IN PARTNERSHIP WITH:
CNRS

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Mines ParisTech

Sorbonne Université (UPMC)

Activity Report 2019

Project-Team QUANTIC

QUANTum Information Circuits

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

RESEARCH CENTER
Paris

THEME
Optimization and control of dynamic systems

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Project-Team QUANTIC

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

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1. 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 [88], [92]. 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 [64]. 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 [61], [55] 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 [63]. Through a recent experimental work [97], 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 [93] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [8]. As shown in Figure 1, this leads to a significant hardware economy for realization of a protected logical qubit. Our goal here is to push these ideas towards a reliable and hardware-efficient paradigm for universal quantum computation.

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

Being at the heart of any QEC protocol, the concept of feedback is central for the protection of quantum information, enabling many-qubit quantum computation or long-distance quantum communication. However,

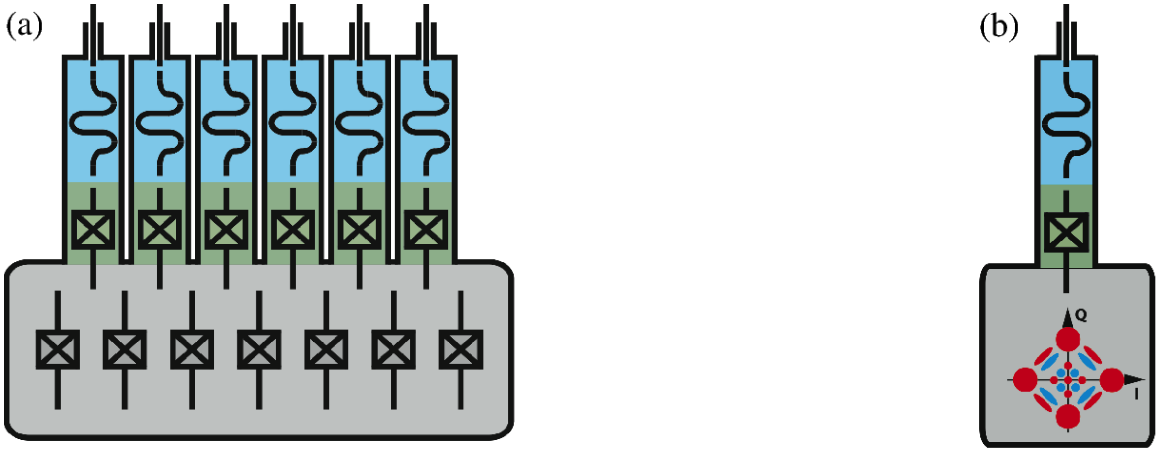

Figure 1. (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [92] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

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 [37]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [57], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [56]. 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 [10] (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 [47], [29], [91] [1]. 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) [45], recent advances in quantum-limited amplifiers [81], [95] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [58]. 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 [95], [80], [39]. 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 [71].

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 [78] and the closely related coherent feedback [69] 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 [54], single-qubit state stabilization [73], and the creation [32] and stabilization [62], [68], [87] 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 [54], [66], [43], [46]. The experimental results based on these protocols have illustrated the efficiency of the approach [54], [87]. Through these experiments, we exploit the strong dispersive interaction [85] 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 [83], [59][7], [6].

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 [82], [29], [90], [84], [91][9], [1] 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 [1]: 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 [98]; 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 [76]. 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 [58], [39].

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 [33] and is related to quantum trajectories [41], [44]. A modern and mathematical exposure of the diffusive models is given in [31]. In [99] 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 [82], [90]. This stability result is extended to a large class of continuous-time filters in [30]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [34]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [49], [74].

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 [38] that post-selection statistics and “past quantum” state analysis [50] 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 [78], [69]. 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 [9] [87], [54], 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 [77]). 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., [28][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 [9], [7] [87], [54] 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 [53], [52]. We will start with [86] and [79] where, based on a theorem due to Birkhoff [35], 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 [94] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [70].

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 [75], 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 [96], [67] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [36], 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 [57], [51]. 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 [65].

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 [40] 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 [48] and invariant manifold techniques [42] 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 [60] 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 [54], [87], [66].

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.

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

5. Highlights of the Year

5.1. Highlights of the Year

- Zaki Leghtas has obtained an ERC starting grant in pannel PE3 entitled ECLIPSE (Exotic superconducting CIrcuits to probe and protect quantum States of light and mattEr).
- Our team (Zaki Leghtas and Mazyar Mirrahimi) has obtained a european QUANTERA grant entitled QuCOS (Quantum Computation with Schrödinger cat states).
- Philippe Campagne-Ibarcq was hired as a CRCN Inria in the QUANTIC team.
- Zaki Leghtas was an invited speaker of American Physical Society March Meeting in Boston, USA.
- Pierre Rouchon was a semi-plenary speaker at the IFAC Mechatronics and NOLCOS conference, September 4-6, Vienna, Austria.
- Successful PhD defense of Gerardo Cardona, under the direction of P. Rouchon and A. Sarlette.
- Successful PhD defense of Lucas Verney, under the direction of M. Mirrahimi and Z. Leghtas.
- Successful PhD defense of Zhifei Zhang, under the direction of A. Sarlette at Ghent University.

6. New Results

6.1. Highly coherent spin states in carbon nanotubes coupled to cavity photons

Participants: Zaki Leghtas

Spins confined in quantum dots are considered as a promising platform for quantum information processing. While many advanced quantum operations have been demonstrated, experimental as well as theoretical efforts are now focusing on the development of scalable spin quantum bit architectures. One particularly promising method relies on the coupling of spin quantum bits to microwave cavity photons. This would enable the coupling of distant spins via the exchange of virtual photons for two qubit gate applications, which still remains to be demonstrated with spin qubits. Here, we use a circuit QED spin-photon interface to drive a single electronic spin in a carbon nanotube based double quantum dot using cavity photons. The microwave spectroscopy allows us to identify an electrically controlled spin transition with a decoherence rate which can be tuned to be as low as 250kHz. We show that this value is consistent with the expected hyperfine coupling in carbon nanotubes. These coherence properties, which can be attributed to the use of pristine carbon nanotubes stapled inside the cavity, should enable coherent spin-spin interaction via cavity photons and compare favourably to the ones recently demonstrated in Si-based circuit QED experiments. This experimental result is a collaboration between Zaki Leghtas (QUANTIC) and the group of Takis Kontos at ENS and was published in [13].

6.2. Escape of a Driven Quantum Josephson Circuit into Unconfined States

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

Josephson circuits have been ideal systems to study complex nonlinear dynamics that 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 work, we show that these drives lead to an instability that 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 nonlinearities 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 experimental work published in [17] demonstrates elements of the theory derived by [22].

6.3. Structural Instability of Driven Josephson Circuits Prevented by an Inductive Shunt

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

Superconducting circuits are a versatile platform to implement a multitude of Hamiltonians that 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 in situ control of couplings, which cannot be obtained by near-equilibrium Hamiltonians. However, as shown in this theoretical study, out-of-equilibrium systems are easily plagued by complex dynamics, leading to instabilities. The prediction and prevention of 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 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 theoretical result was published in [22] and analyzes the experiment [17].

6.4. Fast and virtually exact quantum gate generation in $U(n)$ via Iterative Lyapunov Methods

Participants: Pierre Rouchon

This work presents an iterative algorithm published in [20] and named RIGA for Reference Input Generation Algorithm. This algorithm constructs smooth control pulses for quantum gate preparations of closed quantum systems. It combines right translation invariance and Lyapunov trajectory tracking. It exhibits exponential convergence when the system is controllable. It can be seen as a closed-loop version of the widely used GRAPE algorithm. Two numerical case-studies borrowed from the recent literature are addressed. The first one is relative to a system of 10 coupled qubits with local controls. The second one considers a C-NOT gate generation involving the lower levels of two coupled nonlinear cavities (transmon-qubits).

6.5. Benchmarking maximum-likelihood state estimation with an entangled two-cavity state

Participants: Pierre Rouchon

The efficient quantum state reconstruction algorithm described in the PhD of Pierre Six, a former student of the Quantic team, (see [89]) is experimentally implemented on the non-local state of two microwave cavities entangled by a circular Rydberg atom. In [19], we use information provided by long sequences of measurements performed by resonant and dispersive probe atoms over time scales involving the system decoherence. Moreover, we benefit from the consolidation, in the same reconstruction, of different measurement protocols providing complementary information. Finally, we obtain realistic error bars for the matrix elements of the reconstructed density operator. These results demonstrate the pertinence and precision of the method, directly applicable to any complex quantum system.

6.6. Towards tight impossibility and possibility results for string stability

Participants: Alain Sarlette

This is the last step of the PhD thesis of Arash Farnam under the direction of A. Sarlette at Ghent University. The aim was to study which elements are really essential in so-called “string instability” results, which exist in several variants and with several assumptions. In [15], we have significantly extended the often frequency-based linear approach, by showing how the assumptions lead to string instability also in any nonlinear systems with reasonable bandwidth. This should allow to clarify that how the problem setting must be adapted in order to obtain more positive results. In [14], we show how other elements do not help, and we clarify how the knowledge of individual vehicles’ absolute velocity is key to enable strong versions of string stability, in conjunction with PID control. Previous studies had only considered weaker versions, with PD type control. A more detailed study of string stability with absolute velocity control has also been published in [25].

6.7. Stabilization of quantum systems under continuous non-demolition measurements

Participants: Gerardo Cardona, Alain Sarlette and Pierre Rouchon

The stabilization of quantum states or quantum subspaces using feedback signals from quantum non-demolition measurements is a basic control task; in discrete-time, this is the fundamental control property shown in the first quantum feedback experiment by Serge Haroche. In continuous-time, the problem is harder. So-called Markovian feedback can stabilize some states, but in particular the quantum non-demolition eigenstates which would be marginally stable under measurements, cannot be stabilized asymptotically with this technique. Stochastic control techniques, based on feedback from a full state estimator, have been proposed and analyzed to stabilize such eigenstates, proving convergence but not much more. In [12], we prove how a relatively simple controller, feeding back Wiener noise with a gain that depends on eigenstate populations, allows to exponentially stabilize the target eigenstate. This generalizes our previous results about the qubit. In [24], we provide a similar scheme and convergence proof for stabilizing an invariant subspace of the measurement, namely the codespace of a repetition code for quantum error correction. To the best of our knowledge there was no convergence proof so far for stabilizing such subspaces on the basis of continuous measurements.

6.8. Modified Integral Control Globally Counters Symmetry-Breaking Biases

Participants: Alain Sarlette

This is the end of the PhD thesis of Zhifei Zhang, under joint supervision of A.Sarlette at Ghent University and Zhihao Ling at ECUST Shanghai. The work [23] builds on our earlier proposal of formulating integral control on nonlinear groups as the integral of proportional correcting feedback actions: since these actions belong to a Lie algebra, they can be integrated in this vector space and applied at the current point. We here show how this controller can be modified in order to recover coordinated motion among steering-controlled vehicles, in a situation where biases would make the standard controller fail. We prove how the simple addition of the integral controller allows to recover global convergence towards the coordinated motion, restoring symmetry exactly.

6.9. Quantum Fast-Forwarding: Markov Chains and graph property testing

Participants: Alain Sarlette

This is the end of the PhD thesis of S.Apers, under supervision of A.Sarlette at Ghent University. In [11], we propose a quantum algorithmic routine, called Quantum Fast-Forwarding, which allows to simulate a Markov chain quadratically faster on a quantum computer than on a classical one. The key novelty, from an application point of view, is that we can achieve this acceleration not only for reaching the asymptotic distribution, but also for any intermediate time that one would be interested in. Such transient behaviors of Markov chains are important in algorithmic context, for instance to distinguish clusters in graphs. We explicitly work out those applications on graph properties.

6.10. Quantum Adiabatic Elimination: extension to rotating systems

Participants: Paolo Forni, Timothée Launay, Alain Sarlette and Pierre Rouchon

Adiabatic elimination is a technique to eliminate fast converging variables of a large system, while retaining their impact on slower dynamics of interest. Its most extreme form is a standard procedure when neglecting the dynamics of e.g. actuators or measurement devices in dynamical systems. In quantum systems it is particularly relevant to eliminate subsystems in tensor product structure. However, a major constraint is to obtain a reduced system in quantum form (Lindblad equations), preserving positivity and the unit trace. After having set up the framework for quantum adiabatic elimination to arbitrary order as a series expansion during the thesis of Rémi Azouit, we had worked out first- and second-order Lindblad equations only. With Paolo Forni, we have been pursuing the development of explicit formulas for higher-order cases. In [26], we present an extension of the technique for the case where the slowly decaying subsystem of interest, is subject to fast Hamiltonian dynamics. This appears e.g. in systems with significant detunings, where a description in rotating frame would lead to time-dependent equations if one does not want to neglect fast oscillating terms.

6.11. Minimizing decoherence on target in bipartite open quantum systems

Participants: Paolo Forni and Alain Sarlette

We consider a target quantum system, coupled to an auxiliary quantum system which dissipates rapidly at somewhat adjustable rates. The goal is to minimize the dissipation induced on the target system by this coupling. In [27], we use explicit model reduction formulas to express this as a quadratic optimization problem. We prove that maybe counterintuitively, when the auxiliary system dissipates along Hermitian (entropy-increasing) channels, the minimum induced dissipation is reached by maximizing the dissipation rate of the auxiliary system. This may be interpreted as a dynamical decoupling among the target system and the auxiliary one, induced not by standard Hamiltonian control acting on the target, but by noise acting on the environment. This link has been pursued with PhD student Michiel Burgelman and should lead to further results next year.

6.12. Repetition Cat Qubits for Fault-Tolerant Quantum Computation

Participants: Jérémie Guillaud and Mazyar Mirrahimi

We present a 1D repetition code based on the so-called cat qubits as a viable approach toward hardware-efficient universal and fault-tolerant quantum computation. The cat qubits that are stabilized by a two-photon driven-dissipative process exhibit a tunable noise bias where the effective bit-flip errors are exponentially suppressed with the average number of photons. We propose a realization of a set of gates on the cat qubits that preserve such a noise bias. Combining these base qubit operations, we build, at the level of the repetition cat qubit, a universal set of fully protected logical gates. This set includes single-qubit preparations and measurements, not, controlled-not, and controlled-controlled-not (Toffoli) gates. Remarkably, this construction avoids the costly magic state preparation, distillation, and injection. Finally, all required operations on the cat qubits could be performed with slight modifications of existing experimental setups.

This result was recently published in Physical Review X [16].

6.13. Experimental Implementation of a Raman-Assisted Eight-Wave Mixing Process

Participants: Mazyar Mirrahimi

Nonlinear processes in the quantum regime are essential for many applications, such as quantum-limited amplification, measurement, and control of quantum systems. In particular, the field of quantum error correction relies heavily on high-order nonlinear interactions between various modes of a quantum system. However, the required order of nonlinearity is often not directly available or weak compared to dissipation present in the system. Here, following our earlier theoretical proposal [72] we experimentally demonstrate a route to obtain higher-order nonlinearity by combining more easily available lower-order nonlinear processes, using a generalization of the Raman transition. In particular, we show a transformation of four photons of a high-Q superconducting resonator into two excitations of a superconducting transmon mode and two pump photons, and vice versa. The resulting eight-wave mixing process is obtained by cascading two fourth-order nonlinear processes through a virtual state. We expect this type of process to become a key component of hardware-efficient quantum error correction using continuous-variable error-correction codes. This work in collaboration with the group of Michel Devoret at Yale university was published in [18].

6.14. Stabilized Cat in a Driven Nonlinear Cavity: A Fault-Tolerant Error Syndrome Detector

Participants: Philippe Campagne-Ibarcq and Mazyar Mirrahimi

In quantum error correction, information is encoded in a high-dimensional system to protect it from the environment. A crucial step is to use natural, two-body operations with an ancilla to extract information about errors without causing backaction on the encoded information. Essentially, ancilla errors must not propagate to the encoded system and induce errors beyond those which can be corrected. The current schemes for achieving this fault tolerance to ancilla errors come at the cost of increased overhead requirements. An efficient way to extract error syndromes in a fault-tolerant manner is by using a single ancilla with a strongly biased noise channel. Typically, however, required elementary operations can become challenging when the noise is extremely biased. In this collaborative work with the groups of Steven Girvin and Michel Devoret at Yale University, we propose to overcome this shortcoming by using a bosonic-cat ancilla in a parametrically driven nonlinear oscillator. Such a cat qubit experiences only bit-flip noise, while the phase flips are exponentially suppressed. To highlight the flexibility of this approach, we illustrate the syndrome extraction process in a variety of codes such as qubit-based toric, bosonic-cat, and Gottesman-Kitaev-Preskill codes. Our results open a path for realizing hardware-efficient, fault-tolerant error syndrome extraction. This work was published in [21].

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 PhD fellowship**: We have received funding from DIM SIRTEQ to cover half of the PhD of Jérémie Guillaud under supervision of Mazyar Mirrahimi.
- **DIM SIRTEQ project SCOOP**:Half a PhD grant for Marius Villiers, supervised by Zaki Leghtas and Audrey Cottet (ENS Paris). The project is to use quantum circuits to detect the entanglement of a single Cooper pair. University.
- **EDPIF PhD fellowship**: Ecole Doctorale de Physique en Ile de France has funded half a PhD grant for Marius Villiers.
- **DGA PhD fellowship**: Direction Générale de l’Armement has funded half a PhD grant for Camille Berdou supervised by Zaki Leghtas. The project is to build a repetition code of cat-qubits.
- **Mines Paristech PhD Fellowship**: Ecole des Mines Paristech has funded half a PhD grant for Camille Berdou.
- **PSL working group on “structural stability and chaos in open quantum systems”**: This is a Groupe de Travail with researchers from CEREMADE (Paris Dauphine) and Observatoire de Paris under the direction of Jacques Fejoz. In the framework of the PhD thesis of Michiel Burgelman, we study the dynamics of superconducting Josephson circuits driven by strong microwave drives.

7.2. National Initiatives

- **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 started on april 2019 and will run for 4 years.

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

Program: H2020

Type: ERC

Project acronym: ECLIPSE

Project title: Exotic superconducting CIrcuits to Probe and protect quantum States of light and mattEr

Duration: 2019-

Coordinator: Zaki Leghtas, Mines Paristech

Program: H2020

Type: Quantera

Project acronym: QuCos

Project title: Quantum Computation with Schrödinger cat states

Duration: 2019-

Coordinator: Gerhard Kirchmair, University of Innsbruck, Austria.

Inria contacts: Zaki Leghtas and Mazyar Mirrahimi

Other partners: ENS Lyon (France), Karlsruhe Institut of Technology (Germany), Quantum Machines (Israel), National Institute for Research and Development of Isotopic and Molecular Technologies, Romania.

Abstract: This project seeks to establish a radically new, alternative approach to realizing the fundamental building blocks of quantum computers with superconducting qubits. In the next 3 years, we plan to employ only a handful of realistic components to realize robust error-corrected logical quantum bits. We aim to demonstrate the same level of protection provided by a few hundreds of qubits (with properties beyond the state of the art) in today's mainstream approach of the so-called surface code architecture. Our alternative approach is known as cat codes, because it employs multiple interconnected high coherence cavity modes with non-linear dissipation, to encode a qubit in superpositions of Schrödinger cat states. Our project combines realizing the quantum processor architecture as well as the control system and the protocols that drive it, building towards a full-stack error-corrected quantum computer. The partners in our collaboration form a strong synergetic group that has the full range of expertise needed to design and realize these systems, and to obtain these challenging goals. Furthermore, all partners of our project, including both industry and academia, have worked together and published works in the fields of quantum computing and quantum information processing. We aim to implement error protected qubits, fault tolerant operations, and demonstrate the scalability of this approach by realizing a repetition code. Our project will enable quantum experiments towards the ambitious and well-defined goal of constructing a logical qubit, on which we can perform gates, and most importantly, quantum error-correction (QEC).

7.3.2. 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 continuing collaborations with the teams of Samuel Deleglise and Igor Dotsenko from Laboratoire Kastler Brossel on the theoretical analysis of their experiments.

Partner 3: Ghent University.

Alain Sarlette has been collaborating with applied mathematicians interested in quantum control at UGent in the framework of thesis co-supervisions. One PhD student has successfully defended his thesis this year (Zhifei Zhang).

7.4. International Initiatives

7.4.1. Inria International Labs

Inria@EastCoast
Associate Team involved in the International Lab:

7.4.1.1. TAQUILLA

Title: TAilored QUantum Information protocoLs for quAntum superconducting circuits

International Partner (Institution - Laboratory - Researcher):

Université Yale (United States) -Department of Applied Physics - Michel Devoret

Start year: 2019

See also: https://team.inria.fr/quantic/Taquilla.html

We seek to establish an alternative approach to quantum error correction (QEC) for superconducting qubits. This approach, developed through the Inria-Yale collaboration, is known under the name of cat codes, because it employs multiple interconnected high coherence cavity modes with non-linear dissipation to encode a qubit in superpositions of Schrödinger cat states. We aim to implement error protected qubits, fault tolerant operations, and demonstrate the scalability of this approach. Our project will enable quantum experiments towards the ambitious and well-defined goal of constructing a logical qubit, on which we can perform gates, and most importantly, QEC.

7.4.2. Participation in Other International Programs

- **Yale-ARO subaward:** 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).
- **DARPA:** Alain Sarlette is international key personnel on the DARPA project "The Quantum Computing Revolution and Optimization: Challenges and Opportunities" led by optimization researchers at Lehigh Universty. This project of about 2M dollars can fund some exchanges during the coming years.
- **Berkeley exchange initiative:** P. Rouchon and A. Sarlette have set up an exchange initiative with Birgitta Whaley about quantum control and error correction based on continuous measurements. This initiative has funded a research visit of Gerardo Cardona at Berkeley; a student from Berkeley is bound to visit us soon in return.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

P.S. Pereira da Silva (Escola Politecnica, PTC, University of Sao Paulo, Brazil) made two visits (September 16 to 27 and December 2 to 6) to investigate with Pierre Rouchon motion planning issues based on Lyapunov tracking for quantum gate generations for open quantum systems governed by Lindblad master equations.

7.5.2. Visits to International Teams

7.5.2.1. Research Stays Abroad

- In the framework of our collaborations with Yale (Taquilla associated team), Mazyar Mirrahimi and Michiel Burgelman have spent 3 months at Yale. In the same framework Philippe Campagne-Ibarcq and Christian Siegele also made a visit of 5 days during the same period.
- In the framework of the Berkeley exchange initiative, Gerardo Cardona has spent a month (October 2019) in the research group of Birgitta Whaley at Berkeley University.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Journal

8.1.1.1. Member of the Editorial Boards

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

8.1.1.2. Reviewer - Reviewing Activities

- Philippe Campagne-Ibarcq was a reviewer for Physical Review Letters.
- Zaki Leghtas was a reviewer for Physical Review Letters, Physical Review X and Nature Physics.
- Alain Sarlette was a reviewer for several automatic control and dynamical systems journals and conferences, as well as for Physical Review Journals

8.1.2. Invited Talks

- Philippe Campagne-Ibarcq : GDR-IQFA (Groupement de Recherche sur l'Ingénierie Quantique, des Aspects Fondamentaux aux Applications).
- Jeremie Guillaud: CEA Leti innovation day, Grenoble.
- Jeremie Guillaud: Byron Bay Quantum Workshop on Bosonic Error-Correcting Codes, Australia.
- Zaki Leghtas: GDR Physique Mésoscopique, Aussois.
- Zaki Leghtas: CIFAR Workshop on Quantum Cavities, Jouvence, Canada.
- Zaki Leghtas: American Physical Society march meeting, Boston, USA.
- Zaki Leghtas: Les Houches summer school on Quantum Information Machines.
- Zaki Leghtas: CEA Leti innovation day, Grenoble.
- Zaki Leghtas: Oulu university, Finland.
- Zaki Leghtas: Quantum and neuromorphic computing, C2N Saclay.
- Mazyar Mirrahimi: Lecture series at Les Houches summer school on Quantum Information Machines.
- Mazyar Mirrahimi: Conference on "Marching towards quantum supremacy", Princeton Univ., USA.
- Mazyar Mirrahimi: Conference for "20'th anniversary of superconducting qubits", Tsukuba, Japan.
- Pierre Rouchon: First Quantum Science, Engineering and Technology (qSET) conference, UNSW Canberra, Australia.
- Pierre Rouchon: IFAC Mechatronics and Nolcos Conference, Semi-plenary speaker, Vienna, Austria.
- Pierre Rouchon: 21-hour course on quantum control in the International Graduate School on Mathematical Control, Mathematical College Sichuan University, Chengdu, China.

- Pierre Rouchon: 6-hour course on flat system in the 8eme École d'été de mécanique théorique à destination des doctorants et chercheurs en Mécanique, Quiberon.
- Alain Sarlette: GANIL (Grand Accélérateur National d'Ions Lourd), Caen.
- Alain Sarlette: CIGREF (Club Informatique des Grandes Entreprises Françaises), Paris.
- Alain Sarlette has given an overview of the mathematics involved in quantum dynamics at Ghent University at several occasions.

8.1.3. Scientific Expertise

- 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 member 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.
- Mazyar Mirrahimi is the co-president of Inria's comité des emplois scientifiques.
- Mazyar Mirrahimi was the vice-president of ANR Comité d'Evaluation Scientifique on Quantum Technologies.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

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.

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 : Mazyar Mirrahimi, Automatic control with Applications in Robotics and in Quantum engineering, 8 hour amphi and 16 hours TD, 3rd year, Ecole Polytechnique, France.

Cycle Ingénieur : Mazyar Mirrahimi, Control of dynamical models, 30 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, Sorbonne Université, France.

8.2.2. Supervision

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 : Jérémie Guillaud, Fault-tolerant quantum computation with cat-qubits, advisor: Mazyar Mirrahimi, starting date: Nov 2017.

PhD in progress : Vincent Martin, Fault-tolerance of quantum systems under continuous-time feedback stabilization, advisor: Mazyar Mirrahimi and Alain Sarlette, starting date: Oct 2018.

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 2019.

PhD in progress: Camille Berdou, A cat-qubit repetition code, advisors: Zaki Leghtas and Pierre Rouchon, starting date Sept 2019.

PhD in progress: Christian Siegele, Quantum error correction with grid states of light, advisors: Philippe Campagne-Ibarcq and Mazyar Mirrahimi.

PhD: Lucas Verney, Strongly driven quantum Josephson circuits, advisors: Zaki Leghtas and Mazyar Mirrahimi, Defended on July 11th 2019.

PhD: Gerardo Cardona Sanchez, Exponential stabilization of quantum systems subject to non-demolition measurements in continuous time, advisors: Pierre Rouchon and Alain Sarlette, Defended on October 30th 2019.

8.2.3. Juries

- Zaki Leghtas was a PhD opponent of Iivari Pietikainen, Oulu Finland.
- Zaki Leghtas was a PhD jury member of Romain Albert, CEA Grenoble.
- Mazyar Mirrahimi was an examiner in the PhD defense of Filippo Vicentini, Paris Diderot University.
- Mazyar Mirrahimi was an examiner in the HDR defense of Igor Dotsenko, Collège de France.
- Pierre Rouchon was reviewer for the Habiliation thesis of Hector Ramirez Estay, Université de Franche-Comté.
- Pierre Rouchon was a reviewer of the PhD thesis of Andreas Deutschmann (TU Vienna), Amira Amraoui (Université de Nice), Yuanlong Wang (University of New South Wales in Canberra).
- Pierre Rouchon was a committee member for the PhD thesis of Christophe Zhan (Sorbonne Université), Vincent Metillon (ENS Paris), Yahao Chen (Universté de Rouen), Weichao Liang (Université Paris-Saclay).
- Alain Sarlette has been member of the PhD jury of Nicolas Augier (Ecole Polytechnique) and of Estelle Massart (Université Catholique de Louvain-la-Neuve).

8.3. Popularization

8.3.1. Articles and contents

- Zaki Leghtas article in Usbek and Rica (https://usbeketrica.com/article/aucun-etat-veut-rater-coche-ordinateur-quantique)

8.3.2. Interventions

- Zaki Leghtas: Pint of Science on quantum computing

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