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Project-Team QUANTIC

QUANTum Information Circuits

RESEARCH CENTER
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THEME
Optimization and control of dynamic systems

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Project-Team QUANTIC

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

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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 pro an enabling technology with major impact for the groups working one abstraction layer higher: on quantum algorithms but also on e.g. secure communication and metrology applications.

3. Research Program

3.1. Towards microwave quantum networks

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

Owing to the strength of its coupling to superconducting circuits [55] or Rydberg atoms [73], microwave radiation can also be prepared in many possible non-classical states. Using a sequence of quanta exchanges between superconducting qubits and a microwave cavity, the direct preparation of an arbitrary superposition of Fock states has been demonstrated in 2009 [75] with about 90% fidelity up to 5 photons. Recently, the physicists at Yale university in collaboration with the theorists of QUANTIC team, demonstrated a superposition of classical states, or Schrödinger cat, with 100 photons on average, using the dispersive coupling to a transmon qubit [122].

An important class of states for quantum information processing with continuous variables is that of the Gaussian squeezed states [123]. These states can be seen as a coherent state for which the fluctuations on a quadrature are less than the zero point fluctuations. Of course, owing to Heisenberg uncertainty principle, this comes at the expense of larger fluctuations on the conjugated quadrature. In the optical domain, Gaussian light has been demonstrated and used with single and multimodes decades ago [123]. In the microwave domain, single mode squeezing of thermal noise had been demonstrated already in 1988 [128] but vacuum noise squeezing was only demonstrated in 2008 [53]. Since then, several groups have been able to generate single- and two-mode squeezing of microwave radiation, including us [59], [125], [91], [95], [61]. The two-mode squeezed states are of particular interest for quantum information processing, because they are maximally entangled for a given average number of quanta. In particular, the circuit developed by QUANTIC's experimentalists is able to directly generate two-mode squeezed states on separate transmission lines, at arbitrarily different frequencies [61].

In the perspective of a quantum network using microwave radiation, one needs a way to store and preserve microwave fields in nodes. Arguably, creating a memory for quantum systems able to preserve indefinitely a quantum state is the next big challenge on the road towards quantum computing [56], yet unrealized in any system. In a first step, we focus on a quantum node able to preserve a quantum state for a finite time.

In the optical domain, current implementations of quantum memories [114] rely mainly on two physical effects: the light deceleration due to electromagnetically induced transparency and the transfer of photonic quantum states onto collective atomic coherences (optical or spin). In the microwave domain, several quantum memories have emerged in the last years using spin ensembles [126], [80], [109], mechanical resonators [98], [99] or superconducting circuits [127], [124], such as our device described in [62].

All these microwave implementations have pros and cons. However, only two of them, the mechanical oscillator of the Lehnert group [99] and our device [62] have demonstrated entanglement between the memory and a propagating microwave mode. Specifically, our device consists in a 3D storage microwave cavity whose coupling to a transmission line is performed using an active superconducting circuit: the Josephson ring modulator. In the frequency conversion regime, it acts as a tunable coupler whose rate is solely controlled by the amplitude of a pump signal. In the parametric down-conversion regime, it acts as an entanglement generator, similarly to the mechanical version of the Boulder group. However, the inherently small coupling rate between the transmission line and the mechanical resonator in [99] makes our device [62] a much stronger candidate for a quantum node. Apart from this crucial possibility to generate entanglement, our device is similar to the implementation of Santa Barbara [127]. Both have demonstrated fast tuning (up to 30 MHz for Santa Barbara) with high catching efficiency and storage time of 4 μs. However we believe that two specificities make our route more promising. In their case it is a flux knob which allows tuning of the transparency of a 2D microwave cavity. The core of the device we propose is a 3D storage microwave, an architecture where there is plenty of room to improve the storage time and exceed this figure by orders of magnitude, even without quantum error correction [104]. Moreover the cavity transparency is controlled solely by the amplitude of a microwave tone, free of the complications of hysteresis inherent to fast flux tuning in a superconducting environment.

The quantum information protocols one can envision using the quantum node developed by QUANTIC's experimentalists gets a useful inspiration from what has been realized in the optical domain in the last 20 years. One of the most interesting protocols we would like to implement is the teleportation of a quantum state from the memory into a transmission line or another memory. In optics, this was performed already in 1998 for a coherent state [63], and more recently for a Schrödinger-cat-like state [82]. We could readily reproduce these experiments in the microwave regime. The deterministic teleportation of a superconducting quantum bit was realized only in 2013 [118] but no experiments have shown teleportation of a continuous variable state in the microwave domain up to now. Furthermore, none of the protocols needed for quantum information processing (entanglement distillation and dilution for instance) have ever been realized in the microwave domain with Gaussian states [123]. It is thus of great interest to investigate where the tools specific to superconducting circuits will allow us to go beyond what can be done in the optical domain. In particular, the microwave quantum limited amplifiers [107] developed by QUANTIC's experimentalists lead to unmatched heterodyne measurement efficiencies. Finally using a qubit as a Fock number resolved photocounter unleashes many scenarios in the preparation and manipulation by measurement of an entangled state.

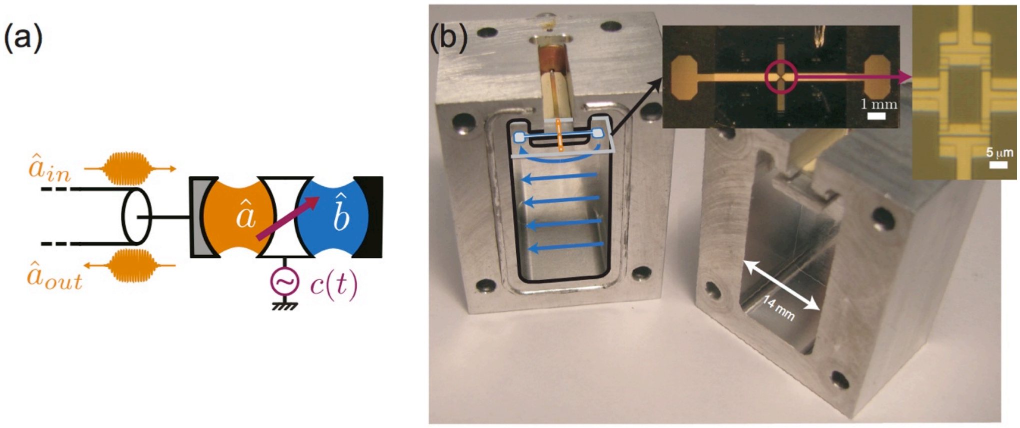

Figure 1. (a) Scheme of the quantum memory. A three-wave mixer is used as a controllable switch between a read/write cavity a and a long storage time cavity b *via the application of a control field c. (b) Picture of the first device. A 2D microstrip resonator on a Sapphire chip is dynamically coupled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

3.2. Hardware-efficient quantum information processing

In this scientific program, we will explore various theoretical and experimental issues concerning protection and manipulation of quantum information. Indeed, the next, critical stage in the development of Quantum Information Processing (QIP) is most certainly the active quantum error correction (QEC). Through this stage one designs, possibly using many physical qubits, an encoded logical qubit which is protected against major decoherence channels and hence admits a significantly longer effective coherence time than a physical qubit. Reliable (fault-tolerant) computation with protected logical qubits usually comes at the expense of a significant overhead in the hardware (up to thousands of physical qubits per logical qubit). Each of the involved physical qubits still needs to satisfy the best achievable properties (coherence times, coupling strengths and tunability). More remarkably, one needs to avoid undesired interactions between various subsystems. This is going to be a major difficulty for qubits on a single chip.

The usual approach for the realization of QEC is to use many qubits to obtain a larger Hilbert space of the qubit register [113], [117]. By redundantly encoding quantum information in this Hilbert space of larger dimension one make the QEC tractable: different error channels lead to distinguishable error syndromes. There are two major drawbacks in using multi-qubit registers. The first, fundamental, drawback is that with each added physical qubit, several new decoherence channels are added. Because of the exponential increase of the Hilbert's space dimension versus the linear increase in the number of decay channels, using enough qubits, one is able to eventually protect quantum information against decoherence. However, multiplying the number of possible errors, this requires measuring more error syndromes. Note furthermore that, in general, some of these new decoherence channels can lead to correlated action on many qubits and this needs to be taken into account with extra care: in particular, such kind of non-local error channels are problematic for surface codes. The second, more practical, drawback is that it is still extremely challenging to build a register of more than on the order of 10 qubits where each of the qubits is required to satisfy near the best achieved properties: these properties include the coherence time, the coupling strengths and the tunability. Indeed, building such a register is not merely only a fabrication task but rather, one requirers to look for architectures such that, each individual qubit can be addressed and controlled independently from the others. One is also required to make sure that all the noise channels are well-controlled and uncorrelated for the QEC to be effective.

We have recently introduced a new paradigm for encoding and protecting quantum information in a quantum harmonic oscillator (e.g. a high-Q mode of a 3D superconducting cavity) instead of a multi-qubit register [84]. 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 [78], [70] 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 [83]. Through a recent experimental work [10], 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). As shown in Figure 2, this leads to a significant hardware economy for realization of a protected logical qubit. Our goal here is to push these ideas towards a reliable and hardware-efficient paradigm for universal quantum computation.

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

Being at the heart of any QEC protocol, the concept of feedback is central for the protection of the quantum information enabling many-qubit quantum computation or long-distance quantum communication. However, such a closed-loop control which requires a real-time and continuous measurement of the quantum system has been for long considered as counter-intuitive or even impossible. This thought was mainly caused by properties of quantum measurements: any measurement implies an instantaneous strong perturbation to the system's state. The concept of *quantum non-demolotion* (QND) measurement has played a crucial role in understanding and resolving this difficulty [47]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [73], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [72]. 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 [7] (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 [58], [38], [116], [40]. 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.

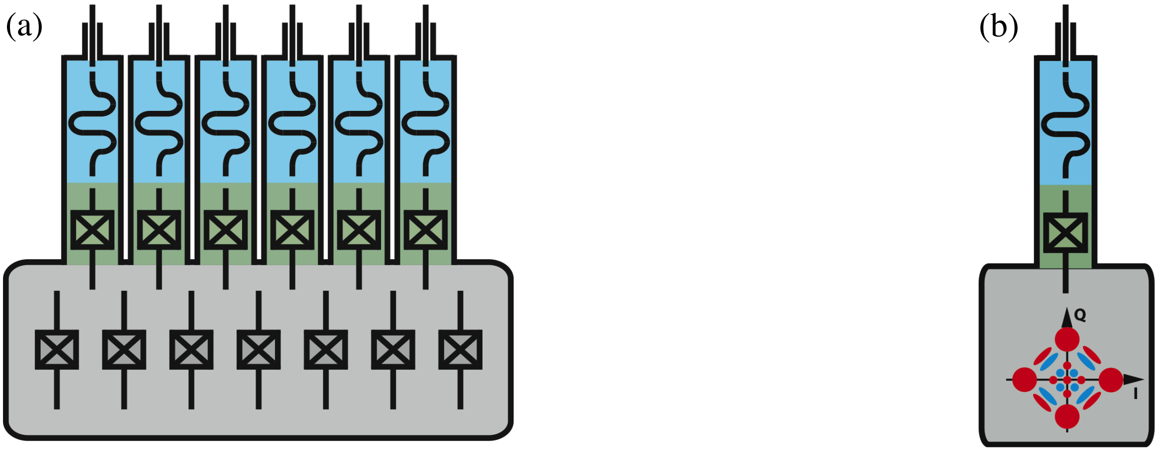

Figure 2. (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [117] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

In the context of circuit quantum electrodynamics (circuit QED) [57], recent advances in quantum-limited amplifiers [107], [120] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [74]. 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 [120], [106], [49]. 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 [92].

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 [103] and the closely related coherent feedback [89] 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 [69], single-qubit state stabilization [94], and the creation [42] and stabilization [79], [88][8] 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 or two qubits [69] [86]. The experimental results based on these protocols have illustrated the efficiency of the approach [69][8]. Through these experiments, we exploit the strong dispersive interaction [111] between superconducting qubits and a single low-Q cavity mode playing the role of a dissipative reservoir. Applying some continuous-wave (cw) microwave drives with well-chosen fixed frequencies, amplitudes, and phases, we engineer an effective interaction Hamiltonian which evacuates entropy from the qubits when an eventual perturbation occurs: by driving the qubits and cavity with continuous-wave drives, we induce an autonomous feedback loop which corrects the state of the qubits every time it decays out of the desired target state. The schemes are robust against small variations of the control parameters (drives amplitudes and phase) and require only some basic calibration. Finally, by avoiding resonant interactions between the qubits and the low-Q cavity mode, the qubits remain protected against the Purcell effect, which would reduce the coherence times.

3.4. System theory for quantum information processing

In parallel and in strong interactions with the above experimental goals, we develop systematic mathematical methods for dynamical analysis, control and estimation of composite and open quantum systems. These systems are built with several quantum subsystems whose irreversible dynamics results from measurements and/or decoherence. A special attention is given to spin/spring systems made with qubits and harmonic oscillators. These developments are done in the spirit of our recent contributions [108], [38], [115], [116], [40][6] [110] resulting from collaborations with the cavity quantum electrodynamics group of Laboratoire Kastler Brossel.

3.4.1. Stabilization by measurement-based feedback

The protection of quantum information via efficient QEC is a combination of (i) tailored dynamics of a quantum system in order to protect an informational qubit from certain decoherence channels, and (ii) controlled reaction to measurements that efficiently detect and correct the dominating disturbances that are not rejected by the tailored quantum dynamics.

In such feedback scheme, the system and its measurement are quantum objects whereas the controller and the control input are classical. The stabilizing control law is based on the past values of the measurement outcomes. During our work on the LKB photon box, we have developed, for single input systems subject to quantum non-demolition measurement, a systematic stabilization method [40]: 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 [129]; 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 [100]. 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 [74] [49].

3.4.2. Filtering, quantum state and parameter estimations

The performance of every feedback controller crucially depends on its online estimation of the current situation. This becomes even more important for quantum systems, where full state measurements are physically impossible. Therefore the ultimate performance of feedback correction depends on fast, efficient and optimally accurate state and parameter estimations.

A quantum filter takes into account imperfection and decoherence and provides the quantum state at time $t \geq 0$ from an initial value at $t = 0$ and the measurement outcomes between 0 and t. Quantum filtering goes back to the work of Belavkin [43] and is related to quantum trajectories [51], [54]. A modern and mathematical exposure of the diffusive models is given in [41]. In [131] 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 [108], [115]. This stability result is extended to a large class of continuous-time filters in [39]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [44]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [64], [96].

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 [48] that post-selection statistics and "past quantum" state analysis [65] enhance sensitivity to parameters and could be interesting towards increasing the precision of an estimation.

3.4.3. Stabilization by interconnections

In such stabilization schemes, the controller is also a quantum object: it is coupled to the system of interest and is subject to decoherence and thus admits an irreversible evolution. These stabilization schemes are closely related to reservoir engineering and coherent feedback [103], [89]. 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 [6], [8] [69], 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 [101]). 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., [37][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 [6], [8] [69], [93] 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 [68], [67]. We will start with [112] and [105] where, based on a theorem due to Birkhoff [45], 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 [119] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [90].

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 [97], 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 [121], [87] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [46], but without considering experimental implementations. A viable stabilization by interaction has to combine the capabilities of these various approaches, and this is a missing piece that we want to address.

3.4.3.1. Perturbation methods

With this subsection we turn towards more fundamental developments that are necessary in order to address the complexity of quantum networks with efficient reduction techniques. This should yield both efficient mathematical methods, as well as insights towards unravelling dominant physical phenomena/mechanisms in multipartite quantum dynamical systems.

In the Schrödinger point of view, the dynamics of open quantum systems are governed by master equations, either deterministic or stochastic [73], [66]. Dynamical models of composite systems are based on tensor products of Hilbert spaces and operators attached to the constitutive subsystems. Generally, a hierarchy of different timescales is present. Perturbation techniques can be very useful to construct reliable models adapted to the timescale of interest.

To eliminate high frequency oscillations possibly induced by quasi-resonant classical drives, averaging techniques are used (rotating wave approximation). These techniques are well established for closed systems without any dissipation nor irreversible effect due to measurement or decoherence. We will consider in a first step the adaptation of these averaging techniques to deterministic Lindblad master equations governing the quantum state, i.e. the system density operator. Emphasis will be put on first order and higher order corrections based on non-commutative computations with the different operators appearing in the Lindblad equations. Higher order terms could be of some interest for the protected logical qubit of figure 2b. In future steps, we intend to explore the possibility to explicitly exploit averaging or singular perturbation properties in the design of coherent quantum feedback systems; this should be an open-systems counterpart of works like [85].

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 [50] for the adiabatic elimination of low-Q cavity). Contrarily to the classical composite systems where we have to eliminate one component in a Cartesian product, we here have to eliminate one component in a tensor product. We will adapt geometric singular perturbations [60] and invariant manifold techniques [52] 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 [76] 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 [69][8] [86].

As particular outcomes for the other subsections, we expect that these developments towards simpler dominant dynamics will guide the search for optimal control strategies, both in open-loop microwave networks and in autonomous stabilization schemes such as reservoir engineering. It will further help to efficiently compute explicit convergence rates and quantitative performances for all the intended experiments.

4. Application Domains

4.1. Quantum engineering

A new field of quantum systems engineering has emerged during the last few decades. This field englobes a wide range of applications including nano-electromechanical devices, nuclear magnetic resonance applications, quantum chemical synthesis, high resolution measurement devices and finally quantum information processing devices for implementing quantum computation and quantum communication. Recent theoretical and experimental achievements have shown that the quantum dynamics can be studied within the framework of estimation and control theory, but give rise to new models that have not been fully explored yet.

The QUANTIC team's activities are defined at the border between theoretical and experimental efforts of this emerging field with an emphasis on the applications in quantum information, computation and communication. The main objective of this interdisciplinary team is to develop quantum devices ensuring a robust processing of quantum information.

On the theory side, this is done by following a system theory approach: we develop estimation and control tools adapted to particular features of quantum systems. The most important features, requiring the development of new engineering methods, are related to the concept of measurement and feedback for composite quantum systems. The destructive and partial [1] nature of measurements for quantum systems lead to major difficulties in extending classical control theory tools. Indeed, design of appropriate measurement protocols and, in the sequel, the corresponding quantum filters estimating the state of the system from the partial measurement record, are themselves building blocks of the quantum system theory to be developed.

On the experimental side, we develop new quantum information processing devices based on quantum superconducting circuits. Indeed, by realizing superconducting circuits at low temperatures and using microwave measurement techniques, the macroscopic and collective degrees of freedom such as the voltage and the current are forced to behave according to the laws of quantum mechanics. Our quantum devices are aimed to protect and process quantum information through these integrated circuits.

5. Highlights of the Year

5.1. Highlights of the Year

- First demonstration of Quantum Zeno Dynamics of light: this important experimental result offers a new scheme to control quantum systems based on light modes and was published in Science in 2015 [13].
- In a collaboration with the team of Michel H. Devoret at Yale university, we engineered a new form of quantum friction. By engineering a particular non-linear interaction between a quantum harmonic oscillator (a superconducting cavity mode) and a driven bath, we were able to stabilize a manifold of quantum states. This result which was published in Science in 2015 [18] should lead to a new direction of research in quantum information processing with driven dissipative systems.
- In a collaboration with the team of Robert J. Schoelkopf at Yale university, we were able to realize a version of Schrdoinger's cat thought experiment. We were able to entangle an artificial atom to a cat state of a quantum harmonic oscillator. We were able to characterize this entanglement using the Clauser-Horne-Shimony-Holt formulation of a Bell test. This result was published in Nature Communications [25].

6. New Results

6.1. Entanglement between stationary and propagating modes

Participants: B. Huard and F. Mallet.

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

The results of this section were published in [14].

Entanglement being instrumental in quantum machines, we have shown how a Josephson mixer can generate and distribute entangled microwave radiations on separated transmission lines and different frequencies by spontaneous parametric down-conversion in 2012. Using two Josephson mixers, we have provided the first demonstration of entanglement between spatially separated propagating fields in the microwave domain. Therefore, a new variety of entangled states, the so-called EPR states (after Einstein, Podolsky and Rosen), which are encoded on continuous variables, is now available in this frequency range.

In 2015, we have shown that it could constitute the central component of a potential quantum network based on continuous-variable entanglement. The device essentially acts as a regular mixer performing frequency conversion but without adding extra noise. Used as a switch, it is able to open and close the coupling to a high-quality factor cavity in a time-controlled way. We have demonstrated how this feature leads to a new kind of quantum memory. Coupled to its ability to generate entanglement, we have demonstrated the time-controlled generation, storage and on-demand release of an entangled state, which is the prerequisite for the node of a quantum network.

Several implementations of quantum memories for microwave radiation have been realized in the past few years. In order to store the state of microwave signals, some use spin ensembles [81], [130], [71], or mechanical oscillators [98], while others use superconducting cavities with tunable input coupling [124], [102]. Our own implementation is sketched in Fig. 3b, where the Josephson Mixer allows an on-demand access to the long lived 3D cavity based on noiseless frequency conversion. Its main advantage consists in the ability to generate entanglement between the memory and the output port.

Noiseless frequency conversion is another regime of the Josephson mixer. The frequency of the pump tone is now chosen to be at the difference between the frequencies of the modes $\widehat{a}$ and $\widehat{b}$, $\Omega = |\omega_a - \omega_b|$. In the rotating frame, the effective Hamiltonian reduces to a beam-splitter Hamiltonian with an implicit frequency conversion:

$$H = \hbar\chi(\widehat{a}^\dagger\widehat{b}\widehat{c} + \widehat{a}\widehat{b}^\dagger\widehat{c}^\dagger).$$

The elementary process corresponds to the conversion of photons between the mode a and b mediated by the pump at a rate $\chi|\langle\widehat{c}\rangle|$ as sketched in Fig. 3c. Therefore, the noiseless frequency conversion generates a coupling between the long lived cavity mode $\widehat{b}$ and the propagating modes at the input of mode $\widehat{a}$. This pump field can then be varied in time to switch on and off the coupling.

A first measurement consists in the capture, storage and retrieval of a microwave pulse. The protocol is quite simple, we turn the pump tone on when the incoming pulse reaches the memory input. The signal pulse has been designed such that it is optimally absorbed by the memory. The pump tone is turned off after the absorption and turned back on at a later time τ to retrieve the pulse in the transmission line. The measured output amplitude in time shown in Fig. 3d demonstrate that this protocol can be performed with a great efficiency for a few microseconds.

However, the unique ability of this device lies in the possibility to combine this storage operation with the entanglement generation demonstrated previously. A second measurement consists in the generation, storage and characterization of an EPR state distributed between the memory and the transmission line. The protocol is sketched in Fig. 4b. The pump is first applied at $\Omega = \omega_a + \omega_b$ to generate an EPR state shared between the memory and the propagating mode. The propagating mode complex amplitude is measured and at a later time, the pump is turned on again at $\Omega = |\omega_a - \omega_b|$ to activate the noiseless conversion. The memory mode is then retrieved in the transmission line and its complex amplitude is measured. By analyzing the cross-correlations between these two measurements, we have been able to show that the memory preserves the entanglement of the EPR state. Furthermore, the contours of the EPR state Wigner function have been inferred from this correlation measurement (Fig. 4c) and the entanglement quantified.

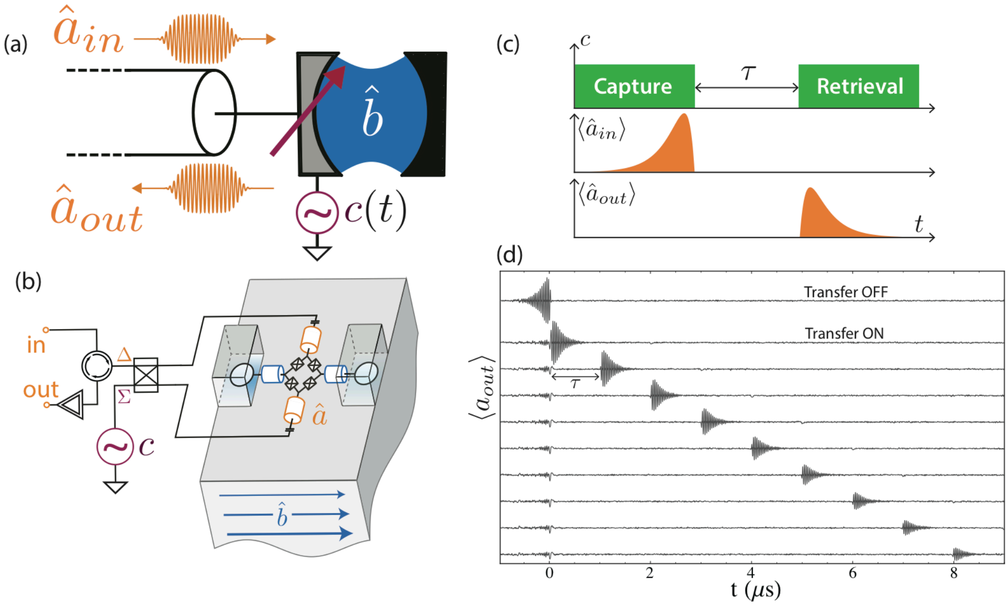

Figure 3. (a) Simplified schematics of the quantum memory. When the pump is driven at $\Omega = |\omega_a - \omega_b|$, the JRM behaves as a beam splitter with an implicit frequency conversion whose transparency depends on the pump amplitude. (b) Schematics of the device. The core of the device is similar to the usual design [107] excepted that one of the two transmission lines is replaced by a superconducting 3D cavity that defines the memory mode. (c) Protocol of the capture, storage and release of a incoming microwave pulse. (d) Measured output amplitude as a function of time. In the first trace, the pump is always turned off and the measured amplitude corresponds to the reflected incoming pulse. In the following traces, the pump is turned on and varied in time as indicated in (c). The storage time is varied from 0 μs to 8 μs.

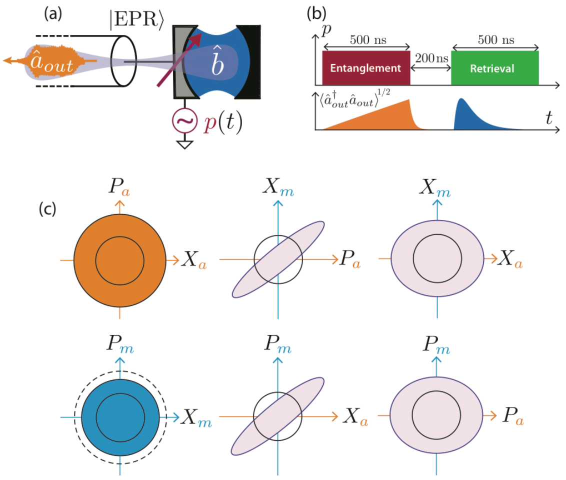

Figure 4. (a) When the pump is shined at $\Omega = \omega_a + \omega_b$, an EPR state is distributed between the transmission line and the memory. (b) Protocol for the entanglement distribution, storage and retrieval. (c) Contour of the marginal Wigner distributions reconstructed from the correlation measurements corresponding to the protocol (b).

6.2. Wideband Josephson mixer

Participants: B. Huard and F. Mallet.

The results of this section were published in [22].

For nearly a decade, the superconducting circuits community develops microwave amplifiers in the quantum regime, i.e. adding only a noise comparable to the vacuum fluctuations of the signal. We participated in this effort in 2012 [107] by adding frequency tunability to the only non-degenerate existing amplifier: the Josephson Parametric Converter (JPC) invented by the group of Michel Devoret at Yale.

However, this amplifier showed the defect of being limited to a few MHz bandwidth for a gain of 20 dB and a dynamic range (maximum input power before changing the gain) capable of amplifying signals typical of circuit-QED. We conducted a theoretical study to understand the various constraints involved in the manufacture of such an amplifier. This study has allowed us to make the first lumped element version of the JPC with bandwidth only limited by the mismatch between the characteristic impedance of the resonators and that of the transmission line.

Finally we have measured the quantum efficiency of this amplifier and obtained almost 70%, which means that only 30% of the noise power observed at the end of line comes from technical noise while 70% is the signal, including quantum noise.

6.3. Quantum Zeno dynamics

Participants: B. Huard, L. Bretheau, P. Campagne-Ibarcq, F. Mallet.

The results of this section were published in [13].

Electromagnetic modes are instrumental for realizing quantum physics experiments and building quantum machines. Their manipulation usually involves the tailoring of their Hamiltonian in time. An alternative control scheme, called Quantum Zeno Dynamics (QZD), consists in restricting the evolution of a mode to a subset of possible states. This promising control scheme had been implemented in 2014 on atomic levels of Rb and of a Rydberg atom.

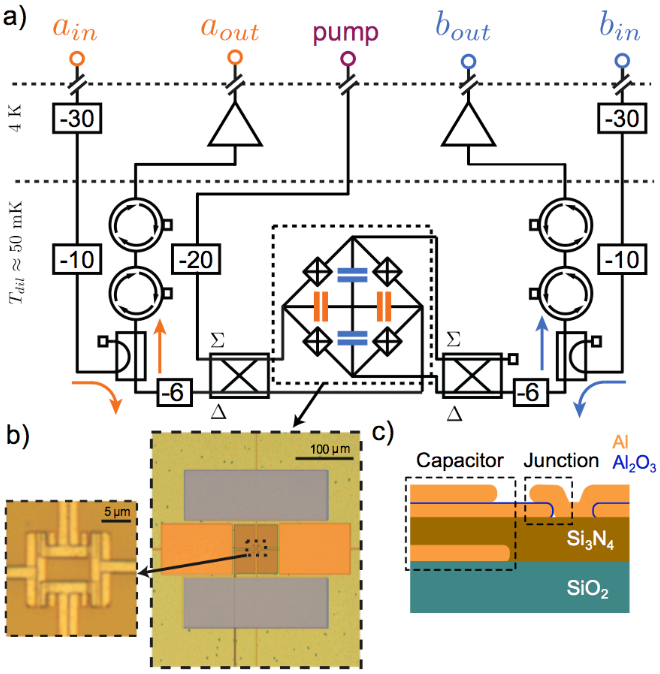

Figure 5. (a) Simplified schematic of the experimental setup. Differential a *and* b *modes of the Josephson mixer are addressed in reflection through two 180 degree hybrid couplers. All input lines are filtered and attenuated (partially shown). Output signals are separated from input signals by a directional coupler and amplified by a low noise HEMT amplifier at 4K. (b) Optical microscope picture of the device showing the planar capacitors (right) and the Josephson junction ring (left). (c) Side view of the device. The thickness of the bottom plate of the capacitors is 35 nm and buried below 200 nm of silicon nitride, the top plate of the capacitors and the Josephson junctions are obtained by double angle deposition of 100 nm and 120 nm of aluminium with an intermediate oxidation.*

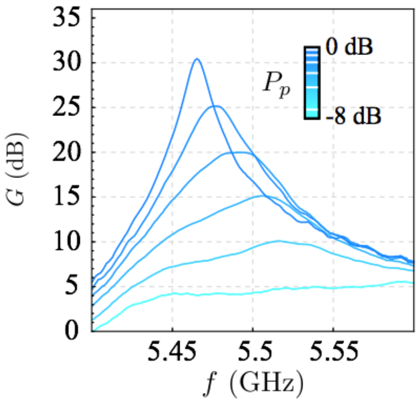

Figure 6. Gain in reflection as a function of frequency for various pump powers. The color bar encodes the pump power referred to the parametric oscillation threshold.

We have made the first observation of QZD of light, using superconducting circuits. By preventing the access to a single energy level, the dynamics of the field is dramatically changed. In this experiment, it was indeed possible to avoid a number of photons N, which was arbitrarily chosen between 2 and 5. Under this constraint, and starting in its ground state, a resonantly driven mode is confined to levels 0 to $N-1$. The level occupation is then found to oscillate in time, similarly to an N-level system. Performing a direct Wigner tomography of the field reveals its non-classical features. In particular, at half period in the evolution, it resembles a "Schrödinger cat state".

In its original definition, the quantum Zeno effect corresponds to the inhibition of coherent transitions from, or to, the pointer states of a strong measurement or dissipative process. Instead of freezing the dynamics, one can restrict it to a given subspace by choosing a measurement with degenerate eigenvalues.

Similar behavior can also be induced by rapid unitary "kicks", leaving the subspace to protect unaffected. It can be understood considering a model for the original Zeno measurement as a series of coherent interactions with ancillary systems. When the interactions are strong enough, departure from the subspace is perfectly suppressed, so that the outcome of the detector is always the same. Therefore, the ancillas are all left in the same state after the interaction and they do not need to be reset. One can then enforce Zeno dynamics by performing repeatedly unitary operations controlling the state of an auxiliary degree of freedom. This amounts to re-using the same ancilla, at the condition that the unitary evolutions are fast enough to effectively randomize the phase of coherences created with the system. In that sense, QZD is a coherent feedback, which engineers the energy level landscape of a system or its environment by coherent coupling with an ancillary degree of freedom.

In the experiment, a qubit in the resolved photon number regime plays the role of the ancillary system. A strong Rabi drive is applied on its transition conditioned on the cavity mode hosting N photons (N = 3 on Fig. 7). The drive hybridizes the levels $|N,g\rangle$ and $|N,e\rangle$ that repel each other. The level $|N\rangle$ is then moved out from the harmonic ladder of the cavity mode. When starting in the vacuum and applying a coherent drive at ω_r, the generated state cannot contain N photons so that it is restricted to N levels.

When measuring the Fock state occupation probabilities as a function of time for this effective driven N-level system, characteristic oscillations appear (see Fig. 7b). Quantum coherence of the field is revealed by direct Wigner tomography (see Fig. 7c). At half-period of the oscillations, fringes with negativities can be observed.

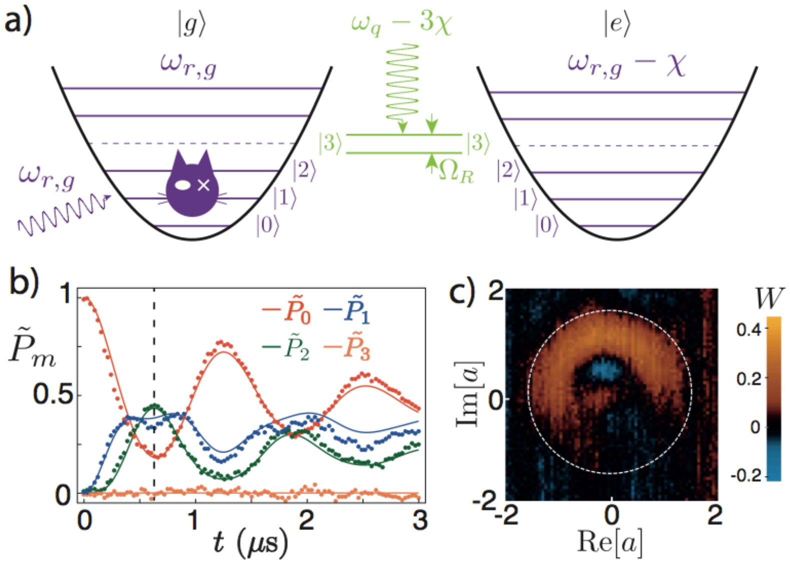

Figure 7. a) Combined energy level diagram for the qubit and cavity. By applying a strong Rabi drive on the $|3,g\rangle \longleftrightarrow |3,e\rangle$ transition, the $|2\rangle \longleftrightarrow |3\rangle$ transition of the cavity becomes off resonant at $\omega_{r,g}$. b) Oscillations of the Fock state occupation when driving the cavity mode from the vacuum and blocking $|3\rangle$. c) Wigner tomography of the field at half period of oscillation (dashed line in b). The quasi-probability density is confined within a circular barrier of radius $\sqrt{3}$ (white circle). Negativities (in blue) reveal a non classical state.

This non classical state is similar to a "Schrödinger cat state", confined in phase space within a circular barrier of radius $\sqrt{N}$.

All these observations are well captured by a model based on N levels only. Our results demonstrate that QZD allows the direct control of the field state in its phase space. This experiment paves the way to the realization of various protocols, such as phase space tweezers, generation and protection of entanglement, and quantum logic operations.

6.4. Efficient quantum filtering for quantum feedback control

Participants: Pierre Rouchon

The results of this section were published in [23].

We discuss an efficient numerical scheme for the recursive filtering of diffusive quantum stochastic master equations. We show that the resulting quantum trajectory is robust and may be used for feedback based on inefficient measurements. The proposed numerical scheme is amenable to approximation, which can be used to further reduce the computational burden associated with calculating quantum trajectories and may allow real-time quantum filtering. We provide a two-qubit example where feedback control of entanglement may be within the scope of current experimental systems.

6.5. Adaptive low-rank approximation and denoised Monte-Carlo approach for high-dimensional Lindblad equations

Participants: Pierre Rouchon

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

We present a twofold contribution to the numerical simulation of Lindblad equations. First, an adaptive numerical approach to approximate Lindblad equations using low-rank dynamics is described: a deterministic low-rank approximation of the density operator is computed, and its rank is adjusted dynamically, using an on-the-fly estimator of the error committed when reducing the dimension. On the other hand, when the intrinsic dimension of the Lindblad equation is too high to allow for such a deterministic approximation, we combine classical ensemble averages of quantum Monte Carlo trajectories and a denoising technique. Specifically, a variance reduction method based upon the consideration of a low-rank dynamics as a control variable is developed. Numerical tests for quantum collapse and revivals show the efficiency of each approach, along with the complementarity of the two approaches.

This work results from a collaboration with Claude Le Bris of the Matherials project-team and in the framework of the ANR-project EMAQS entitled "Evaluation and Manipulation At Quantum Scale" coordinated by Karine Beauchard from ENS-Rennes.

6.6. Stabilization of photon-number states via single-photon corrections: a first convergence analysis under an ideal set-up

Participants: Pierre Rouchon

The results of this section were published in [33].

This work presents a first mathematical convergence analysis of a Fock states feedback stabilization scheme via single-photon corrections. This measurement-based feedback has been developed and experimentally tested in 2012 by the cavity quantum electrodynamics group of Serge Haroche and Jean-Michel Raimond. Here, we consider the infinite-dimensional Markov model corresponding to the ideal set-up where detection errors and feedback delays have been disregarded. In this ideal context, we show that any goal Fock state can be stabilized by a Lyapunov-based feedback for any initial quantum state belonging to the dense subset of finite rank density operators with support in a finite photon-number sub-space. Closed-loop simulations illustrate the performance of the feedback law.

Paulo Sergio Pereira da Silva and Pierre Rouchon are participants to the Inria associate Team CDSS with principal Inria investigator, François Dufour of the Inria Team Project CQFD on the topic "Control of dynamic systems subject to stochastic jumps".

6.7. Convergence and adiabatic elimination for a driven dissipative quantum harmonic oscillator

Participants: Rémi Azouit, Alain Sarlette, Pierre Rouchon

The results of this section were published in [30].

We prove that a harmonic oscillator driven by Lindblad dynamics where the typical drive and loss channels are two-photon processes instead of single-photon ones, converges to a protected subspace spanned by two coherent states of opposite amplitude. We then characterize the slow dynamics induced by a perturbative single-photon loss on this protected subspace, by performing adiabatic elimination in the Lindbladian dynamics.

6.8. Parameter estimation from measurements along quantum trajectories

Participants: Pierre Six, Ph. Campagne-Ibarcq, Benjamin Huard, Pierre Rouchon

The results of this section were published in [34].

The dynamics of many open quantum systems are described by stochastic master equations. In the discrete-time case, we recall the structure of the derived quantum filter governing the evolution of the density operator conditioned to the measurement outcomes. We then describe the structure of the corresponding particle quantum filters for estimating constant parameter and we prove their stability. In the continuous-time (diffusive) case, we propose a new formulation of these particle quantum filters. The interest of this new formulation is first to prove stability, and also to provide an efficient algorithm preserving, for any discretization step-size, positivity of the quantum states and parameter classical probabilities. This algorithm is tested on experimental data to estimate the detection efficiency for a superconducting qubit whose fluorescence field is measured using a heterodyne detector.

6.9. Adding a single state memory optimally accelerates symmetric linear maps

Participants: Alain Sarlette

The results of this section are to be published in IEEE Trans. Automatic Control [24].

This work is exploring the context and benefits of so-called “non-Markovian” dynamics, where the dynamics implied by hidden variables modifies the behavior of an iterative procedure. Such mechanisms appear in both classical and quantum systems, and one of our future goals is to better characterize the benefits of engineered non-Markovianity in terms of stabilizing power in very constrained systems. The precise setting here is a discrete-time linear map, which is unknown except for a lower and upper bound on its eigenvalues. By adding one memory slot to each coordinate, this map can be accelerated quadratically. We prove that by adding more memory slots, this cannot be further improved. This is reminiscent of the acceleration of random walks by lifting them or by quantizing them, which we are currently exploring.

6.10. A common symmetrization framework for iterative (linear) maps

Participants: Alain Sarlette

The results of this section were presented at [29].

We review a “symmetrization” abstraction of iterative consensus algorithms, which allows to generalize them to general discrete group operations including those acting on quantum systems and on sequences of control actions. We highlight a few new applications of the framework including: consensus networks with antagonistic interactions; sub-stochastic matrix iterations; and coordinate descent on (locally) quadratic functions. The purpose is to show which types of iterative dynamics can be covered by this group-theoretic framework, and potentially operationally generalized to non-classical systems.

6.11. Deterministic hidden coordinate for a qubit under fluorescence measurement

Participants: Alain Sarlette, Pierre Rouchon

The experimentalists in the group have set up an experiment with continuous heterodyne measurement of an energy loss operator on a superconducting qubit. We have observed that in the associated mathematical model, due to the degeneracy of the diffusion operator, the resulting quantum trajectories are supported not in the entire Bloch sphere, but instead they belong to the surface of a *deterministically* evolving ellipsoid. We have entirely characterized this fact and highlighted that such behavior is not generic. A paper comparing this to the experimental data and a more general theory about deterministic evolutions in quantum stochastic differential equations are being finalized. This work has been presented at [28].

6.12. Relations between quantum walks, open quantum walks, and lifted walks: the cycle graph

Participants: Alain Sarlette

The convergence time of a random walk on a graph towards its stationary distribution is an important indication of the efficiency of random algorithms based on it. Quantum random walks have been shown to allow quadratically accelerated convergence for large graphs, at least in some cases. The famous Grover search algorithm has been shown to actually fit this framework in an abstracted setting (it is doing the opposite of a random walk: converging from the uniform distribution towards a particular identified element). Yet also with classical dynamics, simple mechanisms have been proposed which allow to quadratically accelerate the convergence with respect to a standard random walk. Some basic principles have been conjectured to cause this acceleration, basically transforming a diffusion-like behavior into a more transport-like behavior, but with remaining trail. We are working towards formally characterizing the effect of these principles, and extracting similar principles in the quantum walks. This should help identify key effects to be protected in the associated quantum algorithms. We currently have worked out the equivalence of all these accelerating settings for the simplest example of the cycle graph. Quantum coherences turn out to play no major role and a classical feedback structure can be identified. We are now working towards other graphs, where the convergence effect of quantum coherences might be hidden in propagating classical information. This work has been presented at [35].

6.13. Confining the state of light to a quantum manifold by engineered two-photon loss

Participants: Zaki Leghtas and Mazyar Mirrahimi

Physical systems usually exhibit quantum behavior, such as superpositions and entanglement, only when they are sufficiently decoupled from a lossy environment. Paradoxically, a specially engineered interaction with the environment can become a resource for the generation and protection of quantum states. This notion can be generalized to the confinement of a system into a manifold of quantum states, consisting of all coherent superpositions of multiple stable steady states. In a collaboration with the team of Michel H. Devoret at Yale university, we have confined the state of a superconducting resonator to the quantum manifold spanned by two coherent states of opposite phases and have observed a Schrödinger cat state spontaneously squeeze out of vacuum before decaying into a classical mixture. As suggested by our earlier work [93], this experiment points toward robustly encoding quantum information in multidimensional steady-state manifolds and should lead to significant hardware shortcuts for quantum error correction and fault-tolerant quantum computation.

This experimental work was published in Science [18].

6.14. Single-Photon-Resolved Cross-Kerr Interaction for Autonomous Stabilization of Photon-Number States

Participants: Zaki Leghtas and Mazyar Mirrahimi

Quantum states can be stabilized in the presence of intrinsic and environmental losses by either applying active feedback conditioned on an ancillary system or through reservoir engineering. Reservoir engineering maintains a desired quantum state through a combination of drives and designed entropy evacuation. In a collaboration with the team of Robert J. Schoelkopf at Yale university, we propose and implement a quantum reservoir engineering protocol that stabilizes Fock states in a microwave cavity. This protocol is realized with a circuit quantum electrodynamics platform where a Josephson junction provides direct, nonlinear coupling between two superconducting waveguide cavities. The nonlinear coupling results in a single photon resolved cross-Kerr effect between the two cavities enabling a photon number dependent coupling to a lossy environment. The quantum state of the microwave cavity is discussed in terms of a net polarization and is analyzed by a measurement of its steady state Wigner function.

This work was published in Physical Review Letters [15].

6.15. Characterizing entanglement of an artificial atom and a cavity cat state with Bell's inequality

Participants: Zaki Leghtas and Mazyar Mirrahimi

The Schrödinger's cat thought experiment highlights the counterintuitive concept of entanglement in macroscopically distinguishable systems. The hallmark of entanglement is the detection of strong correlations between systems, most starkly demonstrated by the violation of a Bell inequality. No violation of a Bell inequality has been observed for a system entangled with a superposition of coherent states, known as a cat state. In a collaboration with the team of Robert J. Schoelkopf at Yale university, we use the Clauser-Horne-Shimony-Holt formulation of a Bell test to characterize entanglement between an artificial atom and a cat state, or a Bell-cat. Using superconducting circuits with high-fidelity measurements and real-time feedback, we detect correlations that surpass the classical maximum of the Bell inequality. We investigate the influence of decoherence with states up to 16 photons in size and characterize the system by introducing joint Wigner tomography. Such techniques demonstrate that information stored in superpositions of coherent states can be extracted efficiently, a crucial requirement for quantum computing with resonators.

This work was published in Nature Communications [25].

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Emergences-Ville de Paris program, QuMotel project

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

7.1.2. PSL structuring project TOCOSUQI*

In the framework of the creation of the QUANTIC project-team, we have benefited from a 2-year PSL* funding from september 2013 to August 2015. The PSL* project TOCOSUQI (Tools of the control of superconducting quantum circuits) aims at developing new system theory tools for preparing, manipulating and protecting non-classical states of a microwave field in the framework of quantum Josephson circuits and circuit quantum electrodynamics, and applying them directly in the experiments. This project was led by Benjamin Huard.

7.2. National Initiatives

7.2.1. ANR project GEARED

This three-year collaborative ANR project, entitled “Reservoir engineering quantum entanglement in the microwave domain” and coordinated by Mazyar Mirrahimi, started on October 2014. The participants of the project are Mazyar Mirrahimi, François Mallet and Benjamin Huard (QUANTIC project-team), Daniel Esteve and Fabien Portier (Quantronics group, CEA Saclay), Nicolas Roch and Olivier Buisson (Institut Neel, Grenoble). This project deals with robust generation of entanglement as a key resource for quantum information processing (quantum simulation, computation and communication). The entangled states are difficult to generate and sustain as interaction with a noisy environment leads to rapid loss of their unique quantum properties. Through Geared we intend to investigate different complementary approaches to master the entanglement of microwave photons coupled to quantum superconducting circuits.

7.2.2. ANR project TIQS

This three-year young researcher ANR project, entitled “Thermodynamics of quantum information with superconducting circuits” and led by Benjamin Huard was run between September 2012 and August 2015. We realized two versions of Maxwell’s demon either classical or quantum, and based on superconducting circuits. This opens the way to different types of thermal machines in the quantum regime. In addition, we developed the best amplifier that is non-degenerate at radiofrequency in terms of noise and bandwidth. Finally, we have demonstrated experimentally the duality between preparation and post-selection in quantum mechanics.

7.2.3. ANR project EMAQS

Pierre Rouchon is a participant to this "Projet Blanc" entitled "Evaluation and Manipulation At Quantum Scale" EMAQS. This 4-year project started on January 2012. The participants of the project are Karine Beauchard (coordinator, ENS-Rennes), Vahagn Nersesyan and Jean-Pierre Puel (univ. Versailles), Gabriel Turinici and Julien Salomon (univ. Paris-Dauphine), Grigoriu Andrea and Yvon Maday (univ Pierre et Marie Curie), Michel Brune (College de France) and Claude Le Bris (Ecole des Ponts, Matherials project-team). The project is based on 3 thematic axis: open loop control, feedback stabilization and estimation with a specific effort towards quantum systems of infinite dimension and/or subject to decoherence.

7.3. European Initiatives

7.3.1. Collaborations with Major European Organizations

Partner 1: University of Padova

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

Partner 2: Ghent University.

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

Partner 3: University of Liverpool.

P. Rouchon is collaborating with Jason Ralph from the Department of Electrical Engineering and Electronics at the University of Liverpool on the numerical schemes for efficient quantum filtering in real-time feedback strategies. These collaborations have recently led to a publication in Physical Review A [23].

7.4. International Initiatives

7.4.1. Inria Associate Teams not involved in an Inria International Labs

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

7.4.2. Inria International Partners

7.4.2.1. Informal International Partners

Partner 1: University of Yale

The long-term collaborations with the teams of Michel H. Devoret, Robert J. Schoelkopf, Liang Jiang and Steven M. Girvin, enforced through a two year sabbatical visit of Mazyar Mirrahimi at Yale university, have led to a set of contributions ranging from the theoretical analysis and performance optimization of ongoing experiments on weak quantum measurements [74] and preparation of non-classical field states through single photon Kerr effect [77] to the design of new experiments on single qubit cooling [69] and stabilization of maximally entangled states of superconducting qubits [8] by reservoir engineering techniques. Through these collaborations, Zaki Leghtas and Mazyar Mirrahimi have introduced a new direction for hardware-efficient universal quantum computation [84], [93]. These theoretical proposals have already led to groundbreaking experiments [10], [9], [4]. We are intending to formalize these collaborations through the creation of an Inria associated team in the framework of Inria@EastCoast program.

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

Pierre Rouchon is collaborating with P. S. Pereira da Silva (Escola Politécnica – PTC, University of SaoPaulo, Brazil) and H. B. Silveira Federal (University of Santa Catarina (UFSC), Florianópolis, Brazil) on the system theory problems behind the experiment on the feedback stabilization of the photon box. These collaborations have recently led to a publication in IEEE Conference on Decision and Control [33].

7.5. International Research Visitors

7.5.1. Visits to International Teams

7.5.1.1. Research stays abroad

Mazyar Mirrahimi spent four months in the Quantronics Laboratory of Michel H. Devoret and in the Rob Schoelkopf Lab at Yale University. In this framework Joachim Cohen also spent three months in the same group. Finally, Nicolas Didier also spent two weeks at Yale University and two weeks at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific events organisation

Benjamin Huard organized and was a member of the program committee of two international conferences in 2015: the CTCQED15 conference in Dresden (1 week in June/July) and the Third Conference on Quantum Thermodynamics in Porquerolles (1 week in October).

Alain Sarlette has organized an invited session on “quantum control” at IEEE Conference on Decision and Control (CDC) 2015 in Osaka.

8.1.2. Journal

8.1.2.1. Member of the editorial boards

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

Pierre Rouchon is an associate editor of SIAM J. of Control and Optimization.

8.1.2.2. Reviewer - Reviewing activities

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

François Mallet served as a referee for Physical Review Letters .

Mazyar Mirrahimi served as a referee for Nature Comm., Reviews of Modern Physics, and Physical Review Journals.

Pierre Rouchon served as referee for IEEE Trans. Automatic Control, Automatica, System and Control Letters, and New J. of Physics.

Alain Sarlette has been a reviewer for several automatic control and dynamical systems journals and conferences.

8.1.3. Invited talks

Benjamin Huard gave an invited talk at the Colloquium of the Université de Sherbrooke, Canada, June 2015.

Benjamin Huard gave an invited talk at the PIERS conference, Prague, July 2015.

Benjamin Huard gave an invited talk at the Colloquium of the Physics department, University of Basel, Switzerland, Oct 2015.

Benjamin Huard gave an invited talk at the workshop of University of Tokyo- Ecole Normale Superieure, Tokyo, Japan, Nov 2015.

Philippe Campagne-Ibarcq gave an invited talk at the “Congrès du GDR IQFA”, Palaiseau, France, Novembre 2015.

Philippe Campagne-Ibarcq gave an invited talk at the American Physical Society’s March Meeting in Saint Antonio, Texas, March 2-6.

Benjamin Huard and Mazyar Mirrahimi gave invited talks at the conference organized for the 30 years of Quantronics: Paris, June 22-25.

François Mallet gave an invited talk at the 14th International Conference on Squeezed States and Uncertainty Relations In Gdansk, 29 June- 3 July.

Mazyar Mirrahimi gave an invited talk at the Frontiers of Quantum and Mesoscopic Thermodynamics (FQMT) conference in Prague: July 27-August 1.

Mazyar Mirrahimi gave an invited talk at the Gordon Research Conference on Quantum Control of Light and Matter: Mount Holyoke College, MA, August 2-7.

Mazyar Mirrahimi gave an invited talk at Quantum Science Symposium in Cambridge, MA: Sept 21-22.

Pierre Rouchon gave an invited talk at the Workshop on Control Systems and Identication Problems January 12-16, 2015 in Valparaso, CHILE.

Mazyar Mirrahimi and Pierre Rouchon gave invited talks at the Oberwolfach Workshop on Mathematical Methods in Quantum Molecular Dynamics.

Pierre Rouchon gave an invited talk at the PRACQSYS meeting in Sydney: 20-25 July 2015.

Alain Sarlette gave an invited talk at the International Conference on Industrial and Applied Mathematics (ICIAM) in Beijing, August 10-14.

Alain Sarlette gave an invited talk at the second international conference on Geometric Science of Information in Palaiseau, France, Oct 28-30.

8.1.4. Scientific expertise

Benjamin Huard was a member of the ANR CES30 committee in 2015.

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

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

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

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

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

Benjamin Huard has taught a “préceptorat” (16 hours) in Quantum Physics for L3 students in ESPCI, Paris.

François Mallet has taught approximately 192 hours as a university associate professor. Besides undergrad teaching, he has done classes on quantum physics (30 hours) and solid state physics (15 hours) for M1 at UPMC, and quantum transport for M2 ICFP (20 hours).

Mazyar Mirrahimi and Pierre Rouchon have given a course (20 hours) entitled "UE : Analyse et contrôle de systèmes quantiques " in the "Master de sciences et technologies, mention mathématiques et applications, Université Pierre et Marie Curie".

Pierre Rouchon has given a course (25 hours) entitled "Cryptographie, théorie des nombres et information quantique" at Mines Paristech.

Pierre Rouchon has given a course (12 hours) entilted "Modelling, simulation and feedback of open quantum systems " in the "module d’Ingénierie Quantique" of the "parcours doctoral de PSL-ITI".

Pierre Rouchon and Alain Sarlette gave a one week course (22 hours) on feedback control of quantum systems in the European Embedded Control Institute in 23-27 March 2015.

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

8.2.2. Supervision

PhD: Philippe Campagne-Ibarcq successfully defended his PhD thesis at ENS in June 2015. He presented his works on “Measurement back action and feedback in superconducting circuits”. (advisor: Benjamin Huard).

PhD: Pascal Combes, Mines Paristech. “Control of electrical drive” with Schneider-Electric. He has obtained his PHD in December 2015. (advisors: Pierre Rouchon and Philippe Martin).

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

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

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

PhD in progress: Joachim Cohen. ENS. “Fault-tolerant quantum computation for experiments in circuit QED”. Nov 2013 (advisor: Mazyar Mirrahimi).

PhD in progress: Noad Hamze El Badaoui. Mines Paristech. “Real-time estimation for Laser Gyroscope” with Thales. January 2013. (advisors: Pierre Rouchon and Philippe Martin).

PhD in progress: Pierre Six. Mines Paristech. “Parameter and quantum state estimation relying on quantum measurements”. Sept 2013. (advisor: Pierre Rouchon).

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

PhD in progress: Alain Sarlette is co-supervising 3 PhD students with his former institution UGent (Simon Apers, Zhifei Zhang, Arash Farnam). Simon Apers is working on (quantum) network algorithms accelerations and intends to address other quantum control questions.

8.2.3. Juries

Benjamin Huard was a member the PhD defense committees of Kevin Lalumière (Université de Sherbrooke, Canada), Eric Holland (Yale University, New Haven, CT USA) and Pasi Lähteenmäki (Aalto University, Finland).

Pierre Rouchon was a member the PhD defense committees of Achraf Kallel (Mines ParisTech, Sophia Antipolis), Axel Barrau (Mines ParisTech), Giovanni De Nunzio (Université de Grenoble), Philippe Laurent (Université de Nantes).

8.3. Popularization

Benjamin Huard gave a talk at Journée X-ENS, Ecole Polytechnique, Palaiseau, France (May 2015) in front of an assembly of professors in “classes prépas”. He also gave a seminar for students at ENS Paris (Jan 2015).

Benjamin Huard, François Mallet and Mazyar Mirrahimi gave interviews for newspapers, magazines and websites (Libération, La Recherche, Phys.org, les Echos, 01net, Silicon).

Benjamin Huard wrote an article for La Recherche: B Huard, Les microprocesseurs du futur, La Recherche 501, 62 (Juillet 2015).

Pierre Rouchon gave a lecture on "Stabilisation par feedback quantique de la boite à photons du LKB" (May 21, 2015) during the "journées de l’école doctorale des Universités de Bourgogne et de Franche Comté".

Alain Sarlette is answering questions about quantum control and quantum computing on the website "ik-heb-een-vraag.be" where Flemish layman can ask questions to scientific experts.

9. Bibliography

Major publications by the team in recent years

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[2] L. Bretheau, P. Campagne-Ibarcq, E. Flurin, F. Mallet, B. Huard. *Quantum dynamics of an electromagnetic mode that cannot have N photons*, in "Science", May 2015, vol. 348, 776 p. [*DOI :* 10.1126/science.1259345], https://hal.archives-ouvertes.fr/hal-01154446

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[11] P. CAMPAGNE-IBARCQ. *Measurement back action and feedback in superconducting circuits*, Ecole Normale Supérieure (ENS), June 2015, https://hal.archives-ouvertes.fr/tel-01248789

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