting the encoded information. We experimentally demonstrate a fault-tolerant error-detection scheme that suppresses spreading of ancilla errors by a factor of 5, while maintaining the assignment fidelity. The same method is used to prevent propagation of ancilla excitations, increasing the logical qubit dephasing time by an order of magnitude. Our approach is hardware-efficient, as it uses a single multilevel transmon ancilla and a cavity-encoded logical qubit, whose interaction is engineered in situ by using an off-resonant sideband drive. The results demonstrate that hardware-efficient approaches that exploit system-specific error models can yield advances toward fault-tolerant quantum computation. This work is a collaboration between the Quantic team and the group of Robert Schoelkopf at Yale university and was published in [17].

6.9. Coherent oscillations inside a quantum manifold stabilized by dissipation

Participants: Zaki Leghtas, Mazyar Mirrahimi

Manipulating the state of a logical quantum bit usually comes at the expense of exposing it to decoherence. Fault-tolerant quantum computing tackles this problem by manipulating quantum information within a stable manifold of a larger Hilbert space, whose symmetries restrict the number of independent errors. The remaining errors do not affect the quantum computation and are correctable after the fact. Here we implement the autonomous stabilization of an encoding manifold spanned by Schrödinger cat states in a superconducting cavity. We show Zeno-driven coherent oscillations between these states analogous to the Rabi rotation of a qubit protected against phase flips. Such gates are compatible with quantum error correction and hence are crucial for fault-tolerant logical qubits. This experimental work follows our previous theoretical proposal [70]. It is a collaboration between the Quantic team and the group of Michel Devoret at Yale university and was published in [18].

6.10. To catch and reverse a quantum jump mid-flight

Participants: Mazyar Mirrahimi

A quantum system driven by a weak deterministic force while under strong continuous energy measurement exhibits quantum jumps between its energy levels. This celebrated phenomenon is emblematic of the special nature of randomness in quantum physics. The times at which the jumps occur are reputed to be fundamentally unpredictable. However, certain classical phenomena, like tsunamis, while unpredictable in the long term, may possess a degree of predictability in the short term, and in some cases it may be possible to prevent a disaster by detecting an advance warning signal. Can there be, despite the indeterminism of quantum physics, a possibility to know if a quantum jump is about to occur or not? We answer this question affirmatively by experimentally demonstrating that the completed jump from the ground to an excited state of a superconducting artificial atom

can be tracked, as it follows its predictable "flight," by monitoring the population of an auxiliary level coupled to the ground state. Furthermore, we show that the completed jump is continuous, deterministic, and coherent. Exploiting this coherence, we catch and reverse a quantum jump mid-flight, thus preventing its completion. This real-time intervention is based on a particular lull period in the population of the auxiliary level, which serves as our advance warning signal. Our experimental results, which agree with theoretical predictions essentially without adjustable parameters, support the modern quantum trajectory theory and provide new ground for the exploration of real-time intervention techniques in the control of quantum systems, such as early detection of error syndromes. This work is a collaboration between the Quantic team and the group of Michel Devoret at Yale university and is recently submitted for publication [22].

6.11. Remote entanglement stabilization and concentration by quantum reservoir engineering

Participants: Nicolas Didier, Jérémie Guillaud, Mazyar Mirrahimi

Quantum information processing in a modular architecture requires the distribution, stabilization, and distillation of entanglement in a qubit network. We present autonomous entanglement stabilization protocols between two superconducting qubits that are coupled to distant cavities. The coupling between cavities is mediated and controlled via a three-wave mixing device that generates either a two-mode squeezed state or a delocalized mode between the remote cavities depending on the pump applied to the mixer. Local drives on the qubits and the cavities steer and maintain the system to the desired qubit Bell state. Most spectacularly, even a weakly squeezed state can stabilize a maximally entangled Bell state of two distant qubits through an autonomous entanglement concentration process. Moreover, we show that such reservoir-engineering-based protocols can stabilize entanglement in the presence of qubit-cavity asymmetries and losses. This work was published in [12].

7. Partnerships and Cooperations

7.1. Regional Initiatives

- **Paris EMERGENCE project ENDURANCE:** In the framework of the Paris Ile de France program "EMERGENCE", Zaki Leghtas has received a funding for his research program "Multi-photon processes in superconducting circuits for quantum error correction". This grant of 230k euros has allowed us to purchase the experimental equipment to complement the experiment based at ENS.
- **DIM SIRTEQ project Sputthy:** Zaki Leghtas has received 50k euros from the DIM SIRTEQ to purchase a sputtering system. With this machine, we will fabricate high quality resonators made out of Niobium and high kinetic inductance material such as NbTiN.
- **DIM SIRTEQ PhD fellowship:** We have received funding from DIM SIRTEQ to cover half of the PhD of Jérémie Guillaud under supervision of Mazyar Mirrahimi.
- **FSMP postdoctoral fellowship:** Paolo Forni has been selected for a postdoctoral fellowship by the Fondation des Sciences Mathématiques de Paris (FSMP) for the academic year 2018-2019: this 12-month postdoc fellowship extends a previous one supported by the programme Math-PSL of PSL Research University.

7.2. National Initiatives

- **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 and ended on September 2018. The participants of the project were Mazyar Mirrahimi (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). QUANTIC received a funding of 114k in this framework.

- **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. The project started in March 2016 for 42 months.
- **ANR project HAMROQS:** In the framework of the ANR program JCJC, Alain Sarlette has received a funding for his research program "High-accuracy model reduction for open quantum systems". This grant of 212k euros will start on april 2019 and will run for 4 years.

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. The ANR-JCJC project HAMROQS by Alain Sarlette has Benjamin Huard as external supporting collaborator.

Partner 2: Laboratoire Kastler Brossel

We have been collaborating with Samuel Deleglise and Emmanuel Flurin from Laboratoire Kastler Brossel to understand and analyze their experimental data. In this aim, we have developed new adiabatic elimination techniques for multi-partite open quantum systems with non-trivial zero-order dynamics.

Partner 3: University of Padova

Alain Sarlette has been pursuing 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.

Partner 4: Ghent University.

Alain Sarlette has been collaborating with applied mathematicians interested in quantum control at UGent (Dirk Aeyels, Lode Wylleman, Gert De Cooman) in the framework of thesis co-supervisions. Two PhD students have successfully defended their thesis this year (Arash Farnam, on distributed control of lattices; Simon Apers, on quantum walks). He is further coaching a Master thesis intern working on nonlinear deterministic structures in quantum SDEs.

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 continued our collaborations between Inria and Yale in 2018. Jérémie Guillaud visited Yale for 3 months (Sept-Nov), and Mazyar Mirrahimi for 4 months (Sept-Dec). Clarke Smith and Steven Touzard, PhD students at Yale, visited us for 1 week at the occasion of PRACQSYS meeting. Clarke Smith joins Quantic team as a postdoc in January 2019.

7.4.2. Participation in Other International Programs

In the framework of the collaborations with Yale university, Quantic team has received a sub-award of 500k dollars over 4 years starting in 2018 from Yale university. This sub-award is part of an ARO (Army Research Office) grant received by our collaborators at Yale and covers the expenses related to our collaborations (hiring of new PhD students and postdocs at Inria and travels between Inria and Yale).

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- In the framework of Inria's invited professor program, Tryphon Georgiou (University of California at Irvine) visited us for about 2 months. This visit had for subject to initiate collaborations on the subject of open quantum systems and quantum channels.
- Yves Bérubé-Lauzière (University of Sherbrooke, Institut Quantique) accompanied by two PhD students made a 6-month visit from March to August 2018 to investigate with Pierre Rouchon feedback protocols for stabilizing quantum states in a high-quality cavity.
- P.S. Pereira da Silva (Escola Politécnica, PTC, University of Sao Paulo, Brazil) made a 2-week visit (June 25 to July 6) 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 our collaborations with the group of Michel Devoret at Yale university, Jérémie Guillaud and Mazyar Mirrahimi visited Yale for 3 months and 4 months, respectively, in fall 2018.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

Pierre Rouchon was the main organizer of the spring thematic quarter at Institut Henri Poincaré entitled "Measurement and control of quantum systems: theory and experiments" (16 April – 13 July 2018). This thematic quarter includes courses, lectures and conferences. In particular a research school of one week at CIRM, two 3-day workshops in May and June and the 2018 issue of PRACQSYS conference in July, were organized in this framework. This thematic quarter involved several hundred of participants. See IHP web page (<http://www.ihp.fr/en/CEB/T2-2018>), CIRM web page (<https://conferences.cirm-math.fr/1732.html>) and the specific quarter web site (<https://sites.google.com/view/mcqs2018/home>).

8.1.1.2. Member of the Organizing Committees

- Zaki Leghtas co-organized a conference on quantum computing ICOQC 2018 at ENS Paris (<https://icoqc.sciencesconf.org>).
- Mazyar Mirrahimi was a co-organizer of the PRACQSYS conference at IHP in July 2018 (<https://sites.google.com/view/mcqs2018/pracqsys-2018>).

8.1.2. Journal

8.1.2.1. Member of the Editorial Boards

Pierre Rouchon is member of the editorial board of Annual Reviews in Control.

8.1.2.2. Reviewer - Reviewing Activities

- Zaki Leghtas and Mazyar Mirrahimi were reviewer of Physical Review Journals.
- Pierre Rouchon and Alain Sarlette were reviewer for several automatic control and dynamical systems journals and conferences.

8.1.3. Invited Talks

- Zaki Leghtas: Sirteq 2018. Institut d'optique Paris. Invited by Patrice Bertet.
- Zaki Leghtas: ONE-QOS workshop. Max Planck, Erlangen, Germany. Invited by Florian Marquardt.
- Zaki Leghtas: IHP workshop on quantum control and feedback, Paris, France. Invited by Eleni Diamanti.
- Zaki Leghtas: LIA CNRS-Université de Sherbrooke workshop, Saint-Rémy, France. Invited by Denis Vion.
- Zaki Leghtas: University of Berkeley. Berkeley, USA. Invited by Irfan Siddiqi.
- Zaki Leghtas: Rigetti Quantum Computing. Berkeley, USA. Invited by Chad Rigetti.
- Pierre Rouchon: lecture at the QUACO ANR Meeting in Besançon, September 24-26, Models and feedback issues for open quantum systems.
- Pierre Rouchon: plenary speaker at Mexican Annual Conference on Automatic Control. 10-12 October 2018, San Luis Potosi, Dynamical models and feedback issues for super-conducting quantum circuits.
- Pierre Rouchon: 2-hour course in the Colloquium of the Physics Department, ENS-Paris, October 23 (introduction to quantum cryptography, computation and error correction).
- Alain Sarlette: dynamical systems seminar series, March 2018, Jussieu.
- Alain Sarlette: seminar at IHP trimester on Quantum Control, May 2018.
- Alain Sarlette: Praqsys: Principles and Applications of Control in Quantum Systems, IHP, Paris, July 2018.
- Mazyar Mirrahimi: American Physical Society March Meeting, Los Angeles, March 2018.
- Mazyar Mirrahimi: Semi-plenary speaker at MTNS (Mathematical Theory of Networks and Systems), Hong Kong, July 2018.
- Mazyar Mirrahimi: Centre de Recherche Mathématique de Montreal, Octobre 2018.
- Mazyar Mirrahimi: 4-hour course at Institut d'Optique, Introduction to Quantum Computing, June 2018.
- Alain Sarlette: lectures on quantum control and quantum computing at the Ecole d'Automatique de Grenoble summer school, August 2018
- Pierre Rouchon, Alain Sarlette, Rémi Azouit, Paolo Forni and Francesca Chittaro have given a lecture series about "adiabatic elimination for open quantum systems" at the IHP trimester on Quantum Control.
- Jérémie Guillaud: Yale university, Nov 2018.

8.1.4. Research Administration

- 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.
- Mazyar Mirrahimi is the co-president of Inria's comité des emplois scientifiques.

- Mazyar Mirrahimi was a member of ANR Comité d’Evaluation Scientifique on Quantum Technologies.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Cycle Ingénieur : Mazyar Mirrahimi, Automatic Control with Applications in Robotics and in Quantum Engineering, 8 hours amphi and 8 hours TD, 3rd year, Ecole Polytechnique, France.

Cycle Ingénieur : Mazyar Mirrahimi, Contrôle de modèles dynamiques, 36 hours TD, 2nd year, Ecole Polytechnique, France.

Cycle Ingénieur : Mazyar Mirrahimi, Module algorithmique Quantum Control, 24 hours TD, 2nd year, Ecole Polytechnique, France.

Master: Mazyar Mirrahimi and Pierre Rouchon, Dynamics and control of quantum systems, 18 hours amphi, M2, Jussieu, France.

Cycle Ingénieur: Alain Sarlette, Probabilities and Stochastic Processes, 24 hours TD, Mines ParisTech, France.

Master: Alain Sarlette, Robotics, 24 hours, Ghent University, Belgium.

Cycle Ingénieur : Zaki Leghtas, Quantum Mechanics and Statistical Physics, Mines ParisTech, 12 hours, France.

Cycle Ingénieur : Zaki Leghtas, Quantum Computing, Mines ParisTech, 20 hours, France.

8.2.2. Supervision

- PhD in progress : Gerardo Cardona, "Beyond static gains in analog quantum feedback control", advisors: Pierre Rouchon and Alain Sarlette, starting date: Nov 2016.
- PhD in progress: Michiel Burgelman, "A systematic study of strongly driven and dissipative quantum systems towards high-accuracy quantum control designs", advisors: Pierre Rouchon and Alain Sarlette, starting date: Nov 2018.
- PhD in progress: Vincent Martin, "Fault-tolerance of quantum systems under continuous-time feedback stabilization", advisors: Mazyar Mirrahimi and Alain Sarlette, starting date Oct 2018.
- PhD in progress: Jérémie Guillaud, "Modular architecture for quantum information processing", advisor: Mazyar Mirrahimi and Pierre Rouchon, starting date Oct 2017.
- PhD in progress: Lucas Verney, "Robust processing of quantum information with superconducting circuits", advisor: Mazyar Mirrahimi and Zaki Leghtas, starting date Oct 2016.
- PhD in progress: Raphaël Lescanne, "Engineering Multi-Photon Dissipation In Superconducting Circuits For Quantum Error Correction", advisors: Zaki Leghtas and Takis Kontos, starting date Sept 2016.
- PhD in progress: Marius Villiers, "Probing the spin entanglement of single Cooper pair", advisors: Zaki Leghtas and Takis Kontos, starting date: September 2018.
- Alain Sarlette has been supervising 2 PhD students with his former institution UGent. Arash Farnam has successfully defended his thesis about distributed systems control in October 2018. Simon Apers has successfully defended his thesis about quantum walks on graphs in November 2018.

8.2.3. Juries

Pierre Rouchon was the president of the jury for the Habilitation thesis of Fransceca Chirraro (université de Toulon) and member of the jury for the Habilitation thesis of Nadir Farhi (université Paris-Est).

8.3. Popularization

Alain Sarlette, 5 December 2018, prospective Ordinateur Quantique at the comité de pilotage du CETIM, Senlis.

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Major publications by the team in recent years

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Publications of the year

Articles in International Peer-Reviewed Journals

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