Grant Agreement n. 233747

Information and Communication Technologies

“Collective quantum operations for information technologies”

PROJECT FINAL REPORT

Grant agreement number	233747
Project acronym	COQUIT
Project title	Collective quantum operations for information technology
Funding scheme	Collaborative project
Period covered	1.5.2009 – 30.9.2012

Name, title and organization of the scientific representative of the project's coordinator:

Dr. Michael Keyl

Fondazione Istituto per l'Interscambio Scientifico (ISI)

Via Alassio 11/c 10126 Torino – Italy

Tel: +390116603090 – Fax: +390116600049 – E-mail: projects@isi.it

Project website address: http://coquit.isi.it/COQUITWiki

Table of Contents

4.1. Final publishable summary report

4.1.1 Summary

The purpose of the COQUIT project was to study quantum systems which allow only a partial control by a constrained set of quantum operations. Typical examples are many particle quantum systems like cold atoms in optical lattices or other multi-atom ensembles, which can be manipulated collectively but not individually. Such restrictions are currently one of the biggest obstacles against working quantum devices.

To get a detailed understanding of the potentials and – in particular – restrictions of current technical equipment and techniques we have gathered (with the help of a number of outstanding experimental groups) information about existing experiments and experimental techniques, and brought them into a form which is appropriate for further theoretical analysis. This research led to a number of models for limited control tailored for different contexts like gate models, lattice systems or continuous variable systems. Based on these results we have developed a number of applications which finally led to a number of exciting new experimental proposals, which have already in part been realized. In parallel to this application oriented research line, we have also made advances on more general, model independent theories which have the potential for significant impact in several areas, particularly on the theory of the simulation of quantum systems.

Major scientific highlights of the project include:

- A general theory of quantum circuits suitable for optimization purposes.
- A detailed structural theory of quantum cellular automata.
- New applications of continuous variable systems including in particular Bell inequalities and the simulation of quantum fields.
- We have advanced the theory of matter-light interactions by using mean-field methods. In this context we have made proposals for multi-mode quantum memory.
- Fault ignorant quantum computation – a new concept to deal with noise – was introduced.
- Several exiting new experiments including the simulation types of quantum walks, quantum reading and higher-order quantum computation were proposed.

4.1.2 Project context and objectives

In spite of the remarkable progress in the experimental control of quantum systems achieved in recent years, the goal of building a quantum computer has remained rather elusive. In theory the requirements seem quite simple: one has to realize only a small set of quantum operations, known as a “universal gate set”, from which arbitrarily complex quantum operations can then be composed. Several experimental projects, using quite different physical systems, have by now achieved the goal of providing such a gate set, at least in principle. Yet none of these systems has achieved the accuracy and the composability, which would allow the realization of a large scale quantum computation.

Typically, in each realization there is a set of “easy” operations, which can be performed quickly and with high fidelity. On the other hand, some operations in the universal gate set may be “hard” in the sense that they require much larger experimental effort, hence typically require longer time, and are subject to more error sources. The basic idea of this project is to take this distinction seriously, and to develop theoretical tools to deal with it, and to make more efficient use of the easy operations.

Moreover we want to address the still unresolved question of scalability. This is a rather essential restriction for most of the current experimental proposals. We are therefore particularly interested in possibilities to design algorithms which can be implemented in terms of easy operations on many particle quantum systems. We expect that this class is already big enough to address interesting problems not just on a “proof of concept” stage but also on a level which is potentially useful beyond the quantum information community.

The core of the project will be the utilization of the easy/hard distinction, with a particular focus on large scale systems. The concrete objectives are the following:

- **Easy vs. hard.** Analyze the distinction between easy and hard operations in concrete experimental situations and express it in an abstract implementation independent way. Important in this context are in particular quantitative statements, because the easy/hard distinction will never be absolute. A full account of the system should therefore assign “control costs” to each operation, and the aim of the theoretical analysis would be to find a sequence of operations minimizing the overall costs.
- **Computational power.** For a given set of quantum gates, together with a classification of easy and hard operations we will investigate the computational

power. This includes in particular the question, whether the given set can be simulated efficiently on a classical computer. Results on the contrary would point us towards problems which can not be solved efficiently on a classical computer.

- **Errors.** The identification and furthermore the analysis of reasonable error models is also a major part of our research program. For example even easy operations are subjected to noise. Hence, one question will be to analyze how a product of easy operations may drift away from the mathematically defined easy subgroup. More generally, we will look at error correction under the special conditions of a distinction between easy gates and hard gates, as well as high fidelity gates vs. noisy gates.
- **Quantum simulations.** We want to find interesting applications for the easy gate sets identified so far. Even if a model is to restrictive to allow for universal quantum computation, it is not necessarily useless. Indeed the simulation of a specific quantum system does not need quantum gates which can generate all possible quantum operations, but only those which allow for an approximation of the time evolution induced by the system's Hamiltonian. An important subproblem concerns again classical simulability. Since in the foreseeable future only a few “hard” operations will be possible in an experiment, it is of interest to see just how far one can get with a fixed number of these while the rest of the algorithm can run on a classical computer.
- **Drafting new experiments.** Of course, the extensive theoretical study of realistic restriction models will not only answer questions about their computational power, but will also point us towards new setups. Hence, another major part of our research program will consist of developing proposals for new experimental setups explicitly taking into account experimental imperfections as discussed with our experimental partners. Moreover, our analysis will help to identify roadblocks, i.e., experimental limitations whose removal would be especially rewarding.

4.1.3 Main S&T results/foregrounds

To achieve the goals described in the last section, the project had to bridge concrete experimental experiences in many different areas of quantum information science with abstract theoretical and mathematical concepts. To guarantee a sufficiently intensive flow of information in both directions, the proposal followed two different strategies: Since the project was, nevertheless, purely theoretical, the consortium joined few theory groups, each of which with outstanding expertise in abstract quantum information theory, *as well as* at least one more specialized area such as quantum optics or many particle physics. They were supplemented by a small number of leading experimental scientists which cover different areas of experimental quantum information (NMR quantum computation, quantum optics, atomic ensembles, optical lattices and microfabricated optical devices). Their task was to supply the information about possibilities and limitations of current experimental setups which was crucial for the success of the project.

The second strategy we followed was the special organization of the project into work packages and their relation to each other. The basic idea was to divide the six scientific work packages into three main groups resembling different levels of abstractness.

- Work package WP1 was devoted to the interface between concrete experimental implementations and the lowest level of theoretical abstraction. The task was in other words to gather information about current experiments and to formulate them in a language concrete enough to suit the needs of the experimental partner groups, while being at the same time powerful enough to allow further abstraction in other work packages. A second important objective was to check the more abstract results of other work packages for experimental feasibility and to make concrete proposals for new experiments
- The information gathered in WP1 was processed in WP2, WP3 and WP4 each of which was devoted to a different type of experimental limitation: non-universal sets of gates in WP2, lattice models suffering from limited addressability in WP3, and in WP4 the need for non-Gaussian operations within continuous variable modes. The mathematical language used here was much more abstract than in WP1 and perfectly suited for the needs of the systems in question. This included groups of unitaries like Clifford gates in WP2, quantum cellular automata in WP3 and phase-space quantum mechanics in WP4. The objectives were: to reformulate the results from WP1 accordingly, to develop an appropriate structure theory, and to apply the

abstract methods to be developed in WP5 and WP6.

- The last group consisting of WP5 and WP6 represented the highest level of abstraction. Here the results from WP2, WP3 and WP4 were generalized and supplemented, to form a general theory, being as far as possible implementation independent. The main objectives were to develop approximation methods (which allow to decide whether a given information theoretical tasks can be performed within a given setup), design guidelines for the implementation of such tasks (both in WP5), and strategies to cope with errors and decoherence (in WP6).

4.1.3.1 WP1. Experimental interface

The COQUIT project aimed at a systematic study of the quantum computational tasks which can be performed already with present-day technologies. Among the six research work packages which were developed for this reason, WP1 played a quite special role. Its objective was to collect and summarize information about current experimental setups for the purpose of further theoretical analysis in the rest of the work packages (WPs 2-6). At the end of the project we have used the theoretical models developed that way to go back to the experimentalists and to make explicit proposals for new experiments and improvements of general methods of operation.

Gathering information

To achieve the first aim, it was important to gather enough reliable information from research groups that have been dealing with different aspects of experimental quantum information. For this reason we contacted and visited five outstanding experimental partner groups (R. Blatt, Innsbruck; I. Bloch, Munich; S. Glaser, Munich; J. O'Brien, Bristol; E. Polzik, Copenhagen), and organized a series of workshops.

- Coquit project meeting “Atomic Ensembles”, Copenhagen, July 21-24 2009
- (hosted by the group of E. Polzik)
- Coquit project meeting “Optical lattices and NMR Quantum Computing”, Munich, November 22-26,2009 (hosted by the groups of I. Bloch and S. Glaser)
- Coquit project meeting “Ion traps”, Innsbruck, January 27-29, 2010 (hosted by the group of R. Blatt)
- Coquit project meeting “Microfabricated Optical Circuits”, Bristol, April 25-28, 2010

(hosted by the group of J. O'Brien)

In the course of collecting information from our experimental partners, our efforts concentrated on finding and selecting the common aspects of the different approaches. To compare the various experiments, we elaborated a series of questions about the current status of implementable quantum information devices, concentrating on their limitations, i.e., which operations can be performed and which cannot, and which are the main sources of errors. We wanted to be acquainted with the opinions of our partners on the following four big topics:

1. **System.** As a first step we wanted to understand what the whole system studied in the experiment is composed of, more precisely, what are the subsystems which can be identified either as experimental or theoretical entities. Furthermore, we wanted to know which of these parts are treated classically and which quantum mechanically. We asked them to describe the effective system Hamiltonian, including which part of the Hamiltonian can be tuned and controlled. Finally, we requested answers on the experimentally accessible observables, i.e., which quantities they measure in the labs.
2. **Approximations.** This second big topic includes the following issues: what are the standard approximations and their empirical and theoretical justification; what are the different types of possible choices of truncations of the whole Hilbert space; what are the levels with physical “meaning” and levels nearby which have to be included for the simulation of the dynamics; how to identify useful levels (working levels, allowed ancilla levels).
3. **Operations and Control.** This topic includes the following two main questions. Firstly, which quantum operations can be performed, which are the “easy” operations, i.e., which can be performed many times easily with high fidelity? Secondly, what are the tunable parameters and how well can the change of parameters be controlled, monitored and verified?
4. **Errors.** Finally, we were also interested in the most important and typical sources of errors in the different experiments.

The conclusions of the results of the workshops and the opinions of our experimental partners regarding the four main topics above are summarized at the Internet page [1]. Although we did not get in any case the information we asked for (or not as precise as expected) this part of the project was very fruitful and influenced several research lines in other work packages in an essential way. This includes in particular:

1. The general theory of quantum circuits developed in WP2, and in particular its application to passive optical devices.
2. A detailed study of quantum walks in WP3 which led to an intensive collaboration with various experimental groups, including several experimental proposals and implementations.
3. In WP3 and WP4 we studied several aspects of matter-light interactions, which were mainly motivated by the Copenhagen meeting. Apart from an intensified collaboration with the group of E. Polzik, this includes in particular the development of mean-field techniques.
4. The visit of the group of S. Glaser initiated a close collaboration concerning various aspects of quantum control, which lead important results in WP5.

Experimental proposals

Already in the first project year, much earlier than expected, we were able to provide important feedback to experimentalists. This development continued during the second and third year of Coquit, such that we are now able to present a number exciting, new experiments and several powerful new techniques and tools. They are summarized in the following. A more detailed description can be found in the Third Year Report.

Quantum walks

In WP3 a lot of research is done concerning quantum walks. This has lead to three contributions with important experimental implications. Corresponding experiments are already carried out or under consideration.

Molecular binding in interacting quantum walks. We showed that the presence of an interaction in the quantum walk of two atoms leads to the formation of a stable compound, a molecular state. A setup for the experimental realization is proposed in addition to a sketch of the possibility to observe quasiparticle effects in quantum many body systems. [2]

Quantum Walks with Non-Orthogonal Position States. We have developed a theory for quantum walks using non-orthogonal position states. This allows for substantial improvements in experimental implementations, including in particular experiments with smaller step size and more steps. [3]

Time-reversal symmetry breaking quantum walks. We have investigated how breaking time-reversal symmetry in continuous time quantum walks can enable directional control, enhancement, and suppression of quantum transport. [4]

Matter-light interactions

We have made progress in setting up the theoretical framework for atomic-ensemble quantum memories that can store many-mode states of light. The mean-field analysis of matter-light interactions described in WP3 leads furthermore to better understanding of noisy states which are far away from the fully depolarized case. This is a crucial improvement in handling decoherence of such systems. [5][6][7][8]

Quantum Reading

Quantum reading is a method to use quantum information techniques for reading classical information stored in optical memory (cf. WP2). Our research lead to an experimental realization by the group of M. Dusek. [9][10]

Higher-order quantum computation

We considered a new kind of quantum computation, where the connections between gates are themselves programmable on the state of quantum registers (cf. WP2). A first experiment was drafted in detail by the Quantum Optics group at Northwestern University, Illinois. [11][12][13]

Tools and techniques

In addition to explicit proposals for new experiments we have also provided a number of techniques which can significantly improve existing experiments and help to plan new ones; cf. also WP5.

Compressed sensing. We have developed an algorithm for quantum tomography which is basically the quantum version of the highly successful theory of "compressed sensing". It can reduce the complexity of the classical post-processing in many experimental situation [14][15]

Quantum control with Fermions. We have developed a control for Fermions. It makes existing control algorithm available for the design of experiments with Fermionic systems. [16]

4.1.3.2 WP2. Gates

Task 2.1. Restricted gate sets

The aim of this task was to design quantum circuits subject to restrictions in the availability of quantum gates.

If a set of gates is not universal its computational power is usually limited. This is known from Clifford gates and matchgates. In [17] we have complemented these results with the surprising fact that IQP circuits (i.e. circuits involving only commuting gates) can not be efficiently simulated classically (or the polynomial hierarchy collapses).

To consider more sophisticated restrictions we have developed a general theory of circuit optimization, the theory of “Quantum combs” [18]. We have applied it to quantum automatic learning [19] and to an impossibility proof for quantum bit commitment [20].

Input from WP1 was used for some work that started at the end of the first year and is still in progress. This consists in the formulation of a general theory of computations that can be performed through some particular micro-fabricated optical circuits that the group of J. Rarity and J. O’Brien in Bristol showed during the WP1 phase. In this context, the comparison of suboptimal circuits—involving only “cheap” gates (i.e. those acting on a single qubit) and a limited amount of “expensive” ones (i.e. those involving two-qubits)—with optimal circuits can be easily formulated in an algebraic framework.

Task 2.2. Computational power of restricted gate sets

Identify criteria for classical simulability and evaluate the results for the gate sets under consideration. Investigate the applicability of the gate set (identified in WP1) to quantum computational tasks beyond the classical.

Restricted gate sets are often related families of simple groups. We have concentrated in particular to orthogonal groups which belong to quasi free Fermionic systems. In this context we have studied entanglement distillation [21] and quantum control [16].

Another approach starts from the theory of quantum combs, mentioned in Task 2.1. Within this theoretical framework it is possible to represent every admissible quantum circuit through a single positive operator. In [22] an algorithm was developed which generates a concrete implementation of a protocol (i.e a sequence of isometries) from its associated Choi operator. Related results can be found in [11] where a complete classification of extremal elements in the convex set of Choi operators representing quantum protocols was provided, and [23] where the amount of quantum memory (in terms of the dimension of the Hilbert space) which is needed at any step of a given quantum protocol is quantified.

Task 2.3. Cost functions and reachable computations

Assign different costs to the available operations and estimate (and where possible minimize) the overall cost of the computation.

For general many-body systems, during the first year the LUH investigated the implementation of natural dynamics via controlled k-body interactions in the gate model. We achieved it for the case of particles on a lattice [24]. Our plan is to obtain a sub-Riemannian geometry arising from 2-body interactions. Further we want to investigate the time complexity of effective k-body interactions and the asymptotic realizability of general unitary operations in polynomial time.

During the third year, the theory of combs was expanded and completed with a crucial feature that is aimed to tackle one instance of task 2.3: The minimization of the memory cost of a given computation, keeping the performances unchanged [23].

Task 2.4. Theoretical description of typical errors

Identify typical errors occurring in experimental setups and include them in our theoretical model. Provide classification schemes by means of structural similarities. Refine this analysis via WP1. Provide knowledge for error handling strategies tackled in WP6.

We have abandoned this task after our approach towards errors changed substantially. For details cf. the discussion in the last year report.

Task 2.5. Implementable strategies and protocols

Identify optimized feasible protocols by maximizing a suitable figure of merit over all constrained ones by handling constraints, e.g., through the well-established method of Lagrange multipliers.

Using comb theory, in the second year UNIPV solved the optimization of information/disturbance tradeoff in the estimation of a unitary channel [25], and in the third year learning [26] and cloning [27] of von Neumann POVMs. It is remarkable that, applying the result of Ref. [22], simple implementations for all these protocols were provided, which are feasible with current technology. Furthermore we have analyzed circuits containing only passive optical devices using the linear optics counterpart of the general theory of quantum circuits developed in the first year [28]. As an additional line of investigation we studied the discrimination of linear passive optical devices [9]. A proposal for an experimental realization of this last application is under examination. Besides these lines of research during the second year we studied the possible connection between the causal structure of a quantum protocol and the resources needed in order to implement it [29]. Finally the optimization of protocols was fruitfully continued in the last year with the analysis of the general problem of parallelization and optimization of tasks involving the transformation of a given representation of a group of gates (oracles) to a different representation [30].

Task 2.6 Error-influence on computational power

Examine the dependence of the computational power on type and strength of errors and its propagation while computation. Evaluate complexity criteria under the presence of noise. Investigate how different types of errors amplify each other.

Based on the independent error model, during the second year UNIPV studied the correction of quantum measurements [31]. In collaboration with the CORNER project, UNIPV considered error correction in the presence of correlated noise, which is typical in correlated systems like ions in optical lattices, or liquid and solid state NMR samples. This analysis was published in Ref. [32]. Finally, in [33] we analyzed under which circumstances two operations, each of which is specified by a pair of states (reflecting input and output), can be implemented simultaneously.

Task 2.7 Drafting proposals for new experiments

Produce proposals for new experiments in supporting activities of WP1.

Quantum reading. Quantum reading can be schematized as an optical implementation of information encoding into quantum gates rather than states. The idea of quantum reading is based on the observation that digital optical memories store classical information in the optical properties of a media. In the engineering of optical memories and readers, a tradeoff among several parameters must be taken into account. High precision in the retrieving of information is surely an indefeasible assumption, but also energy requirements, size and weight can play a very relevant role for applications. In quantum reading of optical devices, the quantum properties of light are exploited in order to retrieve some classical digital information stored in the optical properties of a given medium, making use of as small amount of energy as possible. In this context quantum reading of optical devices can be recast as a discrimination among different optical devices, with low energy and high precision. The experimental realization was performed thanks to a collaboration between the Pavia node and M. Dusek’s group at the Department of Optics, of the Palacky University, Czech Republic [10][9].

Higher-order quantum computation. In Ref. [11][12] the Pavia node considered a new kind of quantum computation, where the connections between gates are themselves programmable on the state of quantum registers. It was shown that these dynamical quantum networks are more powerful than the usual quantum computers in the sense that they reduce the query complexity for some tasks. This was proved for the case of programming the permutations of N different unitary channels, where the number of uses of each input channel is dramatically reduced from N to 1. The ultrafast switch of Ref. [34] is a sufficient optical element for the implementation of the quantum switch, being able to route entangled photons at high speed without disturbing the quantum state. This practical possibility makes the implementation of QS feasible in the near future, opening important new options and perspectives in the design of new quantum algorithms. The experiment was drafted in detail by the Quantum Optics group at Northwestern University, Illinois, as reported in Ref. [13].

4.1.3.3 WP3. Lattices

In this work package we have investigated spatial constraints of quantum system. The main reason for having devoted a separate work package to this issue is that they play an important role in the experiments (ion traps, optical lattices, etc.).

Task 3.1 Theoretical description of the experimental setups

Use the concept of quantum cellular automata (QCA) and incorporate the restrictions identified within WP1. Obtain a theoretically manageable dynamical description of the exp. setup.

The basic theoretical tool for the description of lattice systems with large scale translation invariance is a quantum cellular automaton. In this work package we identified restrictions of experimental setups to obtain theoretically manageable descriptions for the implementation of quantum cellular automata (QCA) in these setups. This task has been finished within the first year and has output the publications [35][36][37]

Task 3.2 Classical vs. quantum simulation

Identify such QCAs being complex enough to solve classically intractable simulation problems. Separate for a given simulation problem the subparts which admit an efficient classical description from the ones which can only be done by a quantum simulator.

Within this task we investigated the fractal structure of cellular automata on abelian groups, i.e. Clifford cellular automata. This task has not been fully finished, in particular due to change of personnel, but still has led to interesting results summarized in the following publication: [38]. We plan to build future research in this achievement.

Task 3.3 Models of typical errors

Identify typical errors occurring in experimental setups for lattice systems and include them into our theory, in particular, in view of non-translationally invariant reversible QCAs and irreversible QCAs. Refine this analysis via WP1. Provide knowledge for error handling strategies tackled in WP6.

In this task, which is closely tied to task 3.5, we focused on error models for quantum walks, which can be considered as a basic building block for general QCA. The results include the asymptotic evolution of quantum walks with random coin [39] and disordered quantum walks in one lattice dimension [40]. See the second-year report for details. Further related results are summarized in task 3.5.

Task 3.4 Quantum codes

Linked to the results from WP1 and WP6, give construction procedures for quantum error correcting codes under restricted control upon the lattice system. Clarify, according to experiments, which models are implementable and how such a system could be manipulated. Analyze the computational complexity of topologically ordered systems.

In this task we investigated the memory requirements for convolutional codes [41], throughout the runtime of Coquit. The research on the computational complexity of topologically ordered systems has not been finished, in particular, because of the lack of suitable methods. However, the distal split property, which was recently developed, constitutes such a method. Research on this is in progress, as described in detail in the third-year report.

Task 3.5 Error-influence on the computational power

Examine the dependence of the computational power on type and strength of errors and its propagation while computation. Investigate the interplay between different error-types, i.e. boundary-conditions and lattice defects. Derive bounds on the number of steps that can be executed by a QCA, before a given error-threshold is exceeded.

In this task we gained several results, spreading over a diverse range of models. On the one hand, we investigated the influence of different error models in quantum walks [3][42]. On the other hand, we investigated the influence of the necessary continuous monitoring in search algorithms [43]. Furthermore, we investigated simulation issues of quantum channels and the local approximation of observables and commutator bounds [44][45][46]. Details on these results are given in the third year report.

Task 3.6 Drafting proposals for new experiments

Produce proposals for new experiments in supporting activities of WP1.

Building on the results of the previous tasks, we developed proposals for *Simulating Quantum Fields with Cavity QED* [47], the implementation of *Quantum Walks with Non-Orthogonal Position States* [3] and simulating *Molecular binding in interacting quantum walks* [2]. With these results, for which the details are given in the third-year report, the task can be considered to be finished. However, with the ongoing project of fluctuations of mean-field quantum systems (See task 3.7) it is expected that the improved description of matter-light interactions will lead to new ideas for experiments. Furthermore we investigated the influence of time-reversal symmetry breaking in continuous quantum walks, in collaboration with Ben Lanyon (Innsbruck) from one of the earlier contacted experimental groups and several other members of the Quantum Information Unit of ISI [4]. Details are provided in the third-year report.

Task 3.7 Mean field theory and quantum memory.

Use methods of mean field theory to describe matter light interactions.

The promising project of mean-field fluctuations, which was started in the third year of COQUIT, is still ongoing research. We developed a set of conditions for the existence of a fluctuation limit for permutation invariant systems consisting of many qubits and derived a description of the dynamics in the limit [7][8]. This enhances the understanding of the atomic-ensemble experiments, e.g. by the group of Eugene Polzik. In particular, the results are applicable beyond the Holstein-Primakoff transformation. However, the whole potential of the mean-field fluctuations has not been exploited, yet. For further details see the third-year report.

4.1.3.4 WP4. Continuous variables

Task 4.1. Limitations of Gaussian operations and measurements.

Identify new limitations for Gaussian operations (preserving entanglement over long distances). For a given figure of merit discuss the existence of Gaussian optimizers among all operations. Determine the accuracy of Gaussian approximations by delivering quantitative bounds.

The limitations of Gaussian operations were analyzed in a joint work between COQUIT and one of the experimental partners [5] (see also task 4.6) which led also to a followup publication [6]. Another line of research within this task concerned Gaussian operations of Fermionic systems where phase space techniques for fermion systems are developed [48]. In [21] these anticommutative phase space techniques are applied to analyze entanglement of Fermionic Gaussian states. The main result is a technique to identify and extract the most entangled subsystem, in terms of an analysis of the two-point correlation matrix.

After successful delivery of previous results (at the end of year 1) a rather spectacular effect of superactivation of the quantum capacity of Gaussian channels has been observed [49]. We proved in [50] that the more easily implementable and in some contexts more natural passive interactions, which conserve the total number of excitations, should not suffice for superactivation and we address in [51] the question how squeezing – as a resource – is most efficiently used, when the more easily implementable passive operations are for free.

Other results, connected to the semigroup structure of Gaussian channels are presented in publications [52][53][54].

Task 4.2. Non-Gaussian addons.

Identify non-Gaussian resources which are sufficient for the successful implementation of a given protocol (e.g. photon counting). Analyze their implementability and computational power.

Within this task, closely related to the previous one, we have analyzed the combination of Gaussian and non-Gaussian operations having in mind the future realization of a loophole-free Bell test [55] and provided a comparably feasible scheme to observe a large violation of Bell inequalities with continuous-variable measurements. We have also worked on continuous variable quantum information protocols and extended the protocol used to define Information Causality [56] and demonstrated its inequivalence with the principle of Macroscopic Locality [57]. In [58] our research on the non-Gaussianity show that the geometry of non-Gaussian states in the neighborhood of a Gaussian state is definitely not trivial and cannot be subsumed by a differential structure. This task was part of deliverable 10 finished in year 2.

Task 4.3. Continuous variable Bell inequalities.

Based on the fact that Homodyne-based measurements allow for a high detection efficiency, invent new methods for the construction of continuous variable Bell inequalities.

We invented a new way of deriving Bell inequalities from multi-linear contractions [59]. The derived inequalities exploit higher moments of the observables in a way which for three or more parties allows for unbounded violations. In [60] we consider Einstein-Podolsky-Rosen (EPR) entanglement criterion that allows the nonclassicality of a quantum system to be observed in entangled quantum systems which may not violate a Bell inequality, for instance in Gaussian systems. The consequences of these results on cryptographic security has been studied in [61]. This task was part of deliverable 10 finished in year 2.

Task 4.4. Approximation of continuous variable gate families.

Identify gate models in the continuous variable domain based on non-universal sets of gates that are capable to perform non- classical tasks.

The theory reported in task 3.7 falls well into this task as well. Our study of the fluctuator dynamics opens the possibility to modify the state of the light field while it is stored in an atomic-ensemble [7][8]. This leads to new possibility for the manipulation of light. This is ongoing research.

Task 4.5. Simulating quantum fields.

Employ the results from WP5 and the knowledge about non-Gaussian addons (Task 4.2.) to construct simulation protocols for relativistic quantum fields by means of continuous variable systems.

In collaboration with QUEVADIS a new classical methodology for simulating quantum fields has been developed through a continuous variable generalization of the multiscale entanglement renormalization ansatz [62]. Further details can be found in WP5.

Led by the Pavia group, we have also analyzed the possibility of simulating a second-quantized field by a quantum cellular automaton, in the form of a topologically homogeneous computational network with graph-dimension equal to the space-time dimension, the topological homogeneity corresponding to the universality of the physical law represented by the field theory. [63]

Task 4.6. Drafting proposals for new experiments.

Produce proposals for new experiments in supporting activities of WP1.

A joint work between COQUIT and one of the experimental partners was focused on the analysis of the experiment described in [5] which constitutes a crucial building block for a quantum repeater: a quantum memory – implemented in an atomic ensemble which is capable of storing quantum states of light. The close collaboration between theory and experiment allowed for a much more rigorous analysis compared to previous works on the topic. The collaboration with the EU-STREP project QUEVADIS and with one of the experimental partners of COQUIT, namely the group of E. Polzik in Copenhagen (QUANTOP) is stressed also by a follow-up publication [6].

4.1.3.5 WP5. Simulation toolbox

Task 5.1. Basic simulation theory

Introduce a set of basic definitions and concepts which give the notion of quantum simulation a precise mathematical meaning.

A basic scheme of simulation theory was outlined in deliverable D6 of the first-year report. The related publications are listed in the closely related task 5.2, see below.

Task 5.2. Analysis of sample problems

Reformulate typical classical simulations (e.g. Quantum Monte Carlo algorithms) within the general scheme developed in Task 5.1. Rewrite a classical algorithm in terms of reversible ``easy gates''. Split it into its easy and its hard part.

The investigated sample problems, which were inspired from the collaboration with the experimental partner groups, involve light-matter interaction, quantum quench, and equivalence classes between different systems. Details are given in the first-year report. The results led to the following publications: [64][65][17][66][67][68].

Task 5.3. Classical versus quantum simulations

Develop general model independent techniques to extract the hard part of a given simulation problem that can only be done efficiently by means of quantum technology.

The research in this task was two-fold. In the first year of the project we investigated the relationship between classical and quantum computation from a computer science perspective. We provided compelling evidence that the task of sampling the output probability distributions of an IQP circuit is unlikely to be achievable by any efficient classical means [17]. For details see the first-year report.

In the second year we focused on entanglement properties of many-body systems and developed methods for classical simulation of quantum systems via a *Time-dependent variational principle for quantum lattices* [69]. and *Entanglement renormalization for quantum fields* [62], finishing the task. Furthermore we obtained results on the *Entanglement of quasifree Fermions* [21]. Details are given in the second-year report.

Task 5.4 Efficiently reachable states

Identify which portion of the state space can be efficiently reached and exploited for quantum simulations. Analyze which states can be approximated with arbitrary precision according to the operational criteria established by Task 5.1.

In this task we throughout the project investigated relevant parts of the state space of different types of quantum systems, partly by adopting techniques developed under task 5.3. The results include the *Reachability properties of translation-invariant Fermionic Gaussian states under Gaussian operations* [16], *Information propagation for interacting particle systems* [70] and *Local approximation of observables and commutator bounds* [44], as well as *Variational Matrix Product Ansatz for Nonuniform Dynamics in the Thermodynamic Limit* [71], *Quantum Walks with Non-Orthogonal Position States* [3] *Molecular binding in interacting quantum walks* [2], *Decidability questions relating reachability* [72][73][74], *Reversed problem of reachability* [75]. For details see the second-year and third-year report.

Task 5.5 Estimation and Tomography

Consider devices used for quantum estimation and tomography. Adapt these techniques to the case where the sources of states to be reconstructed or estimated are non i.i.d.

In this task we investigated improved schemes for tomography of quantum systems under different given conditions. The results include compressed sensing [14][15], tomography on the permutation invariant submanifold [76] and quantum tomography under prior information [77]. Furthermore, we developed a description of the full counting statistics of stationary particle beams [78], an algebraic characterization of extremal generalized quantum instruments [79] and a characterization of informational completeness for covariant phase space observables [80]. Details are given in the yearly reports.

Task 5.6 Advanced simulation theory

Develop a general approximation theory for complex systems. Input from WP2 -- WP4 is needed: adapt the notions for "simulability", developed by Task 5.1. to more concrete and realistic scenarios.

This task was devoted to approximation methods for quantum lattice systems in view of classical simulation. We developed a path integral approach for the continuum limit of a tensor network [81], a variational matrix product ansatz for non-uniform dynamics in the thermodynamic limit [71] and an information geometric approach to the renormalization group [82]. Additionally, we developed a control theory for Fermionic systems [16]. For details see the third-year report.

Task 5.7 Application design

Build from the results related to Task 5.4. a formalism which enables to give concrete design rules for simulation protocols

We included concrete design rules for the specific physical systems into the proposals for new experiments, namely *Simulating Quantum Fields with Cavity QED* [47] and *Quantum Walks with Non-Orthogonal Position States* [3]. Also, we investigated the *forgetfulness of quantum channels* [83], which is of fundamental importance for quantum simulation and computation in a realistic setting. See the third-year report for details.

4.1.3.6 WP6. Errors

Task 6.1. Error types.

Develop techniques for the classification of errors by using the knowledge that has been attained by WP2 – WP4. Identify those errors which are “ignorable”, “correctable” and “uncorrectable”.

A mathematically precise description of these errors can be found on the corresponding wiki page [84]. A general theory of error correction with limited resources is possible, but to derive interesting and in particular useful results is very difficult. More promising approaches are to either study special setups and only restricted, very specific error models or, if we can not get rid of the noise, accept it and try to work around – see results in task 6.3.

Partially relevant for this task are also [85][86] on joint measurability and non-destructiveness of measurements where the effects of a measurement induced errors on subsequent ones is characterized and quantified.

Task 6.2. Error correcting codes.

Provide a constructive approach for finding good quantum error correcting schemes with constrained operations. by finding optimized encoding and decoding operations.

The work on this task was done partly in cooperation with the CORNER project where error correction strategies against correlated noise are analyzed [32]. The systems where this type of noise occurs are relevant for COQUIT, too. The promising nature of fault-ignorant protocols from task 6.3 led us to addressing later task in more depth than the former one.

Task 6.3. Fault ignorant protocols.

Explore the possibility of fault ignorant protocols: find implementations of protocols where not the success but merely the run-time depends on the error rate.

This topic provides a very promising alternative to error correction and has been fully addressed (see the third year report). In [87] we rigorously develop the notion of fault-ignorant computation and develop a framework for description of algorithms, that work under any amount of decoherence, unlike error correcting codes that require decoherence rate below some specific threshold. Fault-ignorant algorithms are then able to deliver correct results with desired success probability even if the noise rate is unknown and, hence, can be run even under situations where the decoherence is not fully under experimental control.

As a specific example an algorithm for noisy quantum search under fault-ignorant setting is presented, showing that quadratic speedup is possible only under very small amount of noise. Presented algorithms however prove to be faster than the best classical one also for (small) decoherence rates where quadratic speedup is not achievable any more. Another important aspect of presented algorithms is their ignorance of the error rate – the result is presented independently on the error rate; only the runtime depends on the amount of the noise.

Task 6.4. Encoding into complementary variables.

Investigate to what extent a non-local (band limited) encoding prevents from distortion by local noise. The developed ideas shall be generalized to other pairs of conjugate variables (not necessarily related by a Fourier transform).

The promising nature of task 6.3 led us to focus attention on fault-ignorant computation while not addressing this task. We believe that this shift of attention will be accepted.

4.1.4 Potential impact

Our project has developed theoretical models and techniques which enhances our understanding of quantum systems with limited control and therefore allow the implementation of new experiments which make more efficient use of the available equipment, and the development of new experimental techniques which can remove crucial limitations. Some of our experimental proposals are already realized or will be realized in the near future, which shows the validity and power of our approach. Moreover, our research led to some collaborations with experimental groups (or theoretical groups with very close ties to experimentalists), which will continue after the end of COQUIT to work on several follow up projects. This includes in particular the following.

- **Quantum walks and automata.** We have substantially advanced the theory of discrete quantum systems and our knowledge has already led to new perspectives in experiments with trapped ions and optical lattices. In fact most of the experimental proposal we have made belong to this area. We are currently collaborating with the experimental groups of D. Meschede (Bonn) and T. Schaetz (Freiburg) on experimental implementations of quantum walks. The continuation of this collaboration will most likely lead to new results concerning quantum simulation with discrete quantum systems.

- **Quantum control.** The theory of quantum control provide powerful methods to design quantum devices and circuits, and in the past it was applied very successfully in NMR experiments. To make these techniques available to more setups, COQUIT started a collaboration with the experimental group of S. Glaser (Munich) where know-how on control and on different types of systems (like Bosons and Fermions) is combined. During the runtime of COQUIT this research has reached a maturity, where we can start to make proposals towards new experimental setups like cold Fermions in optical lattices. More recently new work on noisy control was started, too.

- **Matter-light interactions.** Already in the beginning of COQUIT we started to cooperate with the experimental group of E. Polzik (Copenhagen) on matter-light interactions and its applications to quantum memory. Later this cooperation was extended to the group of G. Toth (Bilbao). Using methods from mean-field theory and the theory of quantum fluctuations we were able to extend the theoretical understanding in this area substantially. On the experimental side the results developed so far will improve the handling of noise and decoherence (or more generally the handling of atomic ensembles which are very far away from the fully polarized states). This includes in particular possibilities to actually *use* the noise in a positive way. An explicit example for the latter is a proposal to use a special form of noise in order to store d(d-1)/2 modes of light in an ensemble of d-level atoms (rather than the only d-1 modes which we would get with the polarized case). Future research in this collaboration will concentrate on the one hand on implementation of the new experimental we have made and on the other on further consolidation of the theoretical models. The latter concerns in particular a better understanding of the d>2 case and the treatment of dissipative dynamics.
- **Superactivation.** In the COQUIT topic of Continuous variables (WP4) a collaboration of TUM partner with external partner of the group of Prof. Glaser has been established during the project duration. The collaboration, represented by the current research on the resources needed for superactivation of Gaussian channels, is still on-going and is now supported by Bavarian elite network QCCC - an international PhD program of excellence based in Munich and jointly held by research groups at the TU Munich (department of chemistry), the LMU Munich and the Max Planck Institute for Quantum Optics.

COQUIT can be regarded as a part of a general trend in the quantum information community away from abstract and overly ambitious project like quantum computers to more realistic goals which will most likely lead in the near future to usable quantum technologies. In this context we are convinced that the followup projects outlined above will provide substantial contributions to the following two fields.

- **Quantum simulation.** This is currently a very hot research topic and COQUIT has provided several important results via WP5. The next goal in this area is to develop explicit proposals for simulations which can really outperform their classical counterparts. We expect that the ongoing work quantum walks and on quantum control described above will provide important contributions into this direction.

- **Quantum communication.** One big obstacle against large scale usage of quantum communication and in particular the corresponding cryptography is the lack of repeaters and routers. Quantum memory and related techniques are an important building block and the project on matter-light interactions mentioned above should be able to advance this area substantially. On-going research on superactivation has also a potential for developing experimentally more feasible schemes for the study and possible application of this intricate effect.

COQUIT had big impacts also on fundamental questions, since most of the theorertical research described in this document is deeply rooted in the fundamentals of quantum mechanics and quantum information theory. COQUIT research with a substantial impact on fundamental topics include:

- **Discrete quantum dynamics.** This concerns basically all the research in WP3 on lattice systems. Our work on quantum cellular automata and quantum walks can and should be regarded as a general structure theory for discrete time, discrete time dynamics of quantum lattice system (i.e. systems discretized in space).
- **Continuous quantum dynamics.** We have discussed also various aspects of the dynamics of continuous variable quantum systems. This includes in particular the relation between Gaussian and non-Gaussian time-evolution, discretization strategies (e.g. simulation of quantum fields), superactivation of Gaussian channels and continuum limits, i.e. approximations of discrete systems by continuous ones.
- **Controlled dynamics.** Although quantum control is topic with huge impact on applied topics and even engineering, it is also important for the discussion of fundamental questions like reachability and preparability. COQUIT made here important contributions for Fermionic systems.
- **Quantum measurements and estimation.** Lots of our result on measurement and more generally on improving experimental strategies have a fundamental aspect, too. Important examples are our work on Bell-inequalities and the estimation results in WP5.
- **Fault-ignorant computation.** We have provided quantum search algorithms

capable of providing desired results irrespective of the noise rate with only the run-time being affected by the noise. This algorithm provides an example of a new competitional paradigm for computation under noise and decoherence.

As a project on quantum information theory the our main dissemination strategies were publication in high profile refereed journals including but not restricted to the Physical Review family, New Journal of Physics, Communications in Mathematical Physics and Quantum Information and Communication and presentation on international conferences. In addition all our important results are openly accessible via the e-print archives http://www.arxiv.org/quant-ph, http://www.arxiv.org/math-ph and http://www.arxiv.org/cond-mat.

4.1.5 Project website

The project website can be found at https://coquit.isi.it/COQUITWiki.

Bibliography

1: Experimental limitations, http://coquit.isi.it/COQUITWiki/ExperimentalLimits

2: A. Ahlbrecht, A. Alberti, D. Meschede, V. B. Scholz, A. H. Werner and R. F. Werner, Molecular binding in interacting quantum walks, New J. Phys. 14, 073050 (2012)

3: R. Matjeschk, A. Ahlbrecht, M. Enderlein, Ch. Cedzich, A. H. Werner, M. Keyl, T. Schaetz and R. F. Werner, Quantum Walks with Non-Orthogonal Position States, arXiv:1206.0220

4: Z. Zimborás, M. Faccin, Z. Kádár, J. Whitfield, B. Lanyon and J. Biamonte, Quantum Transport Enhancement by Time-Reversal Symmetry Breaking , preprint arXiv:1208.4049

5: K. Jensen, W. Wasilewski, H. Krauter, T. Fernholz, B.M. Nielsen, A. Serafini, M. Owari, M.B. Plenio, M.M. Wolf, E.S. Polzik, Quantum memory for entangled two-mode squeezed states, Nature Physics 7, 13-16 (2011)

6: K. Jensen, W. Wasilewski, H. Krauter, T. Fernholz, B.M. Nielsen, J.M. Petersen, J.J. Renema, M.V. Balabas, M. Owari, M.B. Plenio, A. Serafini, M.M. Wolf, C.A. Muschik, J.I. Cirac, J.H. Müller, E.S. Polzik, Quantum memory, entanglement and sensing with room temperature atoms, J. Phys.: Conf. Ser. 264, 012022 (2011)

7: Z. Kádár, M. Keyl, R. Matjeschk, G. Tóth and Z. Zimborás, Simulating continuous quantum systems by mean field fluctuations, preprint, arXiv:1211.2173

8: M. Keyl, J. Kiukas, R. Matjeschk and R. F. Werner, Schwarz Operators, in preparation

9: A. Bisio, M. Dall'Arno and G. M. D'Ariano, Tradeoff between energy and error in the discrimination of quantum-optical devices, Phys. Rev. A 84, 012310 (2011)

10: M. Dall'Arno, A. Bisio, G. M. D'Ariano, M. Mikova, M. Jezek and M. Dusek, Experimental implementation of unambiguous quantum reading, Phys. Rev. A 85, 012308 (2012)

11: G. Chiribella, G. M. D'Ariano, P. Perinotti and B. Valiron, Beyond causally ordered quantum computers, submitted to Phys. Rev. A, preprint: arXiv:0912.0195

12: Colnaghi, G. M. D'Ariano, S. Facchini and P. Perinotti, Quantum computation with programmable connections between gates, Phys. Lett. A 376, 2940 - 2943 (2012)

13: T. Rambo, J. Altepeter, G. M. D'Ariano and P. Kumar, Functional Quantum Computing: An Optical Approach, arXiv:1211.1257

14: D. Gross, Yi-Kai Liu, S. T. Flammia, S. Becker and J. Eisert, Quantum state tomography via compressed sensing., Phys. Rev. Lett. 105, 150401 (2010)

15: D. Gross, Recovering low-rank matrices from few coefficients in any basis, IEEE Trans. Inf. Theory 57, 1248 - 1566 (2011)

16: Z. Zimborás, R. Zeier, M. Keyl, and T. Schulte-Herbrüggen, A Dynamic Systems Approach to Fermions with Interrelation to Spins, preprint, arXiv:1211.2226

17: M. J. Bremner, R. Josza and D. Shepherd, Classical simulation of commuting quantum computations implies collapse of the polynomial hierarchy, Proc. R. Soc. A 467, 459-472 (2010)

18: G. Chiribella, G. M. D'Ariano and P. Perinotti, Theoretical framework for quantum networks, Phys. Rev. A 80, 022339 (2009)

19: A. Bisio, G. Chiribella, G. M. D'Ariano, S. Facchini and P. Perinotti, Optimal quantum learning of a unitary transformation, Phys. Rev. A 80, 022339 (2010)

20: G. Chiribella, G. M. D'Ariano, P. Perinotti, D. M. Schlingemann and R. F. Werner, A short impossibility proof of Quantum Bit Commitment, arXiv:0905.3801

21: Z. Kadar, M. Keyl and D. Schlingemann, Entanglement distillation from quasifree fermions, Quant. Inf. Comp. 12, 0074-0104 (2012)

22: A. Bisio, G. Chiribella, G. M. D'Ariano and P. Perinotti, Minimal computational-space implementation of multi-round quantum protocols, Phys. Rev. A 83, 022325 (2011)

23: A. Bisio, G. M. D'Ariano, P. Perinotti and M. Sedlák, , Phys. Rev. A , 032333 (2012)

24: P. Arrighi, V. Nesme and R. F. Werner, Unitarity plus causality implies localizability, J. Comp. Sys. Sci. 77, 372-378 (2011)

25: A. Bisio, G. Chiribella, G. M. D'Ariano and P. Perinotti, Information - Disturbance Tradeoff in the Estimation of a Unitary Transformation, Phys. Rev. A 82, 062305 (2010)

26: A. Bisio, G. Chiribrlla, G. M. D'Ariano and P. Perinotti, Quantum learning algorithms for quantum measurements, Phys. Lett. A 375, 3425-3434 (2011)

27: A. Bisio, G. M. D'Ariano, P. Perinotti and M. Sédlak, Cloning of a quantum measurement, Phys. Rev. A 84, 42330 (2011)

28: A. Bisio, M. Dall'Arno, G. M. D'Ariano, P. Perinotti and M. Sedlak, in preparation

29: G. M. D'Ariano, S. Facchini and P. Perinotti, No-signaling, entanglement-breaking, and localizability in bipartite channels, Phys. Rev. Lett. 106, 010501 (2011)

30: A. Bisio, G. M. D'Ariano, P. Perinotti and M. Sedlak, in preparation

31: M. Dall'Arno, G. M. D'Ariano and M. F. Sacchi, Purification of noisy quantum measurements, Phys. Rev. A 82, 042315 (2010)

32: G. Chiribella, M. Dall'Arno, G.M. D'Ariano, C. Macchiavello and P. Perinotti, Quantum error correction with degenerate codes for correlated noise, Phys. Rev. A 83, 052305 (2011)

33: D. Reeb, M. J. Kastoryano and M. M. Wolf, Hilbert's projective metric in quantum information theory, J. Math. Phys. 52, 082201 (2011)

34: M. A. Hall, J. B. Altepeter, and P. Kumar, Ultrafast Switching of Photonic Entanglement, Phys. Rev. Lett. 106, 053901 (2011)

35: J. Guetschow, S. Uphoff, R. F. Werner and Z. Zimborás, Time Asymptotics and Entanglement Generation of Clifford Quantum Cellular Automata, J. Math. Phys. 51, 015203 (2010)

36: Z. Kádár and Z. Zimborás, Entanglement entropy in quantum spin chains with broken reflection symmetry, Phys. Rev. A 82, 032334 (2010)

37: D. Gross and V. Nesme and H. Vogts and R. F. Werner, Index theory of one dimensional quantum walks and cellular automata, Comm. Math. Phys. 310, 419 (2012)

38: J. Gütschow, V. Nesme and R. F. Werner, The fractal structure of cellular automata on abelian groups, arXiv:1011.0313

39: Andre Ahlbrecht, Albert H. Werner and Reinhard F. Werner, Asymptotic evolution of quantum walks with random coin, J. Math. Phys. 52, 042201 (2011)

40: A. Ahlbrecht, V. B. Scholz and A. H. Werner, Disordered Quantum Walks in one lattice dimension, arXiv:1101.2298

41: J. Gütschow, PhD thesis, in preparation

42: A. Ahlbrecht, Ch. Cedzich, R. Matjeschk, V. B. Scholz, A. H. Werner and R. F. Werner, Asymptotic behavior of quantum walks with spatio-temporal coin fluctuations, Quant. Inf. Proc. 11, 1219 (2012)

43: F. A. Grünbaum, L. Velázquez, A. H. Werner and R. F. Werner, Recurrence for discrete time unitary evolutions, preprint arXiv:1202.3903

44: B. Nachtergaele, V. B. Scholz and R. F. Werner, Local approximation of observables and commutator bounds, preprint arxiv:1103.5663

45: C. Bény, Perturbative quantum error correction, Phys. Rev. Lett. 107, 080501 (2011)

46: C. Bény and O. Oreshkov, Approximate simulation of quantum channels, Phys. Rev. A 84, 022333 (2011)

47: S. Barrett, K. Hammerer, S. Harrison, T. E. Northup and T. J. Osborne, Simulating Quantum Fields with Cavity QED, preprint arxiv:1206.4988

48: M. Keyl, D. Schlingemann, The algebra of Grassmann canonical anticommutation relations and its applications to fermionic systems, J. Math. Phys. 51, 023522 (2010)

49: G. Smith, J.A. Smolin, J. Yard, Quantum communication with Gaussian channels of zero quantum capacity, Nature Photonics 5, 624-627 (2011)

50: D. Lercher, G. Giedke, M.M. Wolf, Super-activation for Gaussian channels requires squeezing, preprint arXiv:1209.5574 [quant-ph]

51: D. Lercher, T. Schulte-Herrbruggen, M.M. Wolf, R. Zeier, in preparation

52: T. Heinosaari, A.S. Holevo, M.M. Wolf, The semigroup structure of Gaussian channels, Quantum Inf. Comp. 10, 0619-0635 (2010)

53: A. Ipsen, Mixing Gaussian quantum channels, Thesis, 2010

54: C. Carmeli, T. Heinosaari, A. Toigo, Sequential measurements of conjugate observables, J. Phys. A: Math. Theor. 44, 285304 (2011)

55: D. Cavalcanti, N. Brunner, P. Skrzypczyk, A. Salles, V. Scarani, Large violation of Bell inequalities using both particle and wave measurements, Phys. Rev. A 84, 022105 (2011)

56: M. Pawlowski, T. Paterek, D. Kaszlikowski, V. Scarani, A. Winter, M. Zukowski, Information causality as a physical principle, Nature 461, 1101-1104 (2009)

57: M. Navascues, H. Wunderlich, A glance beyond the quantum model, Proc. R. Soc. A 466, 881-890 (2010)

58: M.G. Genoni, P. Giorda, M.G.A. Paris, Geometry of perturbed gaussian states and quantum estimation, J. Phys. A 44, 152001 (2011)

59: A. Salles, D. Cavalcanti, A. Acin, D. Perez-García, M.M. Wolf, Bell inequalities from multilinear contractions, Quant. Inf. Comp. 10, 0703-0719 (2010)

60: T. Eberle, V. Handchen, J. Duhme, T. Franz, R.F. Werner, R. Schnabel, Strong einstein-podolsky-rosen entanglement from a single squeezed light source, Phys. Rev. A 83, 052329 (2011)

61: T. Franz, F. Furrer, R.F. Werner, Extremal Quantum Correlations and Cryptographic Security, Phys. Rev. Lett. 106, 250502 (2011)

62: J. Haegeman, T.J. Osborne, H. Verschelde, F. Verstraete, Entanglement renormalization for quantum fields, Phys. Rev. Lett. submitted, preprint arXiv:1102.5524 (2011)

63: G. M. D'Ariano, Physics as Quantum Information Processing: Quantum Fields as Quantum Automata, Foundations of Probability and Physics - 6, AIP Conf. Proc. 1424, 371 (2012)

64: Elementary simulation theory, http://coquit.isi.it/COQUITWiki/ElementarySimTheory

65: M. Keyl and D. Schlingemann and Z. Zimborás, Quantum central limit theorem for non-critical states, to be published, arXiv:1006.3461

66: L. Campos Venuti and P. Zanardi, Unitary equilibrations: Probability distribution of the Loschmidt echo, Phys. Rev. A 81, 022113 (2010)

67: L. Campos Venuti and P. Zanardi, Universality in the equilibration of quantum systems after a small quench , Phys. Rev. A 81, 032113 (2010)

68: L. Campos Venuti and M. Roncaglia, Equivalence between XY and dimerized models, Phys. Rev. A (R), (2010)

69: J. Haegeman and J. I. Cirac and T. J. Osborne and I. Pizorn and H. Verschelde and F. Verstraete, Time-dependent variational principle for quantum lattices, Phys. Rev. Lett. 107, 070601 (2011)

70: Norbert Schuch and Sarah K. Harrison and Tobias J. Osborne and Jens Eisert, Information propagation for interacting particle systems, Phys. Rev. A 84, 032309 (2011)

71: A. Milsted, J. Haegeman, T. J. Osborne and F. Verstraete, Variational Matrix Product Ansatz for Nonuniform Dynamics in the Thermodynamic Limit, preprint arXiv:1207.0691

72: M.M. Wolf, T.S. Cubitt, D. Perez-Garcia , Are problems in Quantum Information Theory (un)decidable?, preprint arXiv:1111.5425

73: M.M. Buchinger, Master thesis, 2012

74: M.M. Buchinger and M.M. Wolf, in preparation

75: T. Heinosaari, M. A. Jivulescu, D. Reeb and M. M. Wolf, Extending quantum operations, J. Math. Phys. 53, 102208 (2012)

76: G. Toth and W. Wieczorek and D. Gross and R. Krischek and C. Schwemmer and H. Weinfurter, Permutationally invariant quantum tomography, Phys. Rev. Lett. 105, 250403 (2010)

77: T. Heinosaari, L. Mazzarella and M.M. Wolf, Quantum Tomography under Prior Information, preprint arXiv:1109.5478

78: J. Kiukas, A. Ruschhaupt and R. F. Werner, Full Counting Statistics of Stationary Particle Beams, arXiv:1009.1109

79: M. Dall'Arno, G. M. D'Ariano and M. F. Sacchi, Informational power of quantum measurements, Phys. Rev. A 83, 062304 (2011)

80: J. Kiukas, P. Lahti, J. Schultz, R. F. Werner, Characterization of informational completeness for covariant phase space observables, J. Math. Phys 53, 102203 (2012)

81: Ch. Brockt, J. Haegeman, D. Jennings, T. J. Osborne and F. Verstraete, The continuum limit of a tensor network: a path integral representation, preprint arXiv:1210.5401

82: C. Bény and T. J. Osborne, Information geometric approach to the renormalisation group, preprint arXiv:1206.7004

83: A. Ahlbrecht, F. Richter and R. F. Werner, How long can it take for a quantum channel to forget everything?, preprint arXiv:1205.0693

84: Ignorable errors, http://coquit.isi.it/COQUITWiki/IgnorableErrors

85: T. Heinosaari, T. Miyadera, D. Reitzner, Strongly Incompatible Quantum Devices, submitted to Journal of Physics A, preprint arXiv:1209.1382 [quant-ph]

86: T. Heinosaari, M.M. Wolf, Non-disturbing quantum measurements, J. Math. Phys. 51, 092201 (2010)

87: P. Vrana, D. Reeb, D. Reitzner, M.Wolf, Fault-ignorant Quantum Search, in preparation

4.2. Use and dissemination of foreground

Section A

A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	**Title**	**Main author**	**Title of the periodical or the series**	**Number, date or frequency**	**Publisher**	**Place of publication**	**Year of publication**	**Relevant pages**	**Permanent identifiers (if available)**	**Is/Will open access provided to this publication?**
1	Quantum memory for entangled two-mode squeezed states	*K. Jensen*	*Nature Physics*	*7*	*Nature Publishing Group*		*2010*	*13-16*	full text	yes
2	No-signaling, entanglement-breaking, and localizability in bipartite channels	G. M. D'Ariano	Physical Review Letters	106	American Physical Society		2011	010501	abstract	Yes
3	Perturbative quantum error correction	C. Bény	Physical Review Letters	107	American Physical Society		2011	050801	abstract	Yes
4	Extremal Quantum Correlations and Cryptographic Security	T. Franz	Physical Review Letters	106	American Physical Society		2011	250502	abstract	Yes
5	Time-dependent variational principle for quantum lattices	J. Haegeman	Physical Review	107	American Physical Society		2011	070601	abstract	Yes

			Letters							
6	Permutationally invariant quantum tomography	G. Toth	Physical Review Letters	105	American Physical Society		2010	250403	abstract	Yes
7	Molecular binding in interacting quantum walks	A. Ahlbrecht	New J. Physics	14	IOP Publishing		2012	73050-73070	abstract	Yes
8	Quantum memory, entanglement and sensing with room temperature atoms	K. Jensen	J. Phys.: Conf. Series	264	IOP Publishing		2011	012022	abstract	Yes
9	Entanglement distillation from quasifree fermions	M. Keyl	Quant. Inf. Comp.	12	Rinton Press		2012	74-104	abstract	Yes
10	The semigroup structure of Gaussian channels	T. Heinosaari	Quant. Inf. Comp.	10	Rinton Press		2010	0619-0635	abstract	Yes
11	Bell inequalities from multilinear contractions	A. Salles	Quant. Inf. Comp.	10	Rinton Press		2010	0703-0719	abstract	Yes
12	Molecular binding in interacting quantum walks	A. Ahlbrecht	New J. Phys.	14	IOP Publishing		2012	073050	full text	Yes
13	Index theory of one dimensional quantum walks and cellular automata	D. Gross	Comm. Math. Phys.	310	Springer-Verlag		2012	419	abstract	Yes
14	Tradeoff between energy and error in the discrimination of quantum-optical devices	A. Bisio	Phys. Rev. A	84	American Physical Society		2011	012310	abstract	Yes
15	Experimental implementation of	Dall'Arno	Phys. Rev. A	85	American Physical		2012	012308	abstract	Yes

	unambiguous quantum reading				Society					
16	Theoretical framework for quantum networks	G. Chiribella	Phys. Rev. A	80	American Physical Society		2009	022339	abstract	Yes
17	Optimal quantum learning of a unitary transformation	A. Bisio	Phys. Rev. A	81	American Physical Society		2010	032324	abstract	Yes
18	Minimal computational-space implementation of multi-round quantum protocols	A. Bisio	Phys. Rev. A	83	American Physical Society		2011	022325	abstract	Yes
19	Memory cost of quantum protocols	A. Bisio	Phys. Rev. A	85	American Physical Society		2012	032333	abstract	Yes
20	Information - Disturbance Tradeoff in the Estimation of a Unitary Transformation	A. Bisio	Phys. Rev. A	82	American Physical Society		2010	062305	abstract	Yes
21	Cloning of a quantum measurement	A. Bisio	Phys. Rev. A	84	American Physical Society		2011	042330	abstract	Yes
22	Purification of noisy quantum measurements	M. Dall'Arno	Phys. Rev. A	82	American Physical Society		2010	042315	abstract	Yes
23	Quantum error correction with degenerate codes for correlated noise	G. Chiribella	Phys. Rev. A	83	American Physical Society		2011	052305	abstract	Yes
24	Entanglement entropy in quantum spin chains with broken reflection symmetry	Z. Kádár	Phys. Rev. A	82	American Physical Society		2010	032334	abstract	Yes

25	Approximate simulation of quantum channels	C. Bény	Phys. Rev. A	84	American Physical Society		2011	022333	abstract	Yes
26	Large violation of Bell inequalities using both particle and wave measurements	D. Cavalcanti	Phys. Rev. A	84	American Physical Society		2011	022105	abstract	Yes
29	Strong Einstein-Podolsky-Rosen entanglement from a single squeezed light source	T. Eberle	Phys. Rev. A	83	American Physical Society		2011	052329	abstract	Yes
30	Unitary equilibrations: Probability distribution of the Loschmidt echo	L. Campos Venuti	Phys. Rev. A	81	American Physical Society		2010	022113	abstract	Yes
31	Universality in the equilibration of quantum systems after a small quench	L. Campos Venuti	Phys. Rev. A	81	American Physical Society		2010	032113	abstract	Yes
32	Equivalence between XY and dimerized models	L. Campos Venuti	Phys. Rev. A	81	American Physical Society		2010	060101(R)	abstract	Yes
33	Information propagation for interacting particle systems	N. Schuch	Phys. Rev. A	84	American Physical Society		2011	032309	abstract	Yes
34	Informational power of quantum measurements	Dall'Arno	Phys. Rev. A	83	American Physical Society		2011	062304	abstract	Yes
35	Quantum computation with programmable connections between gates	G. Colnaghi	Phys. Lett. A	376	Elsevier		2012	2940 - 2943	abstract	Yes
36	Quantum learning algorithms for quantum measurements	A. Bisio	Phys. Lett. A	375	Elsevier		2011	3425–3434	abstract	Yes

37	Unitarity plus causality implies localizability	P. Arrighi	J. Comp. Sys. Sci.	77	Elsevier		2011	372-378	abstract	Yes
38	Classical simulation of commuting quantum computations implies collapse of the polynomial hierarchy	M. J. Bremner	Proc. R. Soc. A	467	Royal Society Publishing		2010	459-472	full text	Yes
39	Hilbert's projective metric in quantum information theory	D. Reeb	J. Math. Phys.	52	AIP Publishing		2011	082201	full text	Yes
40	Time Asymptotics and Entanglement Generation of Clifford Quantum Cellular Automata	J. Gütschow	J. Math. Phys.	51	AIP Publishing		2010	015203	full text	Yes
41	Asymptotic evolution of quantum walks with random coin	A. Ahlbrecht	J. Math. Phys.	52	AIP Publishing		2011	042201	full text	Yes
42	Disordered Quantum Walks in one lattice dimension	A. Ahlbrecht	J. Math. Phys.	52	AIP Publishing		2011	102201	full text	Yes
43	The algebra of Grassmann canonical anticommutation relations and its applications to fermionic systems	M. Keyl	J. Math. Phys.	51	AIP Publishing		2010	023522	full text	Yes
44	Extending quantum operations	T. Heinosaari	J. Math. Phys.	53	AIP Publishing		2012	102208	full text	Yes
45	Characterization of informational completeness for covariant phase space observables	J. Kiukas	J. Math. Phys.	53	AIP Publishing		2012	102203	full text	Yes

46	Non-disturbing quantum measurements	T. Heinosaari	J. Math. Phys.	51	AIP Publishing		2010	092201	full text	Yes
47	Asymptotic behavior of quantum walks with spatio-temporal coin fluctuations	A. Ahlbrecht	Quant. Inf. Proc.	11	Springer US		2012	1219-1249	full text	Yes
48	Geometry of perturbed gaussian states and quantum estimation	M. G. Genoni	J. Phys. A	44	IOP Publishing		2011	152001	full text	Yes

A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	**Type of activities**	**Main leader**	**Title**	**Date/Period**	**Place**	**Type of audience**	**Size of audience**	**Countries addressed**
1	*Conference*	*R. Werner*	*First COQUIT workshop*	*18-20 November 2010*	*University of Hannover*	*Scientific Community*	*80*	*EU*
2	Conference	M. Wolf	Second COQUIT workshop	12-14 February 2012	TUM Munich	Scientific Community	60	EU
3	Conference	M. Keyl	Third COQUIT workshop	11-14 September 2012	ISI Torino	Scientific Community	60	EU
4	Website	M. Keyl	Interactive COQUIT website	July 2009 - December 2012	www	Civil Society and Scientific Community	Unknown	Any
5	Conference talk	T. Heinosaari (speaker)	The Semigroup Structure of Gaussian Channels	23-27 May 2009	Turku, Finland	Scientific Community	50	EU
6	Conference talk	R. Werner (speaker)	Causality and Unitarity in 1D Quantum Systems	15 June 2009	Foundational Principles in Quantum Information, Grenoble	Scientific Community	80	worldwide
7	Conference talk	G. M. D'Ariano (speaker)	The principle of quantumness	16 June 2009	Quantum Theory: Reconsideration of Foundations, Vaxjo, Sweden	Scientific Community	80	EU
8	Conference talk	P. Perinotti (speaker	A general framework for quantun networks	7-27 June 2009	Workshop on Quantum Information, Benasque, Spain	Scientific Community	120	worldwide
9	Conference talk	R. Werner (speaker)	Disordered Quantum Walks	6 July 2009	Workshop on Cooling and Calculating, Quantum Walks and Feedback, Bonn	Scientific Community	60	worldwide
10	Confere	P. Perinotti	Quantum Combs for	6-8 July 2009	Cambridge Summer School	Scientific	100	worldwi

	nce talk	(speakert)	Learning			Community		de
11	Conference talk	L. Campos Venuti (speaker)	Some applications of the Heisenberg model to quantum information processing	17-26 July 2009	Workshop for the 80th anniversary of The Heisenberg Model: Past, Present and Future, ICCMP, Brasilia	Scientific Community	100	worldwide
12	Conference talk	R. Werner (speaker)	Towards a Quantum Chruch Turing Theorem	31 July 2009	Young Researcher's Symposium ICMP, Prague	Scientific Community	150	EU
13	Les Houches School lectures	C. Machiavello (speaker)	Quantum Computing and Entanglement	July 2009	Les Houches School of Physics in Singapore on Ultracold Gases and Quantum Information, Singapore	Scientific Community	120	worldwide
14	DPG Physics School	M. Keyl (speaker)	Quantum information theory	13-18 September 2009	DPG Physics School, Bad Honnef, Germany	Scientific Community	80	Germany
15	Seminar	R. Matjeschk (speaker)	Quantum Simulators	12 October 2009	Bad Honnef, Germany	Scientific Community	20	Germany
16	Conference talk	R. Werner (speaker)	There is a lot to Time	12 October 2009	Arrival Times and Control, Quantum Computing, Control and Communication, Bad Toelz	Scientific Community	50	Worldwide
17	Seminar	M. Keyl (speaker)	Positivity structure in quantum mechanics	4 December 2009	Trento, Italy	Scientific Community	30	Italy
18	Conference talk	D. Gross (speaker)	Non-commutative compressed sensing	15 January, 2010	13th Workshop on Quantum Information Processing, Zurich	Scientific Community	100	worldwide
19	Conference talk	M. Bremner (speaker)	PostIQP=PP, hence classical simulations of temporally unstructured quantum computations imply a collapse of the Polynomial Hierarchy	15 January, 2010	13th Workshop on Quantum Information Processing, Zurich	Scientific Community	100	worldwide
20	Conference talk	V. Nesme (speaker)	Unitarity plus causality implies localizability	15 January, 2010	13th Workshop on Quantum Information Processing,	Scientific Community	100	worldwide

					Zurich			
21	Invited talk	G. M. D'Ariano (speaker)	A Computational Grand-Unified Theory	27 January 2010	PI, Waterloo, Canada	Scientific Community	20	Canada
22	Seminar	P. Perinotti (speaker)	Switching boxes in operational theories	2 February 2010	PI, Waterloo, Canada	Scientific Community	20	Canada
23	Confere nce talk	R. Werner (speaker)	Asymptotic Behaviour of Quantum Walks with Disorder in Space and Time	8 February 2010	46th Karpacz Winter School of Theoretical Physics, Ladek Zdroj	Scientific Community	80	EU
24	Confere nce talk	Z. Zimboras (speaker)	Entanglement in quantum spin chains with broken reflection symmetry	7-13 March 2010	DPG Spring meeting, Hannover	Scientific Community	60	EU
25	Confere nce talk	Z. Zimboras (speaker)	Quantum simulation of QFTs with discrete quantum systems	7-13 March 2010	DPG Spring meeting, Hannover	Scientific Community	60	EU
26	Confere nce talk	M. Keyl (speaker)	Entanglement distillation from quasifree Fermions	15-19 March 2010	DPG Spring meeting, Bonn	Scientific Community	30	EU
27	Confere nce talk	D. Schlingem ann (speaker)	From quantum computation to quantum simulation: becoming more realistic	15-19 March 2010	DPG Spring meeting, Bonn	Scientific Community	30	EU
28	Confere nce talk	P. Perinotti (speaker)	Switching boxes in operational theories	18-24 March 2010	Nagoya Winter Workshop, Japan	Scientific Community	70	worldwi de
29	Confere nce talk	G. M. D'Ariano (speaker)	A Computational Grand-Unified Theory	18-24 March 2010	Nagoya Winter Workshop, Japan	Scientific Community	70	worldwi de
30	Seminar	A. Saller (speaker)	Bell Inequalities from Multilinear Contractions	12-24, April 2010	CQT, Singapore	Scientific Community	30	Singapo re
31	Confere nce talk	M. Wolf (speaker)		6-8 May 2010	Quantum Coherence and Entanglement on Macroscopic Scales, Tenerife	Scientific Community	60	worldwi de

32	Conference talk	M. Keyl (speaker)	Simulating continuous by discrete quantum systems	21-25 May 2010	International Conference on Combinatorics and Control, Madrid	Scientific Community	60	worldwide
33	Conference talk	R. Matjeschk (speaker)		17-30 July 2010	10th Canadian Summer School and Workshop on Algorithms, Computational Models and Foundations of Quantum Mechanics	Scientific Community	100	worldwide
34	Conference talk	M. J. Bremner (speaker)	Classical simulation of commuting quantum computations implies collapse of the polynomia hierarchy	28-31 August 2010	10th Asian Conference on Quantum Information Science (AQIS '10), Tokyo	Scientific Community	80	worldwide
35	Conference talk	M. Sedlak (speaker)	Optimal replication of Von Neuman measurements	6-10 September 2010	QMath11, Mathematical Results in Quantum Physics, Hradec Kralove (Czechia)	Scientific Community	50	EU
36	Seminar	G. M. D'Ariano (speaker)	Physics as Information Theory	20 October 2010	Fermilab Colloquium 2010-2011, Fermiab, Batavia, Illinois	Scientific Community	30	USA
37	Conference talk	M. Wolf (speaker)	Semigroups and time series	26-28 October 2010	October Workshop Quantum Mechanics: Foundations and Open Systems II, Department of Physics and Astronomy, University of Turku	Scientific Community	60	worldwide
38	Seminar	G. M. D'Ariano (speaker)	Physics as Information: Quantum Theory meets Relativity	30 November 2010	Perimeter Institute, Waterloo CA	Scientific Community	20	Canada
39	Seminar	L. C. Venuti (speaker)	Orthogonality catastrophe 40 years later: fidelity approach, criticality and boundary CFT	10 December 2010	Perimeter Institute, Waterloo CA	Scientific Community	20	Canada
40	Conference talk	M. J. Bremner (speaker)	Classical simulation of commuting quantum computations implies collapse of the polynomial	10-14 January 2011	14th Workshop on Quantum Information Processing (QIP 2011), Singapore	Scientific Community	150	worldwide

			hierarchy					
41	Conference talk	G. M. D'Ariano (speaker)	A Quantum digital Universe	18-24 February 2011	The Second Nagoya Winter Workshop on Quantum Information, Measurement, and Foundations, Nagoya, Japan	Scientific Community	120	worldwide
42	Invited talk	Z. Zimborás (speaker)	The use of the quantum fluctuation algebra in quantum statistical mechanics and in quantum information theory	25 March 2011	Research Institute for Particle and Nuclear and Physics, Budapest	Scientific Community	20	Hungary
43	Conference talk	Z. Kádár (speaker)	Quantum fluctuators for simulating continuous quantum systems by discrete ones	31 March 2011	DPG Meeting, Karlruhe	Scientific Community	50	EU
44	Conference talk	Z. Zimborás (speaker)	Quantum fluctuators and the tensor algebra method	31 March 2011	DPG Meeting, Karlruhe	Scientific Community	50	EU
45	Conference talk	G. M. D'Ariano (speaker)	Quantum-Computational and Optical Simulation of the Dirac Equation	9-13 May 2011	18th Central European Workshop on Quantum Optics, Universidad Complutense de Madrid	Scientific Community	200	EU
46	Conference talk	G. M. D'Ariano (speaker)	A Quantum-Digital Universe	3-4 May 2011	xQIT Conference: Difficult Problems in Quantum Information Theory, MIT W. M. Keck Foundation Center for Extreme Quantum Information Theory	Scientific Community	80	worldwide
47	Conference talk	R. F. Werner (speaker)	Point perturbations of quantum walks and walking molecules	20-26 May 2011	Quantum and Classical Random Processes, Benasque	Scientific Community	120	worldwide
48	Conference talk	P. Perinotti (speaker)	Quantum Theory as a Theory of Information Processing	May 2011	Co nceptual Foundations and Foils for Quantum Information Processing, Perimeter Ins titute for Theoretical Physics, Waterloo, Canada	Scientific Community	100	worldwide

49	Conference talk	M. Wolf (speaker)	Partial Quantum Information	May 2011	The 7th Conference on Theory of Quantum Computation, Communication and Cryptography, Tokyo	Scientific Community	150	worldwide
50	Conference talk	P. Perinotti (speaker)	Informational axioms for quantum theory	June 2011	Foundations of Probability and Physics, Linnaeus University, Vaxjo	Scientific Community	100	worldwide
51	Conference talk	P. Perinotti (speaker)	From information processing to Quantum Theory	June 2011	CEQIP 2011, Znojmo (Czech Republic)	Scientific Community	120	EU
52	Conference talk	D. Reeb (speaker)	Hilbert's projective metric in Quantum Information Theory	June 2011	CEQIP 2011, Znojmo (Czech Republic)	Scientific Community	120	EU
53	Conference talk	M. Sedlák (speaker)	Memory cost of quantum protocols	June 2011	9th Central European Quantum Information Processing Workshop, Smolenice, Slovakia	Scientific Community	80	EU
54	Seminar	D. Reeb (speaker)	Extension theorems for quantum operations	August 2011	Turku university, (Finland)	Scientific Community	30	Finland
55	Conference talk	D. Reeb (speaker)	Extension theorems for quantum operations & Hilbert's projective metric in Quantum Information Theory	August 2011	QCCC-Programme, Munich	Scientific Community	40	EU
56	Conference talk	D. Reeb (speaker)	Extension theorems for quantum operations	September 2011	QIPC conference Zurich	Scientific Community	80	worldwide
57	Conference talk	P. Perinotti (speaker)	Causality, Locality, and Spooky Action at a Distance	December 2011	Quantum Foundations in the Light of Quantum Information III, Quantum Information and Processing (QIP) conference, Montreal	Scientific Community	100	worldwide
58	Poster	D. Reeb	Extension theorems for quantum operations	December 2011	Quantum Foundations in the Light of Quantum Information III, Quantum Information and Processing (QIP) conference, Montreal	Scientific Community	100	worldwide

59	Conference talk	P. Perinotti (speaker)	Realistic models for probabilistic theories with spookiness and steering?	February 2012	III Nagoya Winter Workshop on Quantum Information, Measurement, and Foundations, Nagoya, Japan	Scientific Community	120	worldwide
60	Conference talk	Z. Kádár (speaker)	How the dynamics of a continuous quantum field can be encoded by a discrete ensemble	March 2012	DPG meeting, Stuttgart	Scientific Community	40	EU
61	Conference talk	M. Keyl (speaker)	Quantum fluctuations, mean field methods and the simulation of continuous quantum systems	March 2012	DPG meeting, Göttingen	Scientific Community	30	EU
62	Conference talk	D. Reitzner (speaker)	Compatibility of Quantum Measurements: Joint Measurability of Simple Qubit Observables	March 2012	Instituto de Telecomunicacoes, Lisabon	Scientific Community	30	Portugal
63	Conference talk	Z. Zimborás (speaker)	Breaking momentum space reflection invariance in fermionic models	March 2012	DPG meeting, Stuttgart	Scientific Community	40	EU
64	Conference talk	Z. Zimborás (speaker)	Renormalization Group and Continuum Limit of Quantum Cellular Automata	March 2012	DPG meeting, Göttingen	Scientific Community	30	EU
65	Seminar	M. Keyl, Z. Zimborás (speakers)	Mean field approximations and quantum fluctuations	May 2012	Uni. Bilbao, Department of Theoretical Physics	Scientific Community	20	Spain
66	Conference talk	D. Reitzner (speaker)	Quantum Compatibility: When Two Measurements Come From One	May 2012	Pécs Workshop on Quantum Information and Quantum Optics, Pécs (Hungary)	Scientific Community	60	EU
67	Lecture series	M. Keyl (speaker)	Lectures on Quantum Information Theory	May-June 2012	Leipzig University	Scientific Community	40	Germany
68	Poster	D. Reitzner	Incompatibility of Measurement Devices	June 2012	CEQIP 2012, Znojmo (Slovakia)	Scientific Community	60	EU

69	Poster	D. Reeb	Extension theorems for quantum operations	July 2012	Quantum Information conference in Seefeld (Austria)	Scientific Community	50	EU
70	Website	M. Keyl	Experimental Limitations	June 2010	url	Scientific Community		
71	Website	M. Keyl, Z. Zimborás, Z. Kádár and R. Matjeschk	Description of the project and scientific results	Continuous edited during thw project	url	Scientific Community		
72	Preprint	R. Matjeschk, A. Ahlbrecht, M. Enderlein, Ch. Cedzich, A. H. Werner, M. Keyl, T. Schaetz and R. F. Werner	Quantum Walks with Non-Orthogonal Position States	June 2012	url	Scientific Community		
73	Preprint	Z. Zimborás, M. Faccin, Z. Kádár, J. Whitfield, B. Lanyon and J. Biamonte	Quantum Transport Enhancement by Time-Reversal Symmetry Breaking	August 2012	url	Scientific Community		
74	Preprint	Z. Kádár, M. Keyl, R. Matjeschk, G. Tóth and Z. Zimborás	Simulating continuous quantum systems by mean field fluctuations	November 2012	url	Scientific Community		

75	Preprint	G. Chiribella, G. M. D’Ariano, P. Perinotti and B. Valiron	Beyond causally ordered quantum computers	December 2009	url	Scientific Community		
76	Preprint	Z. Zimborás, R. Zeier, M. Keyl, and T. Schulte-Herbrüggen	A Dynamic Systems Approach to Fermions with Interrelation to Spins	November 2012	url	Scientific Community		
77	Preprint	G. Chiribella, G. M. D'Ariano, P. Perinotti, D. M. Schlingemann R. F. Werner	A short impossibility proof of Quantum Bit Commitment	May 2009	url	Scientific Community		
78	Preprint	J. Gütschow, V. Nesme and R. F. Werner	The fractal structure of cellular automata on abelian groups	November 2010	url	Scientific Community		
79	Preprint	F. A. Grünbaum, L. Velázquez, A. H. Werner and R. F. Werner	Recurrence for discrete time unitary evolutions	February 2012	url	Scientific Community		

80	Preprint	B. Nachtergaele, V. B. Scholz R. F. Werner	Local approximation of observables and commutator bounds	March 2011	url	Scientific Community		
81	Preprint	S. Barrett, K. Hammerer, S. Harrison, T. E. Northup T. J. Osborne	Simulating Quantum Fields with Cavity QED	June 2012	url	Scientific Community		
82	Preprint	D. Lercher, G. Giedke, M. M. Wolf	Super-activation for Gaussian channels requires squeezing	September 2012	url	Scientific Community		
83	Preprint	J. Haegeman, T.J. Osborne, H.Verschelde, F. Verstraete	Entanglement renormalization for quantum fields	February 2011	url	Scientific Community		
84	Website	M. Keyl	Elementary simulation theory	June 2010	url	Scientific Community		
85	Preprint	M. Keyl D. Schlingemann Z. Zimborás	Quantum central limit theorem for non-critical states	June 2010	url	Scientific Community		
86	Preprint	A. Milsted, J. Haegeman, T. J. Osborne F. Verstraete	Variational Matrix Product Ansatz for Nonuniform Dynamics in the Thermodynamic Limit	July 2012	url	Scientific Community		
87	Preprint	M.M. Wolf, T.S. Cubitt,	Are problems in Quantum Information	November 2011	abs	Scientific Community		

		D. Perez-Garcia	Theory (un)decidable?					
88	Preprint	T. Heinosaari, L. Mazzarella and M.M. Wolf	Quantum Tomography under Prior Information	September 2011	url	Scientific Community		
89	Preprint	J. Kiukas, A. Ruschhaupt, R. F. Werner	Full Counting Statistics of Stationary Particle Beams	September 2010	url	Scientific Community		
90	Preprint	Ch. Brockt, J. Haegeman, D. Jennings, T. J. Osborne and F. Verstraete	The continuum limit of a tensor network: a path integral representation	October 2012	url	Scientific Community		
91	Preprint	C. Bény and T. J. Osborne	Information geometric approach to the renormalisation group	June 2012	url	Scientific Community		
92	Preprint	A. Ahlbrecht, F. Richter and R. F. Werner	How long can it take for a quantum channel to forget everything?	May 2012	url	Scientific Community		
93	Website	M. Keyl	Ignorable errors	June 2011	url	Scientific Community		
95	**Journal Articles**	**COQUIT members**	**List A1**					

Section B

All the work done in this project is fundamental research. Therefore the generated foreground is of the type: “General advancement of knowledge”, and not (yet) exploitable via patents or other IP rights. Instead, we have started a number of more focused follow-up projects, which are described in detail in Section 4.1.4 Potential Impact.

4.3 Societal implications

A **General Information** *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	233747
Title of Project:	Collective quantum operations for information technologies
Name and Title of Coordinator:	Dr. Michael Keyl

B **Ethics**	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***NO***
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***
RESEARCH ON HUMANS	
• Did the project involve children?	***NO***
• Did the project involve patients?	***NO***
• Did the project involve persons not able to give consent?	***NO***
• Did the project involve adult healthy volunteers?	***NO***
• Did the project involve Human genetic material?	***NO***
• Did the project involve Human biological samples?	***NO***
• Did the project involve Human data collection?	***NO***
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	***NO***
• Did the project involve Human Foetal Tissue / Cells?	***NO***
• Did the project involve Human Embryonic Stem Cells (hESCs)?	***NO***
• Did the project on human Embryonic Stem Cells involve cells in culture?	***NO***
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	***NO***
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	***NO***
• Did the project involve tracking the location or observation of people?	***NO***
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	***NO***
• Were those animals transgenic small laboratory animals?	
• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	

RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	***NO***
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	
• Research having direct military use	***NO***
• Research having the potential for terrorist abuse	***NO***

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	0	4
Experienced researchers (i.e. PhD holders)	0	13
PhD Students	0	5
Other	0	0

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	11 (all men)

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? ○ Yes ¤ No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective	Very effective
Design and implement an equal opportunity policy		○
Set targets to achieve a gender balance in the workforce		○
Organise conferences and workshops on gender		○
Actions to improve work-life balance		○
Other:		

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

Yes- please specify

No ¤

E	Synergies with Science Education
8.	**Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?** Yes- please specify: Buchinger's MD based on COQUIT research No
9.	**Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?** Yes- please specify X No

F	Interdisciplinarity
10.	**Which disciplines (see list below) are involved in your project?** Quantum Information Theory, Condensed matter physics, Computer Science, Mathematics Main discipline[1]: 1.2 Associated discipline: 1.1 ○

G	Engaging with Civil society and policy makers		
11a	**Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)* ¤	○ ¤	Yes No
11b	**If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?** No Yes- in determining what research should be performed Yes - in implementing the research Yes, in communicating /disseminating / using the results of the project		
11c	**In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?**	○ ○	Yes No
12.	**Did you engage with government / public bodies or policy makers (including international organisations)**		
	X No Yes- in framing the research agenda Yes - in implementing the research agenda Yes, in communicating /disseminating / using the results of the project		

1 Insert number from list below (Frascati Manual).

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

Yes – as a **primary** objective (please indicate areas below- multiple answers possible)

Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)

X ¤ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs	Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid	Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport

13c If Yes, at which level?

Local / regional levels

National level

European level

International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**48**
To how many of these is open access[2] provided?	**13**
How many of these are published in open access journals?	**13**
How many of these are published in open repositories?	
To how many of these is open access not provided?	**35**
Please check all applicable reasons for not providing open access:	
X publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[3]: ……………	However, all 48 Articles have a substantially identical version on arxiv.org

[2] Open Access is defined as free of charge access for anyone via Internet.

[3] For instance: classification for security project.

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

Increase in employment, or	❑	In small & medium-sized enterprises
Safeguard employment, or	❑	In large companies
Decrease in employment,	X	None of the above / not relevant to the project
Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	¤

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

Yes ¤X No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

Yes ¤X No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

Press Release	❑	Coverage in specialist press
Media briefing	❑	Coverage in general (non-specialist) press
TV coverage / report	❑	Coverage in national press
Radio coverage / report	❑	Coverage in international press
Brochures /posters / flyers	❑	Website for the general public / internet
DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23	In which languages are the information products for the general public produced?		
	Language of the coordinator Other language(s)	¤	English

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]