

RESEARCH CENTRE

Paris

IN PARTNERSHIP WITH:

CNRS, Sorbonne Université (UPMC),
Ecole normale supérieure de Paris, Mines
ParisTech

2021

ACTIVITY REPORT

Project-Team

QUANTIC

QUANTum Information Circuits

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

DOMAIN

Applied Mathematics, Computation and
Simulation

THEME

Optimization and control of dynamic
systems

Contents

Project-Team QUANTIC	1
1 Team members, visitors, external collaborators	2
2 Overall objectives	3
2.1 Overall objectives	3
3 Research program	3
3.1 Hardware-efficient quantum information processing	3
3.2 Reservoir (dissipation) engineering and autonomous stabilization of quantum systems . .	5
3.3 System theory for quantum information processing	6
3.4 Stabilization by measurement-based feedback	6
3.5 Filtering, quantum state and parameter estimations	6
3.6 Stabilization by interconnections	7
3.6.1 Perturbation methods	7
4 Application domains	8
4.1 Quantum engineering	8
5 Highlights of the year	9
6 New results	9
6.1 Error Rates and Resource Overheads of Repetition Cat Qubits	9
6.2 Combined Dissipative and Hamiltonian Confinement of Cat Qubits	10
6.3 Multiplexed Photon Number Measurement	10
6.4 Characterizing limits and opportunities in speeding up Markov chain mixing	10
7 Bilateral contracts and grants with industry	10
7.1 Bilateral contracts with industry	10
8 Partnerships and cooperations	11
8.1 European initiatives	11
8.1.1 Horizon Europe	11
8.1.2 FP7 & H2020 projects	11
8.2 National initiatives	13
8.3 Regional initiatives	14
9 Dissemination	14
9.1 Promoting scientific activities	14
9.1.1 Journal	14
9.1.2 Invited talks	14
9.1.3 Scientific expertise	15
9.2 Teaching - Supervision - Juries	15
9.2.1 Teaching	15
9.2.2 Supervision	15
9.2.3 Juries	16
9.3 Popularization	16
9.3.1 Articles and contents	16
9.3.2 Interventions	16
10 Scientific production	16
10.1 Major publications	16
10.2 Publications of the year	17
10.3 Other	18
10.4 Cited publications	18

Project-Team QUANTIC

Creation of the Project-Team: 2015 April 01

Keywords

Computer sciences and digital sciences

- A1.1.11. – Quantum architectures
- A4.2. – Correcting codes
- 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 members, visitors, external collaborators

Research Scientists

- Mazyar Mirrahimi [Team leader, Inria, Senior Researcher]
- Philippe Campagne Ibarcq [Inria, Researcher]
- Alain Sarlette [Inria, Researcher]

Faculty Members

- Zaki Leghtas [École Nationale Supérieure des Mines de Paris , Associate Professor]
- Pierre Rouchon [École Nationale Supérieure des Mines de Paris , Professor, HDR]
- Antoine Tilloy [Mines ParisTech, from Oct 2021]

Post-Doctoral Fellows

- Cyril Elouard [Inria, until Sep 2021]
- Vincent Lienhard [École Normale Supérieure de Paris, from Feb 2021]
- Mathys Rennela [Inria, from Mar 2021]
- William Smith [Ecole normale supérieure Paris-Saclay]

PhD Students

- Michiel Burgelman [Inria]
- Ronan Gautier [Inria]
- Francois Marie Le Regent [Alice et Bob]
- Vincent Martin [Inria]
- Matthieu Praquin [École Normale Supérieure de Paris, from Sep 2021]
- Lev Arcady Sellem [Ecole normale supérieure Paris-Saclay]
- Christian Siegele [Inria]
- Aron Vanselow [Inria]

Interns and Apprentices

- Pablo Bermejo [Inria, from Apr 2021 until Jun 2021]
- Leon Carde [École Normale Supérieure de Paris, from Apr 2021 until Jun 2021]
- Louis Paletta [Inria, from Sep 2021]

Administrative Assistant

- Derya Gök [Inria, until Nov 2021]

External Collaborator

- Jeremie Guillaud [Alice et Bob]

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 [86, 89]. 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

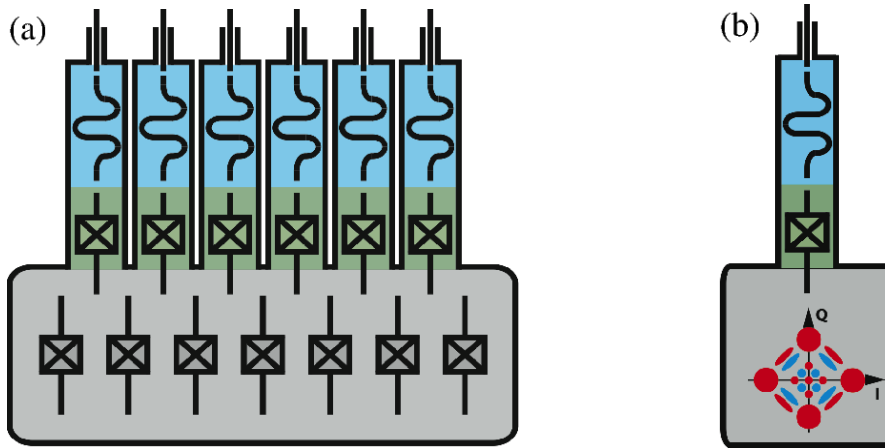


Figure 1: (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [89] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

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 [63]. 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 [60, 52] 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 [62]. Through a recent experimental work [94], 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 [90] 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, 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 [34]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [56], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [53]. 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 [44, 23, 88, 24]. 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) [42], recent advances in quantum-limited amplifiers [79, 92] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [57]. 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 [92, 78, 36]. 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 [70].

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 [68] 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 [51], single-qubit state stabilization [71], and the creation [29] and stabilization [61, 67, 85] 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 [51, 65, 40, 43]. The experimental results based on these protocols have illustrated the efficiency of the approach [51, 85]. 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 [81, 58][7, 5].

3.3 System theory for quantum information processing

In parallel and in strong interactions with the above experimental goals, we develop systematic mathematical methods for dynamical analysis, control and estimation of composite and open quantum systems. These systems are built with several quantum subsystems whose irreversible dynamics results from measurements and/or decoherence. A special attention is given to spin/spring systems made with qubits and harmonic oscillators. These developments are done in the spirit of our recent contributions [80, 23, 87, 82, 88, 24][9] resulting from collaborations with the cavity quantum electrodynamics group of Laboratoire Kastler Brossel.

3.4 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 [24]: 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 [95]; 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 [57, 36].

3.5 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 [30] and is related to quantum trajectories [37, 41]. A modern and mathematical exposure of the diffusive models is given in [28]. In [55] 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, 87]. This stability result is extended to a large class of continuous-time filters in [22]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [31].

Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [46, 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 [35] that post-selection statistics and “past quantum” state analysis [47] enhance sensitivity to parameters and could be interesting towards increasing the precision of an estimation.

3.6 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, 68]. 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] [85, 51], 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., [27][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] [85, 51] 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 [50, 49]. We will start with [84] and [77] where, based on a theorem due to Birkhoff [32], 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 [91] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [69].

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 [93, 66] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [33], 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.

3.6.1 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 [56, 48]. 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 [64].

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 [38] 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 [45] and invariant manifold techniques [39] 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 [59] 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 [51, 85, 65].

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.

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

- Hiring of two new permanent members Tudor-Alexandru Petrescu and Antoine Tilloy as associate professors at Mines Paristech.
- Philippe Campagne-Ibarcq has obtained an ERC starting grant entitled DANCINGFOOL "High-impedance Superconducting Circuits Enabling Fault-tolerant Quantum Computing by Wideband Microwave Control".
- Alain Sarlette is a PI for a new ANR Grant entitled Mecaflex "Control quantique d'un résonateur mécanique ultra-cohérent à l'aide d'un qubit fluxonium".
- Mazyar Mirrahimi is a PI for a new ANR Grant entitled OCTAVES "Dépasser les limites dans le forçage cohérent des circuits supraconducteurs quantiques".
- Antoine Tilloy has received a PSL jeune equipe Grant to start his activity in his new permanent position.
- Quantic team is participating in two "Plan Quantique" PEPRs entitled RobustSuperQ and NISQ2LSQ.
- Successful PhD defense of Jérémie Guillaud on April 13th.

6 New results

6.1 Error Rates and Resource Overheads of Repetition Cat Qubits

Participants: J. Guillaud, M. Mirrahimi

In [13], we estimate and analyze the error rates and the resource overheads of the repetition cat qubit approach introduced in [54]. While in [54], we show that using only bias-preserving gates on the cat-qubits, it is possible to build a universal set of fault-tolerant logical gates at the level of the repetition cat qubit, in this work, we perform Monte-Carlo simulations of all the circuits implementing the protected logical gates, using a circuit-level error model. Furthermore, we analyze two different approaches to implement a fault-tolerant Toffoli gate on repetition cat qubits. These numerical simulations indicate that very low logical error rates could be achieved with a reasonable resource overhead, and with parameters that are within the reach of near-term circuit QED experiments.

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

6.2 Combined Dissipative and Hamiltonian Confinement of Cat Qubits

Participants: R. Gautier, M. Mirrahimi, A. Sarlette

To confine the state of an oscillator to the cat qubit manifold, two main approaches have been considered so far: a Kerr-based Hamiltonian confinement with high gate performances, and a dissipative confinement with robust protection against a broad range of noise mechanisms. In our recent work [18], we introduce a new combined dissipative and Hamiltonian confinement scheme based on two-photon dissipation together with a Two-Photon Exchange (TPE) Hamiltonian. The TPE Hamiltonian is similar to Kerr nonlinearity, but unlike the Kerr it only induces a bounded distinction between even- and odd-photon eigenstates, a highly beneficial feature for protecting the cat qubits with dissipative mechanisms. Using this combined confinement scheme, we demonstrate fast and bias-preserving gates with drastically improved performance compared to dissipative or Hamiltonian schemes. In addition, this combined scheme can be implemented experimentally with only minor modifications of existing dissipative cat qubit experiments.

6.3 Multiplexed Photon Number Measurement

Participants: A. Sarlette, P. Rouchon, Z. Leghtas

In [12], a collaboration with our long-standing experimental partner and former QUANTIC member Benjamin Huard, a new scheme is proposed to measure the photon number operator on a superconducting cavity, thanks to a qubit dispersively coupled to the cavity and probed with a frequency comb. Thanks to this frequency multiplexing, the measurement time can be decreased compared to existing schemes. Our contribution has been to analyze the master equations modeling this experiment, in order to evaluate its benefits and clarify key elements. From a practical perspective, this has enabled us to refine the claim of the paper, identifying the use of so-called heterodyne field detectors as the main current bottleneck. From a theoretical perspective, this model has served as inspiration for developing adiabatic elimination expansions at infinite order and whose generalization we are still pursuing.

6.4 Characterizing limits and opportunities in speeding up Markov chain mixing

Participants: A. Sarlette

In our recent work [11] as a followup to our previously published work in [26, 25], we investigate an astounding point of doubt: can discrete-time quantum walks allow information to spread faster (i.e. in less steps) on a graph, than classical processes? Indeed, "quantum accelerated transport" for instance has sometimes been claimed to lay behind some fast processes, but there also exist acceleration methods for classical dynamics. We have clarified this situation by following the framework of "Lifted Markov Chains", which adds classical memory to the walker much like the quantum walk also does. We have shown that, in principle, for any evolution described by a Quantum Random Walk on a graph, there exists a classical Lifted Markov chain reproducing the same distribution over nodes in time. We have also shown that instances where particularly fast mixing Quantum Walks were known, are also those where rather intuitive Lifted Markov chains can be designed for accelerated mixing. Finally, we have clarified how much the context / constraints imposed on the Walker setting, can influence the ultimately achievable performance, hence explaining why there have been various seemingly contradictory claims in the literature. For instance, reaching a distribution that should be invariant at all time steps can be an important constraint, as well as assuming that the lifted system would start in a particular subspace of all possible distributions. This somewhat demystifies the "accelerated" evolution of Quantum Random Walks.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

- New agreement with the start-up Alice&Bob defining the perimeters of our collaboration on cat qubits.
- New PhD contracts with Alice&Bob for two new students: T. Aissaoui and P. Guilmin.

- Inria-Microsoft lab funding to further study "quantum random walks". This funding has led to the hiring of Mathys Rennela.

8 Partnerships and cooperations

8.1 European initiatives

8.1.1 Horizon Europe

ERC Starting Grant ECLIPSE

- Program: Horizon Europe
 - Type: ERC
 - Project acronym: DANCINGFOOL
 - Project title: High-impedance Superconducting Circuits Enabling Fault-tolerant Quantum Computing by Wideband Microwave Control.
 - Duration: 2022-2027
 - Coordinator: Philippe Campagne-Ibarcq, Inria
- Abstract: A physical system implementing a quantum bit (qubit) is never perfectly isolated from an uncontrolled environment. The system dynamics is thus noisy, modifying randomly the qubit state. This phenomenon of decoherence is the main roadblock to build a stable quantum computing platform. In order to mitigate decoherence, quantum error correction employs only a few code states within a much larger informational space, so that noise-induced dynamics can be detected and corrected before the encoded information gets corrupted. Unfortunately, most known protocols require to control dauntingly complex systems, with a degree of coherence currently out of reach.

Our project is to build autonomously error-corrected qubits encoded in high-impedance superconducting circuits. In our protocol, a qubit is encoded in the vast phase-space of the quantum oscillator implemented by each circuit, in the form of Gottesman-Kitaev-Preskill (GKP) states. The novelty is that the GKP states are fully stabilized by a modular dissipation, induced by the coherent tunneling of charges through a stroboscopically biased Josephson junction. The coherence of the encoded qubit is expected to exceed that of existing superconducting qubits by orders of magnitude. Furthermore, we propose to perform protected logical gates between encoded qubits by varying adiabatically the parameters of the modular dissipation, paving the way toward fault-tolerant quantum computing.

The major experimental challenge of our protocol resides in the exquisite level of control needed over a wide band in the microwave range. We propose to address this challenge by developing novel on-chip filter, tunable couplers and isolators based on periodically modulated, high-impedance, transmission lines. These on-chip components would find a wide range of applications in quantum technologies, and favor the advent of large-scale quantum computing platforms.

8.1.2 FP7 & H2020 projects

ERC Starting Grant ECLIPSE

- Program: H2020
- Type: ERC
- Project acronym: ECLIPSE
- Project title: Exotic superconducting circuits to probe and protect quantum states of light and matter

- Duration: 2019-2024
- Coordinator: Zaki Leghtas, Mines Paristech
- Abstract: Quantum systems can occupy peculiar states, such as superposition or entangled states. These states are intrinsically fragile and eventually get wiped out by inevitable interactions with the environment. Protecting quantum states against decoherence is a formidable and fundamental problem in physics, which is pivotal for the future of quantum computing. The theory of quantum error correction provides a solution, but its current envisioned implementations require daunting resources: a single bit of information is protected by encoding it across tens of thousands of physical qubits. This project intend to encode quantum information in an entirely new type of qubit with two key specificities. First, it will be encoded in a single superconducting circuit resonator whose infinite dimensional Hilbert space can replace large registers of physical qubits. Second, this qubit will be rf-powered, continuously exchanging photons with a reservoir. This approach challenges the intuition that a qubit must be isolated from its environment. Instead, the reservoir acts as a feedback loop which continuously and autonomously corrects against errors. This correction takes place at the level of the quantum hardware, and reduces the need for error syndrome measurements which are resource intensive. The circuits I will develop manipulate quantum states of light, whose utility transcends the long term goal of quantum computing, and can readily be used to probe fundamental properties of matter. In mesoscopic physics where a large number of particles exhibit collective quantum phenomena, the measurement tools to characterize subtle quantum effects are often lacking. Here, the project proposes to measure the spin entanglement of a single Cooper pair, by coupling a superconductor to a circuit composed of microwave resonators and a carbon nanotube. The spin entanglement can be swapped into microwave photons, which can be detected by deploying the arsenal of quantum limited microwave measurement devices.

ERC Advanced Grant Q-Feedback

- Program: H2020
- Type: ERC
- Project acronym: Q-Feedback
- Project title: Quantum feedback Engineering
- Duration: 2020-2025
- Coordinator: Pierre Rouchon, Mines Paristech
- Abstract : Quantum technologies, such as quantum computers and simulators, have the potential of revolutionizing our computational speed, communication security and measurement precision. The power of the quantum relies on two key but fragile resources: quantum coherence and entanglement. This promising field is facing a major open question: how to design machines which exploit quantum properties on a large scale, and efficiently protect them from external perturbations (decoherence), which tend to suppress the quantum advantage?

Making a system robust and stable to the influence of external perturbations is one of the core problems in control engineering. The goal of this project is to address the above question from the angle of control systems. The fundamental and scientific ambition is to elaborate theoretical control methods to analyse and design feedback schemes for protecting and stabilizing quantum information. Q-Feedback develops mathematical methods to harness the inherently stochastic aspects of quantum measurements. Relying on the development of original mathematical perturbation techniques specific to open quantum systems, Q-Feedback proposes a new hierarchical strategy for quantum feedback modeling, design and analysis.

The building block of a quantum machine is the quantum bit (qubit), a system which can adopt two quantum states. Despite major progress, qubits remain fragile and lose their quantum properties before a meaningful task can be accomplished. For this reason, a qubit must be both protected against external perturbations, and manipulated to perform a task. Today, no such qubit has been

built. In collaboration with experimentalists, the practical ambition is to design, relying on the control tools developed here, qubits readily integrable in a quantum processing unit. The physical platform will be Josephson superconducting circuits. Q-Feedback is expected to demonstrate the crucial role of control engineering in emerging quantum technologies.

Quantera Grant QuCos

- Program: H2020
- Type: Quantera
- Project acronym: QuCos
- Project title: Quantum Computation with Schrödinger cat states
- Duration: 2019-2023
- 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).

8.2 National initiatives

- **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.
- **ANR project SYNCAMIL:** In the framework of the ANR program JCJC, Philippe Campagne-Ibarcq has received a funding for his research program "Synthetic Non-Local Hamiltonians for the protection of quantum information". This grant of 380k euros has allowed us to purchase the experimental equipment to perform an experiment on stabilization of GKP grid states at ENS Paris, and to hire a postdoctoral associate, Vincent Lienhard, for 2 years. The project started in December 2020 for 48 months.

- **ANR project Mecaflux:** Alain Sarlette is a PI of this newly obtained ANR Grant. This project aims to couple mechanical oscillators with superconducting circuits at the quantum level, using a new circuit architecture allowing near-resonant coupling. The project is coordinated by mechanical oscillators expert Samuel Deléglise (LKB, U.Sorbonne), other project PIs are Alain Sarlette and Zaki Leghtas (QUANTIC project-team), Emmanuel Flurin and H el ene LeSueur (CEA Saclay). Our new recruit Antoine Tilloy may join with quantum gravity expertise if the level of control attains the objective where those effects become significant.
- **ANR project OCTAVES:** Mazyar Mirrahimi is a PI of this newly obtained ANR Grant. This project aims in studying the measurement problem in circuit QED (non QND effects in presence of probe drives) as well as limitations to the parametric driving for cat qubit stabilization. The project is coordinated by Olivier Buisson (Institut N eel, Grenoble) and other project PIs are Benjamin Huard (ENS Lyon), Mazyar Mirrahimi (Quantic project-team), and Dima Shepelyansky (LPT, Toulouse).

8.3 Regional initiatives

- In the framework of the project “DIM SIRTEQ Domaine d’int er et Majeur: Science et Ing enierie Quantique” of Ile de France Region, we have received two half PhD fellowships covering the PhDs of J er emie Guillaud and Marius Villiers.
- In the framework of the project “DIM SIRTEQ Domaine d’int er et Majeur: Science et Ing enierie Quantique” of Ile de France Region, we have received a 109k  grant to co-fund the purchase of a fast laser lithography system in the frame of the collaborative project "Chip-In" which aims at designing and testing on-chip microwave components for high-coherence and scalable superconducting circuits.
- PSL Jeune Equipe Grant: Antoine Tilloy has obtained a PSL grant to start his activity as an associate professor in our team working on the topic of tensor networks.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Journal

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

Reviewer - reviewing activities

- Philippe Campagne-Ibarcq was a reviewer for Phys. Rev. X.
- Mazyar Mirrahimi was a reviewer for Physical Review and Nature Journals.
- Alain Sarlette has been a reviewer for Physical Review, Journal of the Franklin Institute, npj Quantum Information, and several control theory conferences.

9.1.2 Invited talks

- Philippe Campagne-Ibarcq: American Physical Society, March meeting.
- Philippe Campagne-Ibarcq: ISNTT, Tokyo, Japan.
- Zaki Leghtas: IBM Qiskit
- Carg ese Physique M esocopique School. Corsica.
- Mazyar Mirrahimi: IBM Qiskit.

- Mazyar Mirrahimi: Inria Alumni.
- Mazyar Mirrahimi: Inria Journées scientifiques.
- Pierre Rouchon: plenary talk at 9th International Conference on Systems and Control (ICSC'2021)
- Alain Sarlette: Launch event Inria-Microsoft lab collaboration on quantum algorithms

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

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- Zaki Leghtas: Quantum Mechanics and Statistical Physics at Mines ParisTech (12 hours), Quantum Computing at Mines ParisTech (20 hours).
- Philippe Campagne-Ibarcq: Quantum Mechanics and Statistical Physics at Mines ParisTech (15 hours), Electromagnetism at ESPCI (12 hours).
- Mazyar Mirrahimi: Automatic Control at Ecole Polytechnique (16 hours), Optimization and Control at Ecole Polytechnique (40 hours), Bachelor program thesis instructor (20 hours).
- Pierre Rouchon: Mathematical methods for modeling and control of open quantum systems at International Graduate School on Applied Mathematics LIASFMA (Laboratoire International Associé Sino-Français de Mathématiques Appliquées) (8 hours)
- Alain Sarlette: Robotics at Ghent university (24 hours).

9.2.2 Supervision

- PhD in progress: Christian Siegele, Quantum error correction with grid states of light, advisors: Philippe Campagne-Ibarcq and Mazyar Mirrahimi, starting date: Sept 2019.
- PhD in progress: Aron Vanselow, Autonomous stabilization of GKP grid states in high impedance circuits, advisors: Philippe Campagne-Ibarcq and Mazyar Mirrahimi, starting date: Sept 2020.
- 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 defended : Jérémie Guillaud, Repetition cat-qubits, advisor: Mazyar Mirrahimi, starting date: Nov 2017, Defended: April 2021.
- PhD in progress : Vincent Martin, Fault-tolerance of quantum systems under continuous-time feedback stabilization, advisor: Alain Sarlette, starting date: Oct 2018.
- 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: Alvis Borgognoni. Topologically protected qubits. Supervision of Zaki Leghtas.

- PhD in progress: Ulysse Réglade. A 3D cat-qubit. Supervision of Zaki Leghtas and Raphaël Lescanne.
- PhD in progress: François-Marie Le Régent, Quantum computing architecture with cat-qubits, advisor: Mazyar Mirrahimi and Jérémie Guillaud, Starting date: Sept 2020.
- PhD in progress: Ronan Gautier, Efficient protection and fast gates in bosonic quantum codes. advisor: Alain Sarlette, Starting date: September 2020.
- PhD in progress: Lev-Arcady Sellem. Mathematical methods for simulation and control of open quantum systems, advisors: Claude Le Bris and Pierre Rouchon, Starting date: October 2020.
- PhD in progress: Thiziei Aissaoui, On-chip biasing of superconducting circuits, Starting date: september 2021, Advisors: Alain Sarlette and Anil Murani (Alice&Bob).
- PhD in progress: Matthieu Praquin, Reconfigurable microwave photonics crystals based on granular superconductors, advisors: Philippe Campagne-Ibarcq and Zaki Leghtas, starting date: Sept 2021.

9.2.3 Juries

- Zaki Leghtas was a member of the HDR defence jury of Daniel Garcia-Sanchez (INSP Paris) and the PhD defence jury of Sébastien Leger (Institut Néel Grenoble)
- Mazyar Mirrahimi was a reviewer for two PhD dissertations: Eugenio Pozzoli and Marco Fellous-Asiani.
- Alain Sarlette was a member of PhD defence jury of Antoine Essig at ENS Lyon.

9.3 Popularization

9.3.1 Articles and contents

Alain Sarlette's popularization article in *Interstices* [21].

9.3.2 Interventions

Mazyar Mirrahimi interview on podcast "Decode Quantum", 2021.

10 Scientific production

10.1 Major publications

- [1] S. Apers and A. Sarlette. 'Quantum Fast-Forwarding: Markov chains and graph property testing'. In: *Quantum Information & Computation* (Apr. 2019). URL: <https://hal.inria.fr/hal-02394399>.
- [2] P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zolys-Geller, N. E. Frattini, V. V. Sivak, P. Reinhold, S. Puri, S. Shankar, R. J. Schoelkopf, L. Frunzio, M. Mirrahimi and M. H. Devoret. 'Quantum error correction of a qubit encoded in grid states of an oscillator'. In: *Nature* 584 (Aug. 2020). Text and figures edited for clarity. The claims of the paper remain the same. Author list fixed. URL: <https://hal.inria.fr/hal-03084673>.
- [3] G. Cardona, A. Sarlette and P. Rouchon. 'Exponential stabilization of quantum systems under continuous non-demolition measurements'. In: *Automatica* (Dec. 2019). URL: <https://hal.inria.fr/hal-02394692>.
- [4] J. Guillaud and M. Mirrahimi. 'Repetition Cat Qubits for Fault-Tolerant Quantum Computation'. In: *Physical Review X* (Dec. 2019). <https://arxiv.org/abs/1904.09474> - 22 pages, 11 figures. DOI: [10.1103/PhysRevX.9.041053](https://doi.org/10.1103/PhysRevX.9.041053). URL: <https://hal.inria.fr/hal-02413978>.

- [5] Z. Leghtas, S. Touzard, I. M. Pop, A. Kou, B. Vlastakis, A. Petrenko, K. M. Sliwa, A. Narla, S. Shankar, M. J. Hatridge, M. Reagor, L. Frunzio, R. J. Schoelkopf, M. Mirrahimi and M. H. Devoret. ‘Confining the state of light to a quantum manifold by engineered two-photon loss’. In: *Science* 347.6224 (Feb. 2015), pp. 853–857. DOI: [10.1126/science.aaa2085](https://doi.org/10.1126/science.aaa2085). URL: <https://hal.inria.fr/hal-01240210>.
- [6] R. Lescanne, M. Villiers, T. Peronnin, A. Sarlette, M. Delbecq, B. Huard, T. Kontos, M. Mirrahimi and Z. Leghtas. ‘Exponential suppression of bit-flips in a qubit encoded in an oscillator’. In: *Nature Physics* (Mar. 2020). DOI: [10.1038/s41567-020-0824-x](https://doi.org/10.1038/s41567-020-0824-x). URL: <https://hal.archives-ouvertes.fr/hal-02526631>.
- [7] M. Mirrahimi, Z. Leghtas, V. V. Albert, S. Touzard, R. J. Schoelkopf, L. Jiang and M. H. Devoret. ‘Dynamically protected cat-qubits: a new paradigm for universal quantum computation’. In: *New Journal of Physics* 16.4 (Apr. 2014), p. 045014.
- [8] N. Ofek, A. Petrenko, R. Heeres, P. Reinhold, Z. Leghtas, B. Vlastakis, Y. Liu, L. Frunzio, S. Girvin, L. Jiang, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. ‘Extending the lifetime of a quantum bit with error correction in superconducting circuits’. In: *Nature* 536 (2016), p. 5.
- [9] A. Sarlette, J.-M. Raimond, M. Brune and P. Rouchon. ‘Stabilization of nonclassical states of the radiation field in a cavity by reservoir engineering’. In: *Phys. Rev. Lett.* 107 (2011). 010402.
- [10] C. Sayrin, I. Dotsenko, X. Zhou, B. Peaudecerf, T. Rybarczyk, S. Gleyzes, P. Rouchon, M. Mirrahimi, H. Amini, M. Brune, J.-M. Raimond and S. Haroche. ‘Real-time quantum feedback prepares and stabilizes photon number states’. In: *Nature* 477 (2011), pp. 73–77.

10.2 Publications of the year

International journals

- [11] S. Apers, F. Ticozzi and A. Sarlette. ‘Characterizing limits and opportunities in speeding up Markov chain mixing’. In: *Stochastic Processes and their Applications* 136 (June 2021), Pages 145–191. URL: <https://hal.inria.fr/hal-03097637>.
- [12] A. Essig, Q. Ficheux, T. Peronnin, N. Cottet, R. Lescanne, A. Sarlette, P. Rouchon, Z. Leghtas and B. Huard. ‘Multiplexed Photon Number Measurement’. In: *Physical Review X* 11.3 (Aug. 2021). DOI: [10.1103/PhysRevX.11.031045](https://doi.org/10.1103/PhysRevX.11.031045). URL: <https://hal-mines-paristech.archives-ouvertes.fr/hal-03443020>.
- [13] J. Guillaud and M. Mirrahimi. ‘Error Rates and Resource Overheads of Repetition Cat Qubits’. In: *Physical Review A* 103 (2021). URL: <https://hal.inria.fr/hal-03084665>.
- [14] Z. Mineev, Z. Leghtas, S. Mundhada, L. Christakis, I. Pop and M. Devoret. ‘Energy-participation quantization of Josephson circuits’. In: *npj Quantum Information* 7.1 (Dec. 2021). DOI: [10.1038/s41534-021-00461-8](https://doi.org/10.1038/s41534-021-00461-8). URL: <https://hal-mines-paristech.archives-ouvertes.fr/hal-03467417>.
- [15] P. S. Pereira Da Silva, P. Rouchon and H. B. Silveira. ‘A fixed point algorithm for improving fidelity of quantum gates’. In: *ESAIM: Control, Optimisation and Calculus of Variations* 27 (2021), S9. DOI: [10.1051/cocv/2020057](https://doi.org/10.1051/cocv/2020057). URL: <https://hal-mines-paristech.archives-ouvertes.fr/hal-03500404>.
- [16] J. F. da Silva Barbosa, M. Lee, P. Campagne-Ibarcq, P. Jamonneau, Y. Kubo, S. Pezzagna, J. Meijer, T. Teraji, D. Vion, D. Esteve, R. W. Heeres and P. Bertet. ‘Determining the position of a single spin relative to a metallic nanowire’. In: *Journal of Applied Physics* 129.14 (2021). DOI: [10.1063/5.0042987](https://doi.org/10.1063/5.0042987). URL: <https://hal.inria.fr/hal-03084924>.

Doctoral dissertations and habilitation theses

- [17] J. Guillaud. ‘Repetition Cat Qubits’. École Normale Supérieure, 13th Apr. 2021. URL: <https://hal.archives-ouvertes.fr/tel-03509305>.

Reports & preprints

- [18] R. Gautier, A. Sarlette and M. Mirrahimi. *Combined Dissipative and Hamiltonian Confinement of Cat Qubits*. 3rd Jan. 2022. URL: <https://hal.inria.fr/hal-03507993>.
- [19] U. A. Maciel Neto, P. S. Pereira Da Silva and P. Rouchon. *Motion planing for an ensemble of Bloch equations towards the south pole with smooth bounded control*. 24th Aug. 2021. URL: <https://hal-mines-paristech.archives-ouvertes.fr/hal-03325203>.
- [20] J. Stevens, D. Szombati, M. Maffei, C. Elouard, R. Assouly, N. P. Cottet, R. Dassonneville, Q. Ficheux, S. Zeppetbauer, A. Bienfait, A. N. Jordan, A. Auffèves and B. Huard. *Energetics of a Single Qubit Gate*. 14th Oct. 2021. URL: <https://hal.archives-ouvertes.fr/hal-03378195>.

10.3 Other

Scientific popularization

- [21] A. Sarlette. ‘Construire une machine quantique’. In: *Interstices* (31st Mar. 2021). URL: <https://hal.inria.fr/hal-03220212>.

10.4 Cited publications

- [22] H. Amini, C. Pellegrini and P. Rouchon. ‘Stability of continuous-time quantum filters with measurement imperfections’. In: *Russian Journal of Mathematical Physics* 21 (2014), pp. 297–315.
- [23] H. Amini, M. Mirrahimi and P. Rouchon. ‘Stabilization of a delayed quantum system: the Photon Box case-study’. In: *IEEE Trans. Automatic Control* 57.8 (2012), pp. 1918–1930.
- [24] H. Amini, A. Somaraju, I. Dotsenko, C. Sayrin, M. Mirrahimi and P. Rouchon. ‘Feedback stabilization of discrete-time quantum systems subject to non-demolition measurements with imperfections and delays’. In: *Automatica* 49.9 (2013), pp. 2683–2692.
- [25] S. Apers, A. Sarlette and F. Ticozzi. ‘Simulation of quantum walks and fast mixing with classical processes’. In: *Physical Review A* 98.3 (Sept. 2018), p. 032115. URL: <https://hal.inria.fr/hal-01946763>.
- [26] S. Apers, A. Sarlette and F. Ticozzi. ‘When Does Memory Speed-up Mixing?’ In: *IEEE Conference on Decision and Control*. Melbourne, Australia, Dec. 2017. URL: <https://hal.inria.fr/hal-01634630>.
- [27] S. Attal, A. Joye and C.-A. Pillet, eds. *Open Quantum Systems III: Recent Developments*. Springer, Lecture notes in Mathematics 1880, 2006.
- [28] A. Barchielli and M. Gregoratti. *Quantum Trajectories and Measurements in Continuous Time: the Diffusive Case*. Springer Verlag, 2009.
- [29] J. Barreiro, M. Muller, P. Schindler, D. Nigg, T. Monz, M. Chwalla, M. Hennrich, C. Roos, P. Zoller and R. Blatt. ‘An open-system quantum simulator with trapped ions’. In: *Nature* 470 (2011). 486.
- [30] V. Belavkin. ‘Quantum stochastic calculus and quantum nonlinear filtering’. In: *Journal of Multivariate Analysis* 42.2 (1992), pp. 171–201.
- [31] T. Benoist and C. Pellegrini. ‘Large Time Behavior and Convergence Rate for Quantum Filters Under Standard Non Demolition Conditions’. In: *Communications in Mathematical Physics* (2014), pp. 1–21. URL: <http://dx.doi.org/10.1007/s00220-014-2029-6>.
- [32] G. Birkhoff. ‘Extensions of Jentzch’s theorem’. In: *Trans. Amer. Math. Soc.* 85 (1957), pp. 219–227.
- [33] S. Bolognani and F. Ticozzi. ‘Engineering stable discrete-time quantum dynamics via a canonical QR decomposition’. In: *IEEE Trans. Autom. Control* 55 (2010).
- [34] V. Braginski and F. Khalili. *Quantum Measurements*. Cambridge University Press, 1992.
- [35] P. Campagne-Ibarcq, L. Bretheau, E. Flurin, A. Auffèves, F. Mallet and B. Huard. ‘Observing Interferences between Past and Future Quantum States in Resonance Fluorescence’. In: *Phys. Rev. Lett.* 112 (18 May 2014). 180402. DOI: [10.1103/PhysRevLett.112.180402](https://doi.org/10.1103/PhysRevLett.112.180402). URL: <http://link.aps.org/doi/10.1103/PhysRevLett.112.180402>.

- [36] P. Campagne-Ibarcq, E. Flurin, N. Roch, D. Darson, P. Morfin, M. Mirrahimi, M. H. Devoret, F. Mallet and B. Huard. ‘Persistent Control of a Superconducting Qubit by Stroboscopic Measurement Feedback’. In: *Phys. Rev. X* 3 (2013). 021008.
- [37] H. Carmichael. *An Open Systems Approach to Quantum Optics*. Springer-Verlag, 1993.
- [38] H. Carmichael. *Statistical Methods in Quantum Optics 2: Non-Classical Fields*. Springer, 2007.
- [39] J. Carr. *Application of Center Manifold Theory*. Springer, 1981.
- [40] J. Cohen and M. Mirrahimi. ‘Dissipation-induced continuous quantum error correction for superconducting circuits’. In: *Phys. Rev. A* 90 (2014), p. 062344.
- [41] J. Dalibard, Y. Castin and K. Mølmer. ‘Wave-function approach to dissipative processes in quantum optics’. In: *Phys. Rev. Lett.* 68.5 (1992), pp. 580–583.
- [42] M. H. Devoret, A. Wallraff and J. Martinis. *Superconducting Qubits: A Short Review*. arXiv:cond-mat/0411174. 2004.
- [43] N. Didier, J. Guillaud, S. Shankar and M. Mirrahimi. ‘Remote entanglement stabilization and concentration by quantum reservoir engineering’. In: *Physical Review A* (July 2018). <https://arxiv.org/abs/1703.03379> - 5 pages, 4 figures. DOI: [10.1103/PhysRevA.98.012329](https://doi.org/10.1103/PhysRevA.98.012329). URL: <https://hal.inria.fr/hal-01652766>.
- [44] I. Dotsenko, M. Mirrahimi, M. Brune, S. Haroche, J.-M. Raimond and P. Rouchon. ‘Quantum feedback by discrete quantum non-demolition measurements: towards on-demand generation of photon-number states’. In: *Physical Review A* 80: 013805-013813 (2009).
- [45] N. Fenichel. ‘Geometric singular perturbation theory for ordinary differential equations’. In: *J. Diff. Equations* 31 (1979), pp. 53–98.
- [46] J. Gambetta and H. M. Wiseman. ‘State and dynamical parameter estimation for open quantum systems’. In: *Phys. Rev. A* 64.4 (Sept. 2001). 042105. URL: <http://link.aps.org/doi/10.1103/PhysRevA.64.042105>.
- [47] S. Gammelmark, B. Julsgaard and K. Mølmer. ‘Past Quantum States of a Monitored System’. In: *Phys. Rev. Lett.* 111.16 (Oct. 2013). 160401. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.111.160401>.
- [48] C. Gardiner and P. Zoller. *Quantum Noise*. third. Springer, 2010.
- [49] S. Gaubert and Z. Qu. ‘Checking the strict positivity of Kraus maps is NP-hard’. In: *arXiv:1402.1429* (2014).
- [50] S. Gaubert and Z. Qu. ‘The contraction rate in Thompson’s part metric of order-preserving flows on a cone - Application to generalized Riccati equations’. In: *Journal of Differential Equations* 256.8 (Apr. 2014), pp. 2902–2948. URL: <http://www.sciencedirect.com/science/article/pii/S0022039614000424>.
- [51] K. Geerlings, Z. Leghtas, I. Pop, S. Shankar, L. Frunzio, R. Schoelkopf, M. Mirrahimi and M. H. Devoret. ‘Demonstrating a Driven Reset Protocol of a Superconducting Qubit’. In: *Phys. Rev. Lett.* 110 (2013). 120501.
- [52] D. Gottesman, A. Kitaev and J. Preskill. ‘Encoding a qubit in an oscillator’. In: *Phys. Rev. A* 64 (2001). 012310.
- [53] C. Guerlin, J. Bernu, S. Deléglise, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.-M. Raimond and S. Haroche. ‘Progressive field-state collapse and quantum non-demolition photon counting’. In: *Nature* 448 (2007), pp. 889–893.
- [54] J. Guillaud and M. Mirrahimi. ‘Repetition Cat Qubits for Fault-Tolerant Quantum Computation’. In: *Physical Review X* (Dec. 2019). 22 pages, 11 figures. DOI: [10.1103/PhysRevX.9.041053](https://doi.org/10.1103/PhysRevX.9.041053). URL: <https://hal.inria.fr/hal-02413978>.
- [55] R. van Handel. ‘The stability of quantum Markov filters’. In: *Infin. Dimens. Anal. Quantum Probab. Relat. Top.* 12 (2009), pp. 153–172.
- [56] S. Haroche and J.-M. Raimond. *Exploring the Quantum: Atoms, Cavities and Photons*. Oxford University Press, 2006.

- [57] M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. Sliwa, B. Abdo, L. Frunzio, S. Girvin, R. Schoelkopf and M. H. Devoret. ‘Quantum back-action of an individual variable-strength measurement’. In: *Science* 339 (2013), pp. 178–181.
- [58] E. Holland, B. Vlastakis, R. Heeres, M. J. Reagor, U. Vool, Z. Leghtas, L. Frunzio, G. Kirchmair, M. H. Devoret, M. Mirrahimi and R. Schoelkopf. ‘Single-photon-resolved cross-Kerr interaction for autonomous stabilization of photon-number states’. In: *Phys. Rev. Lett.* 115 (2015), p. 180501.
- [59] T. Kato. *Perturbation Theory for Linear Operators*. Springer, 1966.
- [60] E. Knill, R. Laflamme and G. Milburn. ‘A scheme for efficient quantum computation with linear optics’. In: *Nature* 409 (2001). 46.
- [61] H. Krauter, C. Muschik, K. Jensen, W. Wasilewski, J. Petersen, J. Cirac and E. Polzik. ‘Entanglement Generated by Dissipation and Steady State Entanglement of Two Macroscopic Objects’. In: *Phys. Rev. Lett.* 107 (2011). 080503.
- [62] Z. Leghtas, G. Kirchmair, B. Vlastakis, M. H. Devoret, R. J. Schoelkopf and M. Mirrahimi. ‘Deterministic protocol for mapping a qubit to coherent state superpositions in a cavity’. In: *Phys. Rev. A* 87 (2013). 042315.
- [63] Z. Leghtas, G. Kirchmair, B. Vlastakis, R. J. Schoelkopf, M. H. Devoret and M. Mirrahimi. ‘Hardware-efficient autonomous quantum memory protection’. In: *Phys. Rev. Lett.* 111 (2013). 120501.
- [64] Z. Leghtas, A. Sarlette and P. Rouchon. ‘Adiabatic passage and ensemble control of quantum systems’. In: *J. Phys. B* 44 (2011). 154017.
- [65] Z. Leghtas, U. Vool, S. Shankar, M. Hatridge, S. Girvin, M. H. Devoret and M. Mirrahimi. ‘Stabilizing a Bell state of two superconducting qubits by dissipation engineering’. In: *Phys. Rev. A* 88 (2013). 023849.
- [66] J.-S. Li and N. Khaneja. ‘Ensemble control of Bloch equations’. In: *IEEE Trans. Autom. Control* 54 (2009), pp. 528–536.
- [67] Y. a. J. G. Lin, F. Reiter, T. Tan, R. Bowler, A. Sorensen, D. Leibfried and D. Wineland. ‘Dissipative production of a maximally entangled steady state of two quantum bits’. In: *Nature* 504 (2013), pp. 415–418.
- [68] S. Lloyd. ‘Coherent quantum feedback’. In: *Phys. Rev. A* 62 (2000). 022108.
- [69] L. Mazzarella, A. Sarlette and F. Ticozzi. ‘Consensus for quantum networks: from symmetry to gossip iterations’. In: *IEEE Trans. Automat. Control* (2014). in press.
- [70] M. Mirrahimi, B. Huard and M. H. Devoret. ‘Strong measurement and quantum feedback for persistent Rabi oscillations in circuit QED experiments’. In: *IEEE Conference on Decision and Control*. IEEE Conference on Decision and Control, 2012.
- [71] K. Murch, U. Vool, D. Zhou, S. Weber, S. Girvin and I. Siddiqi. ‘Cavity-assisted quantum bath engineering’. In: *Phys. Rev. Lett.* 109 (2012). 183602.
- [72] A. Negretti and K. Mølmer. ‘Estimation of classical parameters via continuous probing of complementary quantum observables’. In: *New Journal of Physics* 15.12 (2013). 125002. URL: <http://stacks.iop.org/1367-2630/15/i=12/a=125002>.
- [73] H. Nurdin, M. James and I. Petersen. ‘Coherent quantum LQG control’. In: *Automatica* 45 (2009), pp. 1837–1846.
- [74] B. Peaudecerf, T. Rybarczyk, S. Gerlich, S. Gleyzes, J.-M. Raimond, S. Haroche, I. Dotsenko and M. Brune. ‘Adaptive Quantum Nondemolition Measurement of a Photon Number’. In: *Phys. Rev. Lett.* 112.8 (Feb. 2014). 080401. DOI: [10.1103/PhysRevLett.112.080401](https://doi.org/10.1103/PhysRevLett.112.080401). URL: <http://link.aps.org/doi/10.1103/PhysRevLett.112.080401>.
- [75] D. Petz. ‘Monotone Metrics on matrix spaces’. In: *Linear Algebra and its Applications* 244 (1996), pp. 81–96.
- [76] J. Poyatos, J. Cirac and P. Zoller. ‘Quantum Reservoir Engineering with Laser Cooled Trapped Ions’. In: *Phys. Rev. Lett.* 77.23 (1996), pp. 4728–4731.

- [77] D. Reeb, M. J. Kastoryano and M. M. Wolf. ‘Hilbert’s projective metric in quantum information theory’. In: *Journal of Mathematical Physics* 52.8 (Aug. 2011). 082201. arXiv: [1102.5170 \[math-ph\]](https://arxiv.org/abs/1102.5170). URL: <http://dx.doi.org/10.1063/1.3615729>.
- [78] D. Ristè, J. Leeuwen, H.-S. Ku, K. Lehnert and L. Dicarlo. ‘Initialization by measurement of a superconducting quantum bit circuit’. In: *Phys. Rev. Lett.* 109 (2012). 050507.
- [79] N. Roch, E. Flurin, F. Nguyen, P. Morfin, P. Campagne-Ibarcq, M. H. Devoret and B. Huard. ‘Widely tunable, non-degenerate three-wave mixing microwave device operating near the quantum limit’. In: *Phys. Rev. Lett.* 108 (2012). 147701.
- [80] P. Rouchon. ‘Fidelity is a Sub-Martingale for Discrete-Time Quantum Filters’. In: *IEEE Transactions on Automatic Control* 56.11 (2011), pp. 2743–2747.
- [81] A. Roy, Z. Leghtas, A. Stone, M. Devoret and M. Mirrahimi. ‘Continuous generation and stabilization of mesoscopic field superposition states in a quantum circuit’. In: *Phys. Rev. A* 91 (2015), p. 013810.
- [82] A. Sarlette, Z. Leghtas, M. Brune, J.-M. Raimond and P. Rouchon. ‘Stabilization of nonclassical states of one- and two-mode radiation fields by reservoir engineering’. In: *Phys. Rev. A* 86 (2012). 012114.
- [83] D. Schuster, A. Houck, J. Schreier, A. Wallraff, J. Gambetta, A. Blais, L. Frunzio, J. Majer, B. Johnson, M. H. Devoret, S. Girvin and R. J. Schoelkopf. ‘Resolving photon number states in a superconducting circuit’. In: *Nature* 445 (2007), pp. 515–518.
- [84] R. Sepulchre, A. Sarlette and P. Rouchon. ‘Consensus in non-commutative spaces’. In: *Decision and Control (CDC), 2010 49th IEEE Conference on*. 2010, pp. 6596–6601.
- [85] S. a. M. H. Shankar, Z. Leghtas, K. Sliwa, A. Narla, U. Vool, S. Girvin, L. Frunzio, M. Mirrahimi and M. H. Devoret. ‘Autonomously stabilized entanglement between two superconducting quantum bits’. In: *Nature* 504 (2013), pp. 419–422.
- [86] P. Shor. ‘Scheme for reducing decoherence in quantum memory’. In: *Phys. Rev. A* 52 (1995), pp. 2493–2496.
- [87] A. Somaraju, I. Dotsenko, C. Sayrin and P. Rouchon. ‘Design and Stability of Discrete-Time Quantum Filters with Measurement Imperfections’. In: *American Control Conference*. 2012, pp. 5084–5089.
- [88] A. Somaraju, M. Mirrahimi and P. Rouchon. ‘Approximate stabilization of infinite dimensional quantum stochastic system’. In: *Reviews in Mathematical Physics* 25 (2013). 1350001.
- [89] A. Steane. ‘Error Correcting Codes in Quantum Theory’. In: *Phys. Rev. Lett* 77.5 (1996).
- [90] L. Sun, A. Petrenko, Z. Leghtas, B. Vlastakis, G. Kirchmair, K. Sliwa, A. Narla, M. Hatridge, S. Shankar, J. Blumoff, L. Frunzio, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. ‘Tracking photon jumps with repeated quantum non-demolition parity measurements’. In: *Nature* 511 (2014), pp. 444–448.
- [91] J. Tsitsiklis. ‘Problems in decentralized decision making and computation’. In: *PhD Thesis, MIT* (1984).
- [92] R. Vijay, C. Macklin, D. Slichter, S. Weber, K. Murch, R. Naik, A. Korotkov and I. Siddiqi. ‘Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback’. In: *Nature* 490 (2012), pp. 77–80.
- [93] L. Viola, E. Knill and S. Lloyd. ‘Dynamical decoupling of open quantum system’. In: *Phys. Rev. Lett.* 82 (1999), pp. 2417–2421.
- [94] B. Vlastakis, G. Kirchmair, Z. Leghtas, S. Nigg, L. Frunzio, S. Girvin, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. ‘Deterministically encoding quantum information using 100-photon Schrödinger cat states’. In: *Science* 342 (2013), pp. 607–610.
- [95] X. Zhou, I. Dotsenko, B. Peaudecerf, T. Rybarczyk, C. Sayrin, S. Gleyzes, J.-M. Raimond, M. Brune and S. Haroche. ‘Field locked to Fock state by quantum feedback with single photon corrections’. In: *Physical Review Letter* 108 (2012). 243602.