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2020

ACTIVITY REPORT

Project-Team

QUANTIC

## QUANTum Information Circuits

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

DOMAIN

Applied Mathematics, Computation and  
Simulation

THEME

Optimization and control of dynamic  
systems

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## Project-Team QUANTIC

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### 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

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- Jeremie Guillaud [Inria, until Aug 2020]
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- Adrien Rospars [Universié de Lyon, from Jun 2020 until Jul 2020]
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### Administrative Assistant

- Derya Gök [Inria]

### External Collaborator

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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, 91]. 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

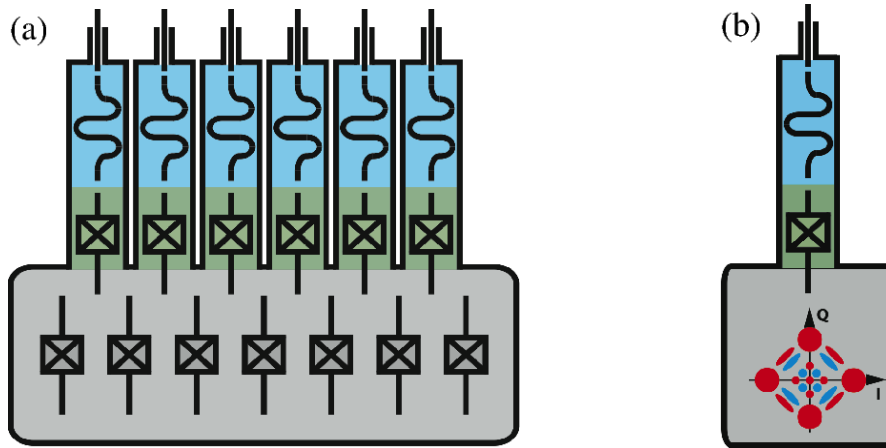


Figure 1: (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [91] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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 [65]. 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 [62, 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 [64]. Through a recent experimental work [96], 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 [92] 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 [37]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [58], 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, 28, 90, 29]. These contributions include the development and optimization of the quantum filters taking into account the quantum measurement back-action and various measurement noises and uncertainties, the development of a feedback law based on control Lyapunov techniques, and the compensation of the feedback delay.

In the context of circuit quantum electrodynamics (circuit QED) [45], recent advances in quantum-limited amplifiers [81, 94] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [59]. 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 [94, 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 [72].

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 [70] 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 [63, 69, 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, 67, 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, 60][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 [82, 28, 89, 84, 90, 29][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 [29]: it is based on a discrete-time formulation of the dynamics, on the construction of a strict control Lyapunov function and on an explicit compensation of the feedback-loop delay. Keeping the QND measurement assumptions, extensions of such stabilization schemes will be investigated in the following directions: finite set of values for the control input with application to the convergence analysis of the atomic feedback scheme experimentally tested in [97]; 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 [59, 39].

### 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 [33] and is related to quantum trajectories [40, 44]. A modern and mathematical exposure of the diffusive models is given in [31]. In [57] 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, 89]. This stability result is extended to a large class of continuous-time filters in [27]. 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.

### 3.6 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 [78, 70]. 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., [30][chapter 4, section 6]). When the goal steady-state is not full rank very few convergence results are available.

We will focus on this geometric situation where the goal steady-state is on the boundary of the cone of positive Hermitian operators of finite trace. A specific attention will be given to adapt standard tools (Lyapunov function, passivity, contraction and Lasalle's invariance principle) for infinite dimensional systems to spin/spring structures inspired of [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 [93] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [71].

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 [95, 68] 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.

#### 3.6.1 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 [58, 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 [66].

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 [41] 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 [61] 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, 67].

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<sup>1</sup> 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

- Pierre Rouchon has obtained an ERC advanced grant in pannel PE7 entitled Q-Feedback (Quantum feedback Engineering).
- Philippe Campagne-Ibarcq has obtained an ANR JCJC grant entitle SYNCAMIL “Synthetic Non-Local Hamiltonians for the protection of quantum information”.
- Philippe Campagne-Ibarcq has obtained a regional DIM SIRTEQ grant for experimental equipment.
- Successful PhD defense of Raphaël Lescanne under the supervision of Zaki Leghtas and Takis Kontos.
- Successful HDR defense of Zaki Leghtas and Alain Sarlette.
- Creation of startup Alice and Bob. Philippe Campagne-Ibarcq, Zaki Leghtas and Mazyar Mirrahimi are members of the scientific board.
- Mazyar Mirrahimi was a plenary speaker at the European Control Conference.

## 6 New results

### 6.1 Exponential suppression of bit-flips in a qubit encoded in an oscillator

Participants: R. Lescanne, M. Villiers, A. Sarlette, M. Mirrahimi, Z. Leghtas.

A quantum system interacts with its environment—if ever so slightly—no matter how much care is put into isolating it. Therefore, quantum bits undergo errors, putting dauntingly difficult constraints on the hardware suitable for quantum computation. New strategies are emerging to circumvent this problem by encoding a quantum bit non-locally across the phase space of a physical system. Because most sources of decoherence result from local fluctuations, the foundational promise is to exponentially suppress errors by increasing a measure of this non-locality. Prominent examples are topological quantum bits, which delocalize information over real space and where spatial extent measures non-locality. Here, we encode a quantum bit in the field quadrature space of a superconducting resonator endowed with a special mechanism that dissipates photons in pairs. This process pins down two computational states to separate locations in phase space. By increasing this separation, we measure an exponential decrease of the bit-flip rate while only linearly increasing the phase-flip rate. Because bit-flips are autonomously

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

corrected, only phase-flips remain to be corrected via a one-dimensional quantum error correction code. This exponential scaling demonstrates that resonators with nonlinear dissipation are promising building blocks for quantum computation with drastically reduced hardware overhead. This experimental work was published in [16].

## 6.2 Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons

Participants: R. Lescanne, Z. Leghtas

Single photon detection is a key resource for sensing at the quantum limit and the enabling technology for measurement-based quantum computing. Photon detection at optical frequencies relies on irreversible photoassisted ionization of various natural materials. However, microwave photons have energies 5 orders of magnitude lower than optical photons, and are therefore ineffective at triggering measurable phenomena at macroscopic scales. Here, we report the observation of a new type of interaction between a single two-level system (qubit) and a microwave resonator. These two quantum systems do not interact coherently; instead, they share a common dissipative mechanism to a cold bath: the qubit irreversibly switches to its excited state if and only if a photon enters the resonator. We have used this highly correlated dissipation mechanism to detect itinerant photons impinging on the resonator. This scheme does not require any prior knowledge of the photon waveform nor its arrival time, and dominant decoherence mechanisms do not trigger spurious detection events (dark counts). We demonstrate a detection efficiency of 58% and a record low dark count rate of 1.4 per millisecond. This work establishes engineered nonlinear dissipation as a key enabling resource for a new class of low-noise nonlinear microwave detectors. This experimental work was published in [15].

## 6.3 Theory of interactions between cavity photons induced by a mesoscopic circuit

Participants: Z. Leghtas

We use a quantum path-integral approach to describe the behavior of a microwave cavity coupled to a dissipative mesoscopic circuit. We integrate out the mesoscopic electronic degrees of freedom to obtain a cavity effective action at fourth order in the light/matter coupling. By studying the structure of this action, we establish sufficient conditions in which the cavity dynamics can be described with a Lindblad equation. This equation depends on effective parameters set by electronic correlation functions. It reveals that the mesoscopic circuit induces an effective Kerr interaction and two-photon dissipative processes. We use our method to study the effective dynamics of a cavity coupled to a double quantum dot with normal metal reservoirs. If the cavity is driven at twice its frequency, the double-dot circuit generates photonic squeezing and nonclassicalities visible in the cavity Wigner function. In particular, we find a counterintuitive situation where mesoscopic dissipation enables the production of photonic Schrödinger cats. These effects can occur for realistic circuit parameters. Our method can be generalized straightforwardly to more complex circuit geometries with, for instance, multiple quantum dots and other types of fermionic reservoirs such as superconductors and ferromagnets. This theoretical work was published in [12].

## 6.4 Quantum error correction of a qubit encoded in grid states of an oscillator

Participants: Philippe Campagne-Ibarcq and Mazhar Mirrahimi

Quantum Error Correction (QEC) derives from the reasonable assumption that noise is local, that is, it does not act in a coordinated way on different parts of the physical system. Therefore, if a logical qubit is encoded non-locally, we can detect and correct noise-induced evolution before it corrupts the encoded information. In 2001, Gottesman, Kitaev and Preskill (GKP) proposed a hardware-efficient instance of such a non-local qubit: a superposition of position eigenstates that forms grid states of a single oscillator.

In this work in collaboration with the group of Michel Devoret at Yale university, we experimentally prepare square and hexagonal GKP code states through a feedback protocol that incorporates non-destructive measurements that are implemented with a superconducting microwave cavity having the role of the oscillator. We demonstrate QEC of an encoded qubit with suppression of all logical errors, in quantitative agreement with a theoretical estimate based on the measured imperfections of the

experiment. This protocol is applicable to other continuous-variable systems and, in contrast to previous implementations of QEC, can mitigate all logical errors generated by a wide variety of noise processes and facilitate fault-tolerant quantum computation.

This work was published in [11].

## 6.5 Scaling up reservoir engineering for error-correcting codes

Participants: Alain Sarlette and Vincent Martin

Error-correcting codes are usually envisioned to counter errors by operating unitary corrections depending on the projective measurement results of some syndrome observables. We here propose a way to use them in a more integrated way, where the error correction is applied continuously and autonomously by an engineered environment. We focus on a proposal for the repetition code that counters bit-flip errors, and how to scale up the network encoding a logical quantum bit, towards stronger information protection. This proposal is motivated by the cat-qubits, which are strongly protected against one type of error and only need a repetition-code type protection against the other type. The challenge has been to devise a network architecture which allows to autonomously correct higher-order errors, while remaining realistic towards experimental realization by avoiding all-to-all or all-to-one coupling. This work [22] submitted to MTNS 2020 (pandemic postponed as MTNS 2021) was proposing a first architecture and analysis tools.

## 6.6 Number-resolved photocounter for propagating microwave mode

Participants: Pierre Rouchon

Detectors of propagating microwave photons have recently been realized using superconducting circuits. However a number-resolved photocounter is still missing. In this work, we demonstrate a single-shot counter for propagating microwave photons that can resolve up to 3 photons. It is based on a pumped Josephson Ring Modulator that can catch an arbitrary propagating mode by frequency conversion and store its quantum state in a stationary memory mode. A transmon qubit then counts the number of photons in the memory mode using a series of binary questions. Using measurement based feedback, the number of questions is minimal and scales logarithmically with the maximal number of photons. The detector features a detection efficiency of  $0.96 \pm 0.04$ , and a dark count probability of  $0.030 \pm 0.002$  for an average dead time of  $4.5 \mu\text{s}$ . To maximize its performance, the device is first used as an *in situ* waveform detector from which an optimal pump is computed and applied. Depending on the number of incoming photons, the detector succeeds with a probability that ranges from  $(54 \pm 2)\%$  to 99%. This experimental result in collaboration with the team of Benjamin Huard at ENS Lyon was published in [13].

## 6.7 Stabilization and operation of a Kerr-cat qubit

Participants: Mazyar Mirrahimi

Quantum superpositions of macroscopically distinct classical states, so-called Schrödinger cat states, are a resource for quantum metrology, quantum communication, and quantum computation. In particular, the superpositions of two opposite-phase coherent states in an oscillator encode a qubit protected against phase-flip errors. However, several challenges have to be overcome in order for this concept to become a practical way to encode and manipulate error-protected quantum information. The protection must be maintained by stabilizing these highly excited states and, at the same time, the system has to be compatible with fast gates on the encoded qubit and a quantum non-demolition readout of the encoded information. Here, we experimentally demonstrate a novel method for the generation and stabilization of Schrödinger cat states based on the interplay between Kerr nonlinearity and single-mode squeezing in a superconducting microwave resonator. We show an increase in transverse relaxation time of the stabilized, error-protected qubit over the single-photon Fock-state encoding by more than one order of magnitude. We perform all single-qubit gate operations on time-scales more than sixty times faster than the shortest coherence time and demonstrate single-shot readout of the protected qubit under stabilization. Our results showcase the combination of fast quantum control with the robustness against errors intrinsic to stabilized macroscopic states and open up the possibility of using these states

as resources in quantum information processing. This experiment performed by the group of Michel Devoret at Yale university was published in [14].

## 7 Bilateral contracts and grants with industry

### 7.1 Bilateral contracts with industry

- New contracts with the start-up Alice and Bob, funding the PhD thesis of François-Marie Le Regent and Vincent Martin.

## 8 Partnerships and cooperations

### 8.1 International initiatives

#### 8.1.1 Inria International Labs

##### TAQUILLA

**Title:** Tailored quantum information protocols for quantum superconducting circuits

**Duration:** 2016 -2020

**Coordinator:** Mazyar Mirrahimi

**Partners:**

- Department of Applied Physics, Yale University (United States)

**Inria contact:** Mazyar Mirrahimi

**Summary:** In this collaboration, we were interested 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 aimed to implement error protected qubits, fault tolerant operations, and demonstrate the scalability of this approach.

#### 8.1.2 Participation in other international programs

- **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 University. This project of about 2M dollars can fund some exchanges during the coming years.
- **Yale-ARO subaward:** In the framework of the collaborations with Yale university, Quantic team has received a sub-award 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). This subaward was terminated in August 2020.
- **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. Due to the pandemic conditions, this initiative has been delayed of one-year until 2021.

## 8.2 European initiatives

### 8.2.1 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).

### 8.2.2 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 4: Ghent University.
- Alain Sarlette is participating in a Belgian (Flanders) initiative on a Bose-Einstein condensate experiment. The experiment setup is being finalized at UGent where Alain Sarlette has been teaching since 2011; he has a standby consulting role with openings for suggestions.

### 8.3 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.

### 8.4 Regional initiatives

- **DIM SIRTEQ** In the framework of the DIM program AAP PME, the DIM Sirteq is co-financing for 50 keuros the purchase of a high-sampling rate Arbitrary Waveform Generator which will be used for experiments in the project SYNCAMIL.
- **DIM SIRTEQ PhD fellowship:** We have received in 2017 a 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.
- **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.

## 9 Dissemination

### 9.1 Promoting scientific activities

#### 9.1.1 Journal

##### Member of the editorial boards

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

##### Reviewer - reviewing activities

- Philippe Campagne-Ibarcq was a reviewer for Physical Review X and Nature.
- Zaki Leghtas was a reviewer for Physical Review Letters, Physical Review X and Nature Physics.
- Mazyar Mirrahimi was a reviewer for Physical Review X Quantum, Physical Review Letters, Reviews of Modern Physics.
- Pierre Rouchon is a reviewer for IEEE TAC, Automatica and Physical Review X.
- Alain Sarlette was a reviewer for several automatic control and dynamical systems journals and conferences, as well as for Physical Review Journals and for Quantum specialized journals.

#### 9.1.2 Invited talks

- Zaki Leghtas: Neuromorphic meets quantum. C2N Palaiseau France. Invited by Danijela Markovic.
- Zaki Leghtas: Ecole Polytechnique, France. Invited by Timothée Nicolas .
- Mazyar Mirrahimi: Plenary Speaker, European Control Conference, Saint-Petersbourg.
- Mazyar Mirrahimi: Colloquium, Inria Sophia Antipolis.
- Alain Sarlette: IFAC world congress, July 2020 (speaker in invited session – virtual meeting): Quantum adiabatic elimination at arbitrary order for photon number measurement.

#### 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 is a member of the “Conseil Scientifique du DIM Math Innov” since 2017.
- Mazyar Mirrahimi is the co-president of Inria's comité des emplois scientifiques.

## 9.2 Teaching - Supervision - Juries

### 9.2.1 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 : Philippe Campagne-Ibarcq, Quantum Mechanics and Statistical Physics, Mines ParisTech, 12 hours.
- Cycle Ingénieur : Philippe Campagne-Ibarcq, Electromagnetism, ESPCI, 15 hours.
- Cycle Ingénieur : Mazyar Mirrahimi, Automatic control with Applications in Robotics and in Quantum engineering, 8 hour amphitheatre and 16 hours TD, 3rd year, Ecole Polytechnique, France.

- Cycle Ingénieur : Mazyar Mirrahimi, Control of dynamical models, 40 hours TD, 2nd year, Ecole Polytechnique, France.
- Cycle Ingénieur : Mazyar Mirrahimi, Module algorithmique quantum control, 20 hours TD, 2nd year, Ecole Polytechnique, France.
- Master: Alain Sarlette, Robotics, 24 hours, Ghent University, Belgium.
- Master: Alain Sarlette and Pierre Rouchon, Dynamics and control of quantum systems, 18 hours amphi, M2, Sorbonne Université, France.

### 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 to be defended : 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, starting date: Oct 2018.
- PhD defended: Raphaël Lescanne, Engineering Multi-Photon Dissipation In Superconducting Circuits For Quantum Error Correction, advisors: Zaki Leghtas and Takis Kontos, Defended on February 20th, 2020.
- 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.

### 9.2.3 Juries

- Philippe Campagne-Ibarcq was a PhD opponent of Daniel Weigand, TU Delft, Netherlands.
- Zaki Leghtas was in the PhD committee of Mario Gely, TU Delft, Netherlands.
- Pierre Rouchon was a reviewer of the HDR Defense of Marcin Nowicky, Poznan University of Technology.
- Mazyar Mirrahimi was in the PhD committee of Rodrigo Cortinas, Ecole Normale Supérieure.

## 9.3 Popularization

### 9.3.1 Interventions

- Philippe Campagne-Ibarcq: Telecom ParisTalks “Quantum computing, from research to engineering”

## 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. Zalusky-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. 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. 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. 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] P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zalusky-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 (19th Aug. 2020). URL: <https://hal.inria.fr/hal-03084673>.

- [12] A. Cottet, Z. Leghtas and T. Kontos. ‘Theory of interactions between cavity photons induced by a mesoscopic circuit’. In: *Physical Review B* 102.15 (Oct. 2020), p. 155105. DOI: [10.1103/PhysRevB.102.155105](https://doi.org/10.1103/PhysRevB.102.155105). URL: <https://hal.archives-ouvertes.fr/hal-03028979>.
- [13] R. Dassonneville, R. Assouly, T. Peronnin, P. Rouchon and B. Huard. ‘Number-Resolved Photocounter for Propagating Microwave Mode’. In: *Physical Review Applied* 14.4 (Oct. 2020). DOI: [10.1103/PhysRevApplied.14.044022](https://doi.org/10.1103/PhysRevApplied.14.044022). URL: <https://hal.inria.fr/hal-03084905>.
- [14] A. Grimm, N. E. Frattini, S. Puri, S. O. Mundhada, S. Touzard, M. Mirrahimi, S. M. Girvin, S. Shankar and M. H. Devoret. ‘Stabilization and operation of a Kerr-cat qubit’. In: *Nature* 584 (12th Aug. 2020), pp. 205–209. URL: <https://hal.inria.fr/hal-02379475>.
- [15] R. Lescanne, S. Deléglise, E. Albertinale, U. Réglade, T. Capelle, E. Ivanov, T. Jacqmin, Z. Leghtas and E. Flurin. ‘Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons’. In: *Physical Review X* 10.2 (May 2020). DOI: [10.1103/PhysRevX.10.021038](https://doi.org/10.1103/PhysRevX.10.021038). URL: <https://hal.archives-ouvertes.fr/hal-03065749>.
- [16] 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>.

#### Doctoral dissertations and habilitation theses

- [17] Z. Leghtas. ‘Exotic superconducting circuits to probe and protect quantum states of light and matter’. ENS Paris - Ecole Normale Supérieure de Paris, 6th Nov. 2020. URL: <https://hal.archives-ouvertes.fr/tel-03112766>.
- [18] A. Sarlette. ‘Habilitation à Diriger des Recherches (HDR)’. Sorbonne Universités, UPMC University of Paris 6, 28th Oct. 2020. URL: <https://hal.inria.fr/tel-03160258>.

#### Reports & preprints

- [19] S. Apers, F. Ticozzi and A. Sarlette. *Lifting Markov Chains To Mix Faster: Limits and Opportunities*. 5th Jan. 2021. URL: <https://hal.inria.fr/hal-03097637>.
- [20] A. Essig, Q. Ficheux, T. Peronnin, N. Cottet, R. Lescanne, A. Sarlette, P. Rouchon, Z. Leghtas and B. Huard. *Multiplexed photon number measurement*. 21st Dec. 2020. URL: <https://hal.inria.fr/hal-03084831>.
- [21] J. Guillaud and M. Mirrahimi. *Error Rates and Resource Overheads of Repetition Cat Qubits*. 21st Dec. 2020. URL: <https://hal.inria.fr/hal-03084665>.
- [22] V. Martin and A. Sarlette. *Scaling up reservoir engineering for error-correcting codes*. 21st Dec. 2020. URL: <https://hal.inria.fr/hal-03084824>.
- [23] Z. K. Mineev, Z. Leghtas, S. O. Mundhada, L. Christakis, I. M. Pop and M. H. Devoret. *Energy-participation quantization of Josephson circuits*. 21st Dec. 2020. URL: <https://hal.inria.fr/hal-03084914>.
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