EDIQIP

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Effects of Decoherence and Imperfections for Quantum Information Processing

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Contents

1. Executive Summary

EDIQIP is a research project which aims to advance European competitiveness in the future emerging technologies of quantum information processing and communication (QIPC).

EDIQIP project investigates decoherence and imperfection effects for quantum information processing. It determines the accuracy bounds and the time scales for reliable computations on realistic quantum processors, develops new efficient quantum algorithms for important physical problems including electron transport in disordered materials, metal-insulator transitions and complex problems of nonlinear classical dynamics.

Research is pursued in the frame of interdisciplinary and transnational European network of 4 participating organizations, including universities and public research centers. Work is conducted in close link with other projects in the IST-FET cluster QIPC. This network operates in a close collaboration with the US national research on quantum computation in the frame of ARO-NSA-ARDA program.

In the report period 01 Jan - 31 Dec 2004 a total of 33 manuscripts have been prepared, most of which have already been published in leading international journals or have been posted in the public domain. The results and achievements of this project have been presented in 33 talks, lectures and posters at scientific conferences in different countries, including Europe, USA, Japan, Korea, Mexico and Belarus. This gives high international visibility to the results obtained in the frame of EDIQIP network.

Special emphasis has been given to the dissemination of the knowledge and advances in the field of quantum information to other fields of physics, computer science and mathematics. In future, this dissemination will be enhanced by the organization of an International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos*, to be held in 2005 in Varenna (directors G.Casati, D.Shepelyansky and P.Zoller) and the Semester at Institute Henri Poincaré, Paris, on *Quantum Information, Computation and Complexity*, in Jan-Apr 2006 (directors Ph.Grangier, M.Santha and D.Shepelyansky).

Two PhD theses have been defended on the subject of quantum information and decoherence, closely related to the EDIQIP research plan. The PhD committee included EDIQIP members from different nodes. This contributed to the education in the field of QIPC on European scale.

Among the highlight results obtained in the frame of this project in 2004 we stress:

(a) An important source of quantum errors comes from internal imperfections generated by residual static couplings between qubits and one-qubit energy level shifts which fluctuate from one qubit to another but remain static in time. These static imperfections may lead to appearance of many-body quantum chaos, which modifies strongly the hardware properties of realistic quantum computer. The effects of static imperfections on the accuracy of quantum computation have been investigated on the examples of quantum algorithms for the models of complex quantum dynamics during the previous year (see, *e.g.*, [1],[7]). As a result a universal law for fidelity decay induced by static imperfections has been established for quantum algorithms simulating dynamics in the regime of quantum chaos ([7], first highlight paper of Eur. Phys. J. D). At the same time it has been realized that the effects of static imperfections for dynamics in an integrable regime are not universal and more complicated. Therefore it is important to investigate the effects of static imperfections on an example of the well known Grover algorithm. In the paper [9] we present extensive numerical and analytical studies which establish the global stability diagram of reliable operability of the Grover algorithm in presence of static imperfections.

(b) The simulation of complex quantum systems on a quantum computer is studied, taking the kicked Harper model as an example [11]. This model also describes the motion of electrons in a magnetic field on a two-dimensional solid-state lattice. This well-known system has a rich variety of dynamical behavior depending on parameters, displays interesting phenomena such as fractal spectra, mixed phase space, dynamical localization, anomalous diffusion, or partial delocalization. Three different quantum algorithms are presented and analyzed, enabling to simulate efficiently the evolution operator of this system with different precision using different resources. Depending on the parameters chosen, the system is near-integrable, localized, or partially delocalized. In each case we identify transport or spectral quantities which can be obtained more efficiently on a quantum computer than on a classical one. In most cases, a polynomial gain compared to classical algorithms is obtained, which can be quadratic or less depending on the parameter regime. We also present the effects of static imperfections on the quantities selected, and show that depending on the regime of parameters, very different behaviors are observed. Some quantities can be obtained reliably with moderate levels of imperfection, whereas others are exponentially sensitive to imperfection strength. In particular, the imperfection threshold for delocalization becomes exponentially small in the partially delocalized regime. Our results show that interesting behavior can be observed with as little as 7-8 qubits, and can be reliably measured in presence of moderate levels of internal imperfections.

(c) The theory of quantum trajectories is applied to simulate the effects of quantum noise sources induced by the dissipative environment on quantum information protocols [15]. We study two models that generalize single qubit noise channels like amplitude damping and phase flip to the many-qubit situation. We calculate the fidelity of quantum information transmission through a chaotic channel using the teleportation scheme with different environments. In this example, we analyze the role played by the kind of collective noise suffered by the quantum processor during its operation. We also investigate the stability of a quantum algorithm simulating the quantum dynamics of a paradigmatic model of chaos, the baker's map. Our results demonstrate that, using the quantum trajectories approach, we are able to simulate quantum protocols in the presence of noise and with large system sizes of more than $n_q = 20$ qubits. As a result of this study, the time scales for reliable quantum computation in a dissipative environment are found. The dissipation rate Γ is proportional to the number of qubits. Thus, the number of gates N_g that can be reliably implemented without quantum error correction drops only polynomially with the number of qubits, $N_g \propto 1/n_q$.

The effect of a dissipative environment on cold atoms transport in laser fields is analyzed in [19]. We show that, for asymmetric potential created by lasers, the dissipation leads to emergence of directed transport (also known as ratchet effect) with underlying strange chaotic attractor.

(d) In [23-24] we describe a quantum algorithm to prepare an arbitrary pure state of a register of a quantum computer with fidelity arbitrarily close to 1. Our algorithm is based on Grover's quantum search algorithm. It is clear that such a state preparation algorithm cannot be efficient for all states. After all, the ability to prepare an arbitrary state has been shown to be equivalent to the ability to perform a wide class of quantum algorithms. Furthermore, preparing an arbitrary computational basis state is as difficult as Grover search, and hence exponential in the number of qubits.

We give precise bounds on the resources needed to perform our algorithm, and show that it is polynomial in the number of qubits for sequences of states with suitably bounded amplitudes. These sequences of states occur naturally in the problem of encoding a classical probability distribution in a quantum register. We have thus given a general solution of the problem of encoding the initial probability distribution in a physical simulation problem.

(e) A general quantum error correction method is presented which is capable of correcting coherent errors originating from static residual inter-qubit couplings in a quantum computer [30]. It is based on a randomization of static imperfections in a many-qubit system by the repeated application of Pauli operators which change the computational basis. This Pauli-Random-Error-Correction (PAREC)-method eliminates coherent errors produced by static imperfections and increases significantly the maximum time over which realistic quantum computations can be performed reliably. Furthermore, it does not require redundancy so that all physical qubits involved can be used for logical purposes.

The obtained results will allow us to develop a deep understanding of decoherence and imperfection effects during quantum information processing. They will provide clear recipes for experimentalists on how to improve the reliability of quantum processors and how to improve the accuracy of quantum computation. The developed quantum algorithms can be used as testing ground for a first generation of quantum computers with up to 10 qubits. The implementation of newly developed efficient quantum algorithms with few tens of qubits would allow to overcome existing classical supercomputers.

2. Work Progress Overview

2.1. Objectives and achievements

Following the contract description of work, the research is pursued with realization of tasks described in workpackages. The global evolution of task performance is presented by Gantt chart (see Fig.1)

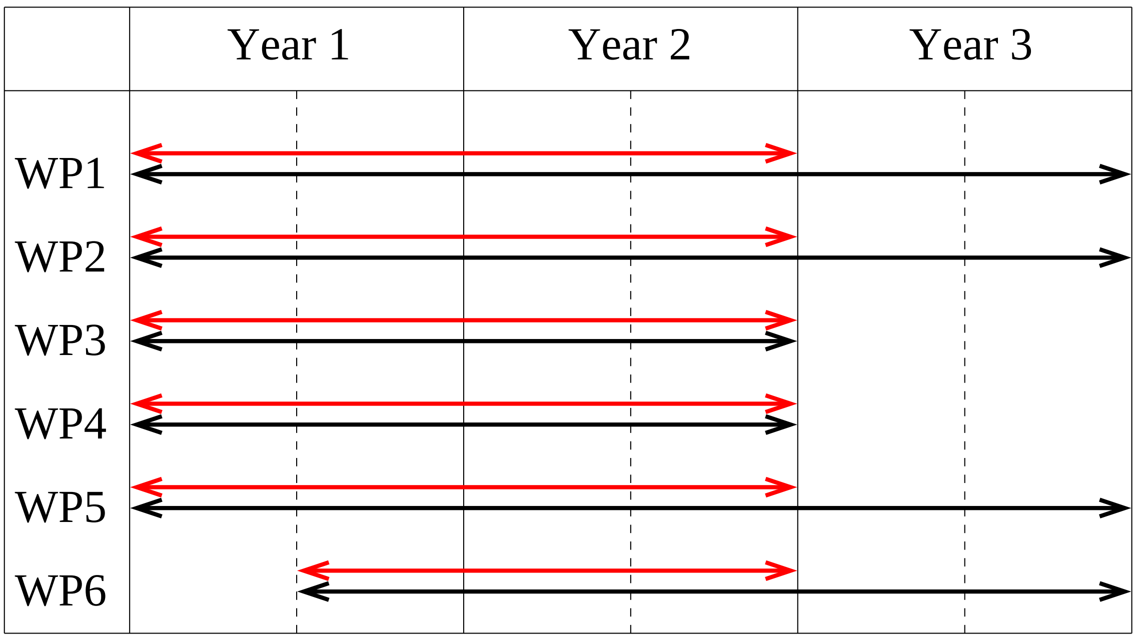

Fig.1. Gantt chart for workpackages: black arrows represent the work to be done and red/gray arrows the work accomplished.

Workpackage progress reports are listed in Appendix A, publications are listed in Appendix B (Appendix B1: papers published or submitted during 2004; Appendix B2: papers published in journals in 2003), the list of EDIQIP talks and posters is presented in Appendix C. The list of PhD theses defended in relation with EDIQIP project is given in Appendix D. A detailed list of EDIQIP deliverables is given in Appendix E. A selection of deliverables is bundled in Annex S.

We list the milestones of our results obtained during the report period. They follow the scientific deliverables of the project, listed below (see also Annex 1 - Description of Work for EDIQIP contract):

D4: Quantum Chaos Algorithms (completed after 12 months)
D7: Static Imperfection Time Scales for QIP (completed after 24 months)
D8: Decoherence Time Scales for QIP (completed after 24 months)
D11: New Quantum Algorithms for Physical Problems
(to be completed after 36 months)
D12: Numerical Simulator of Decoherence/Imperfection Effects
(to be completed after 36 months)

We classify milestones by Parts (a), (b), (c), (d) and (e) described in the Executive Summary and give their global description below.

(a1) In Ref. [9], we study effects of static inter-qubit interactions on the stability of the Grover quantum search algorithm. It is shown in Ref. [10] that, comparing to the random gate errors, the static imperfections reduce the probability of the searched state by a factor of 10 (in numerical studies with about 12 qubits). Therefore, it is important to study the case of static imperfections in the Grover algorithm in great detail. The results are presented in Ref. [9]. Our numerical and analytical results show existence of regular and chaotic phases depending on the imperfection strength ε. The critical border ε_c between two phases drops polynomially with the number of qubits n_q as $\varepsilon_c \sim n_q^{-3/2}$. In the regular phase ($\varepsilon < \varepsilon_c$) the algorithm remains robust against imperfections showing the efficiency gain $\varepsilon_c/\varepsilon$ for $\varepsilon > 2^{-n_q/2}$. In the chaotic phase ($\varepsilon > \varepsilon_c$) the algorithm is completely destroyed. In summary, we have shown that the Grover algorithm remains robust against static imperfections inside a well defined domain and determined the dependence of algorithm efficiency on the imperfection strength.

(a2) In Ref. [20] we study the relation between entanglement and quantum chaos in one- and two-dimensional spin-1/2 lattice models, which exhibit mixing of the noninteracting eigenfunctions and transition from integrability to quantum chaos. Contrary to previous studies of the behavior of entanglement across a quantum phase transition, our investigation does not refer to the ground state but to any typical many-spin quantum state. We study bipartite and pairwise entanglement measures, namely the reduced Von Neumann entropy and the concurrence, and discuss quantum entanglement sharing. Our results suggest that the behavior of the entanglement is related to the mixing of the eigenfunctions rather than to the transition to chaos.

(b1) In the paper [11], we study in detail an important example of quantum map, namely the kicked Harper model. The Hamiltonian of this system has a simple form, yet displays many interesting physical features not present in quantum maps previously studied in this context, such as fractal spectra, stochastic web, anomalous diffusion, or coexistence of localized and delocalized states. It was introduced in the context of solid state physics (motion of electrons in presence of magnetic field), and has been the subject of many studies. Using this model as a test ground, we present three different ways of simulating the quantum map on a quantum computer, two of them inspired by previous works, and compare their efficiency. The comparison shows that while the slice method and the Chebyshev method are approximate, they are much more economical in resources than the exact simulation. Numerical simulations and analytical estimations also evaluate the effects of imperfections in the quantum computer on the estimation of these quantities. We present examples of physical quantities which can be obtained on a quantum computer. It turns out that depending on the parameters of the system, at least polynomial speed-up compared to classical algorithms can be obtained for different quantities. We show that different transport and spectral properties can be obtained more efficiently on a quantum computer than classically, although the gain is only polynomial.

(b2) In Ref. [31] we study the efficiency of quantum algorithms which aim at obtaining phase space distribution functions of quantum systems. Wigner and Husimi functions are considered. Different quantum algorithms are envisioned to build these functions, and compared with the classical computation. Different procedures to extract more efficiently information from the final wave function of these algorithms are studied, including coarse-grained measurements, amplitude amplification and measure of wavelet-transformed wave function. The algorithms are analyzed and numerically tested on a complex quantum system showing different behavior depending on parameters, namely the kicked rotator. The results for the Wigner function show that the largest (polynomial) gain is obtained through the use of the wavelet transform, and that other methods work better in the chaotic regime. For the Husimi distribution, the gain is much larger than for the Wigner function, and is bigger with the help of amplitude amplification and wavelet transforms. We also apply the same set of techniques to the analysis of real images. The results show that the use of the quantum wavelet transform allows to lower dramatically the number of measurements needed, but at the cost of losing a lot of information.

(c1) It is natural to ask to what extent we can know and control the operability and the stability of a quantum computer of large size in presence of dissipative decoherence. Theoretical studies rely on evaluating the reduced density matrix of the system (obtained after tracing out the environment), often in terms of various different approximations. It would therefore be desirable to give an answer for generic quantum protocols and noise models, using exact calculations. In Ref. [15], we propose the numerical simulation of superoperators as a way to do it. By means of quantum trajectories techniques we can reach results for system sizes for which the implementation of chaotic maps becomes relevant for theoretical studies in the field of quantum chaos, having the chance to include any kind of environmental effects.

Instead of solving the density matrix directly, quantum trajectories stochastically evolve the state vector of the system, and after averaging over many runs the same results for the outcomes of any observable are obtained. The use of quantum trajectories in the field of quantum information has been pioneered by R.Schack et al.. In Ref. [15] we focus on the quantum baker's map, one of the most important examples of systems with quantum chaos. This map is fully chaotic and its quantized version consists of conveniently selected quantum Fourier transforms. We model the environment through a phase flip channel and study the fidelity of quantum computing of the quantum baker's map in this noisy environment. We note that the fidelity has already been computed experimentally with a three-qubit NMR quantum processor by D.Cory et al. at MIT. Hence, for the design and construction of quantum hardware with a larger number of qubits, simulations like those performed in Ref. [15] become essential.

Analytical and numerical investigations (with up to 22 qubits) allowed us to determine the law for fidelity decay induced by decoherence. The decay of fidelity induced by phase flip noise is given by $F = \exp\left(-n_q \gamma N_g\right) = \exp(-2\gamma n_q^3 k)$, where $\gamma = \Gamma\tau/\hbar$ is the dimensionless decay rate (τ denotes the time interval between elementary quantum gates) and $N_g = 2n_q^2 k$ is the total number of elementary quantum gates required to implement the k steps forward evolution of the baker's map, followed by k step backward. Therefore, the number of gates that can be reliably implemented without quantum error correction drops only polynomially with the number of qubits, $(N_g)_f \propto 1/n_q$. We would like to stress that this dependence should remain valid also in other environment models that allow only one qubit at a time to perform a transition, like the other dissipative noise channels discussed in Ref. [15].

(c2) In Ref. [19] we test the effects of dissipative decoherence on the dynamics of cold atoms in laser fields. The laser field creates effective kicked potential implementing the kicked rotator model, which has been realized by the groups of M.Raizen (Texas), d'Arcy et al. (Oxford), Amman et al. (Auckland) and Ringot et al. (Lille). Using the method of quantum trajectories we study a quantum chaotic dissipative ratchet appearing for particles in a pulsed asymmetric potential in the presence of a dissipative environment. The system is characterized by directed transport emerging from a quantum strange attractor. For this model, we analyze the working of the correspondence principle, which governs the transition from quantum to classical behavior, and discuss parameter values suitable for implementation of the quantum ratchet effect with cold atoms in optical lattices.

(c3) It is notoriously difficult to evaluate the decoherence functional for chaotic quantum maps. This difficulty leads to the problem of finding a simple criterion for decoherence, i.e., for the vanishing of the off-diagonal elements of the decoherence functional. In [26] we have formulated and proved a necessary and sufficient condition for decoherence of fine-grained histories for arbitrary finite-dimensional maps. We prove that fine-grained histories of arbitrary length decohere for all classical initial states if and only if the unitary evolution preserves classicality of states (using a natural formal definition of classicality). We give a counterexample showing that this equivalence does not hold for coarse-grained histories. Our criterion is an important step towards an analytical treatment of decoherence in chaotic maps.

In [27,28], we generalize the results of [26] in two complementary ways. Ref. [27] provides a version of our decoherence criterion in the case of arbitrary coarse-grainings. Furthermore, we show in [27] that decoherence of arbitrarily long histories for a fixed projective partition, and for all initial states that are naturally induced by the projective partition, implies decoherence for arbitrary initial states. In [28] we make a first step towards a generalization of the results in [27,28] to the case of approximate decoherence.

(d) The first step of many quantum computer algorithms is the preparation of a quantum register in a simple initial state, e.g. the equal superposition of all computational basis states. Some applications of quantum computers, such as the simulation of physical systems and models of quantum chaos, require the initial preparation of more general states. In Refs. [23-24] we consider the state preparation problem in the case that the Hilbert space dimension of the quantum register is so large that listing the complex coefficients of the state is impractical. In these Refs., we describe a quantum algorithm to prepare an arbitrary pure state of a register of a quantum computer with fidelity arbitrarily close to 1. Our algorithm is based on Grover's quantum search algorithm. For sequences of states with suitably bounded amplitudes, the algorithm requires resources that are polynomial in the number of qubits. Such sequences of states occur naturally in the problem of encoding a classical probability distribution in a quantum register. In relation to this research, we have made the first step towards a generalization of these algorithms to irreversible time evolutions [25]. The type of evolution we have looked at can be phrased in terms of Bayesian updating. Specifically, we have studied hypothesis elimination, which is a special case of Bayesian updating, where each piece of new data rules out a set of prior hypotheses. In [25] we describe how to use Grover's algorithm to perform hypothesis elimination for a class of probability distributions encoded on a register of qubits, and establish a lower bound on the required computational resources.

(e) So far techniques of quantum error correction have concentrated predominantly on decoherence caused by uncontrolled couplings to environments. In these cases appropriate syndrome measurements and recovery operations can reverse errors. However, up to now much less is known about the correction of coherent, unitary errors. Even if a quantum information processor (QIP) is isolated entirely from its environment and if all quantum gates are performed perfectly, there may still be residual inter-qubit couplings affecting its performance. Recently, it was demonstrated that static imperfections, i.e. random inter-qubit couplings which remain unchanged during a quantum computation, restrict the computational capabilities of a many-qubit QIP significantly as they cause quantum chaos and quantum phase transitions. Furthermore, in addition to a usual exponential decay such static imperfections also cause a Gaussian decrease of the fidelity with time. At sufficiently long times this Gaussian decrease dominates the decay of the fidelity thus limiting significantly the maximum reliable computation times of many-qubit QIPs (see, e.g., [7]).

In Ref. [30] a general error correcting method is presented for overcoming these disastrous consequences of static imperfections. It is based on the repeated random application of Pauli operators to all the qubits of a QIP. The resulting random changes of the computational basis together with appropriate compensating changes of the quantum gates slow down the rapid Gaussian decay of the fidelity and change it to a linear-in-time exponential one. As a result this Pauli-Random-Error-Correction (PAREC) - method increases significantly the maximum time scale of reliable quantum computation. In addition, neither control measurements nor redundant qubits are required so that all physical qubits are logical qubits.

2.2. Work schedule for 2005

The results obtained in the first 24 months represent a good step towards realization of tasks described in the Workpackages WP5-WP6. We developed the techniques to take into account dissipative decoherence effects in Refs. [15],[19] and we are planning to apply them for realization of tasks WP5-WP6. The studies of decoherence effects in the quantum sawtooth map, which can be implemented experimentally with NMR-based quantum computers in the group of D.Cory at MIT, are also planned in the frame of workpackage WP6. Benjamin Lévi, who finished his PhD thesis in Toulouse, now becomes postdoc in the group of D. Cory at MIT and will work in this direction. In the frame of the tasks of Workpackage WP5, we will continue to construct new quantum algorithms for physical problems and investigate effects of random errors and static imperfections with the help of analytical and numerical methods. In the frame of workpackage WP6, we will continue to develop numerical codes for extensive numerical simulations of quantum algorithms in the presence of imperfections. Software codes are developed to simulate various effects of imperfections and decoherence and error-correction. They will become available to the public at the end of the project.

2.3. Assessment of project results and achievements

The main scientific results are described in the Executive summary, Work progress overview and Appendix A.

3. Reports on the EDIQIP Deliverables

The List of EDIQIP Deliverables is given in Appendix E (it contains only Deliverables applicable for the report period). Also Appendix B1 gives the List of EDIQIP publications during the report period with their attribution to each Deliverable. All scientific Deliverables in the form of selected publications are given in Annex S. Below we present the reports on all EDIQIP Deliverables applicable for the report period.

3.1. Deliverable D6 - Periodic Report

The report on the Deliverable D6 is presented at 30.06.2004. It describes the current status of scientific research progress in the frame of EDIQIP project.

3.2. Deliverable D7 - Static Imperfections, Time Scales for QIP

This scientific Deliverable D7 is completed and it is presented in the publications Refs. [1],[7],[8],[9],[10],[11],[13],[18],[20],[30],[32],[33] given in the Appendix B1. The Issue date is 31.12.2004. The description of the scientific results for Deliverable D7 is given in Sections 1.0 and 2.1. Deliverable D7 in the form of selected publications is given in Annex S.

3.3. Deliverable D8 - Decoherence Time Scales for QIP

This scientific Deliverable D8 is completed and it is presented in the publications Refs. [6],[7],[10],[11],[12],[15],[17],[19],[21],[26],[27],[28],[29],[30],[32],[33] given in the Appendix B1. The Issue date is 31.12.2004. The description of the scientific results for Deliverable D8 is given in Sections 1.0 and 2.1. Deliverable D8 in the form of selected publications is given in Annex S.

3.4. Deliverable D9 - Annual Report

This is the annual report on the Deliverable D9 presented at 07.01.2005. It describes the status of scientific research progress in the frame of EDIQIQP project and gives the description of Deliverables achieved. It is available at the EDIQIP web page http://www.quantware.ups-tlse.fr/EDIQIP/

3.5. Deliverable D11 - New Quantum Algorithms for Physical Problems

This scientific Deliverable D11 is in the working stage. The results obtained for Deliverable D11 are presented in the publications Refs. [1],[2],[3],[4],[11],[16],[23],[24],[25],[31], [32],[33] given in the Appendix B1. The description of the scientific results for Deliverable D11 is given in Sections 1.0 and 2.1. A part of Deliverable D11 in the form of selected publications is given in Annex S. Issue date 31.12.2004, due date 31.12.2005.

3.6. Deliverable D12 - Numerical Simulator of Decoherence and Imperfection Effects

This scientific Deliverable D12 is in the working stage. The results obtained for Deliverable D12 are presented in the publications Refs. [4],[7],[9],[10],[11],[15],[19],[30],[32],[33] given in the Appendix B1. The description of the scientific results for Deliverable D12 is given in Sections 1.0 and 2.1. A part of Deliverable D12 in the form of selected publications is given in Annex S. Issue date 31.12.2004, due date 31.12.2005.

4. Project Management

The consortium members met in various combinations on several occasions during 2004: QIPC meeting at Bratislava (February), TUD Darmstadt (April), Toulouse (July, October, November), Como (June, December), Orlando, FL (August).

The information flow between the partners is assured by the webpage installed in Toulouse (website http://www.quantware.ups-tlse.fr/EDIQIP/).

4.1. Project Promotion

The project promotion is obtained by 33 talks at international conferences held in Europe, USA, Japan, Korea, Mexico and Belarus. The obtained results have been presented at the quantum program review of ARO/NSA/ARDA by D.L.Shepelyansky and G.Casati in August 2004. This gives significant promotion of IST-FET QIPC project.

Future promotion of the obtained results will be assured by the organization of an International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos*, to be held in 2005 in Varenna and the Semester at Institute Henri Poincaré, Paris, on *Quantum Information, Computation and Complexity*, in Jan-Apr 2006.

4.2. Project Collaborations

The project collaborations include joint publications with partners of another QIPC project (group of R.Fazio). Two nodes (Toulouse and Como) participate in the US quantum computing program ARO/NSA/ARDA. This allowed to have close collaborations with American scientists working in the field of quantum information.

Toulouse node collaborates also with the groups of J.-M.Raimond (ENS, Paris), D.Esteve (Saclay) and R.Mosseri (Paris) in the frame of the French government grant ACI Nanosciences-Nanotechnologies LOGIQUANT. Extensive numerical simulations are done on the supercomputers at CalMiP in Toulouse and IDRIS in Orsay the access to which is available to Toulouse node in the frame of French research projects.

Como node participates to the Italian MIUR project on Fault Tolerance, Control and Stability in Quantum Information Processing, in collaboration with the groups of M.Rasetti (Turin), L.Pitaevskii (Trento), F.Illuminati (Salerno) and F.Borgonovi (Brescia).

5. Resources Employed

The EDIQIP partners positions are filled with scientific experts who greatly contribute to the EDIQIP progress:
Toulouse: Dr. Jae-Weon Lee (country of origin is S.Korea, responsible D.L.Shepelyansky)
Toulouse: Dr. José Lages (country of origin is France, before was ARO postdoc at Ames Nat. Lab. Iowa, in Toulouse from october 2004, responsible D.L.Shepelyansky)
Darmstadt: N/A
Como: Dr. Gabriel Carlo (country of origin is Argentina, responsible G.Casati)
London: Dr. Andrei N. Soklakov (country of origin is Belarus, responsible R.Schack)

In addition, in 2004 Toulouse node attracted to the EDIQIP research project CNRS postdoc Dr. O. Giraud (from September 2004) and PhD students B. Levi and A.A. Pomeransky, supported by the French government and ARO/NSA/ARDA grants, respectively. Como node attracted an ARO/NSA/ARDA post-doc, Dr. C.Mejía-Monasterio. Toulouse node had close collaboration with senior researcher Dr. O.V.Zhirov from Budker Institute of Nuclear Physics, Novosibirsk, Russia.

6. Overview of cost incurred and distribution of cost according to Workpackages

In this section we present effort in person-months for the reporting period (1/1/2004-31/12/2004) for postdocs (see Table 6.1) and academics (see Table 6.2). Cost in Euro for post-docs corresponds to the post-doc cost defined by the contract for each partner per month. Other costs are described in the Cost Statement sent separately to the Scientific Officer of the project.

Table 6.1 - Postdocs

	Toulouse				**Darmstadt**				**Como**				**London**				**Total**			
	Period		Total		Period		Total		Period		Total		Period		Total		Period		Total	
WP	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.
WP1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WP2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WP3	5	5	10	10	0	0	0	0	4	4	8	8	5	5	9	9	14	14	27	27
WP4	3	3	6	6	0	0	0	0	6	6	12	12	2	2	4	4	11	11	22	22
WP5	2	2	4	4	0	0	0	0	1	1	2	2	3	3	7	7	6	6	13	13
WP6	2	4.5	4	6.5	0	0	0	0	1	1	2	1	2	2	4	4	5	7.5	10	12.5
Total	12	14.5	24	26.5	0	0	0	0	12	12	24	23	12	12	24	24	36	38.5	72	73.5

Table 6.2 - Academics

	Toulouse				Darmstadt				Como				London				Total			
	Period		Total		Period		Total		Period		Total		Period		Total		Period		Total	
WP	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.	Est.	Act.
WP1	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	1.2	1.2	2.4	2.4
WP2	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6	1.2	1.2	2.4	2.4
WP3	4	4	8	8	2	2	4	4	3	3	6	6	4	4	7	7	13	13	25	25
WP4	3	3	6	6	2	2	4	4	6	6	12	12	2	2	4	4	13	13	26	26
WP5	2	2	4	4	2	2	4	4	1	1	2	2	3	3	7	7	8	8	17	17
WP6	2	2	4	4	1	1	1	1	1	1	2	2	2	2	4	4	6	6	11	11
Total	11.6	11.6	23.2	23.2	7.6	7.6	14.2	14.2	11.6	11.6	23.2	23.2	11.6	11.6	23.2	23.2	42.4	42.4	83.8	83.8

Appendix F - List of EDIQIP Selected Publications for Deliverables

The selected EDIQIP publications for Deliverables are given in the Annex S (printed version, available upon request). Here we give only the list of them. Publications in the total publication list from Appendix B1

7. Information Dissemination

As mentioned in the Executive summary, during the report period 33 manuscripts have been posted in the public domain and published in high quality scientific journals. The results have been presented in 33 talks and posters at scientific schools and conferences in Europe, USA, Japan, Korea, Mexico and Belarus. The sheer amount of high level publications is matched by their highest quality and impact. Some results became the first highlight paper of the Eur. Phys. J. D (Ref. [7]). The results of the project are also presented in the broadly distributed book published by consortium members and entitled *Principles of quantum computation and information*, vol. I, by G. Benenti, G. Casati and G. Strini (World Scientific, Singapore) (Ref. [22]). The publications and review of main results are available at the web sites www.quantware.ups-tlse.fr and www.quantware.ups-tlse.fr/EDIQIP for a broad public access.

8. Updated Dissemination and Use Plan

8.1. Overview

Deliverable D7: Static Imperfection Time Scales for QIP is completed after 24 months of the contract. It determines the universal law for fidelity decay induced by residual couplings between qubits and gives the time scale for reliable quantum computation in presence of static imperfections. The results are presented in the publications given in Appendix B1 (Refs. [1],[7],[8],[9],[10],[11],[13],[18],[20],[30],[32],[33]) and Appendix B2 (Refs. [2],[3],[6],[9]).

Deliverable D8: Decoherence Time Scales for QIP is completed after 24 months of the contract. It determines the universal law for fidelity decay induced by random errors in quantum gates and errors induced by external decoherence for various quantum algorithms. The time scales for reliable quantum computation in presence of external decoherence are obtained. The results are presented in the publications given in Appendix B1 (Refs. [6],[7],[10],[11],[12],[15],[17],[19],[21],[26],[27],[28],[29],[30],[32],[33]) and Appendix B2 (Refs. [1],[4],[5],[6],[10],[12],[13],[14]).

Dissemination of the results is performed through the project website www.quantware.ups-tlse.fr/EDIQIP/. The published results are advertised in international journals and in the electronic preprint server http://arXiv.org/quant-ph.

8.2. Description of Dissemination Plan

The results obtained during the report period are presented in the publications given in Appendix B1 and B2.

The scientific results are also presented at various international Conferences and Workshops, listed in Appendix C.

All scientific information is publicly available at the website www.quantware.ups-tlse.fr/EDIQIP/.

Certain presentations at scientific Conferences are publicly available at the www.quantware.ups-tlse.fr/EDIQIP/ site and at www.quantware.ups-tlse.fr (click at Talks on Line).

The results of the project are highlighted in the textbook "Principles of Quantum Computation and Information", Vol. 1, Basic Concepts, published by World Scientific, Singapore (2004). The second volume is now in preparation and will appear in 2005. This book is used for lectures for students at the University of Insubria. Consortium members also give courses on Quantum Information for students at University Paul Sabatier, Technical University of Darmstadt and Royal Holloway University of London. Two PhD theses have been defended at University Paul Sabatier in close link with EDIQIP project (see Refs. [32],[33] in Appendix B1).

The results of the project will be presented at the Enrico Fermi School "Quantum Computers, Algorithms and Chaos" at Varenna, Italy, during 5th-15th July, 2005. The information about the School is available at the website
http://scienze-como.uninsubria.it/benenti/varenna2005.html

During the third year of the project the consortium members plan to participate to the leading Workshops and Conferences in the field of Quantum Information Processing.

8.3. Description of Use Plan

The obtained theoretical results and numerical codes give clear recipes for experimentalists on how to improve the reliability of quantum information processing and how to improve the accuracy of quantum computation. The numerical codes developed in the project can be used to simulate realistic quantum computers with up to 30 qubits. They allow us to test the accuracy of quantum algorithms simulating complex dynamics in presence of realistic imperfections. The scientific basis of these codes is described in the publications in Appendix B1 (Refs. [4],[7],[9],[10],[11],[15],[19],[30],[32],[33]) and Appendix B2 (Refs. [1],[3],[10],[12],[13],[14]). These codes may be used for NMR-based quantum computation in the group of D. Cory, MIT, in which a former PhD student from Toulouse (B. Lévi) works as a postdoc since December 2004.

Appendix A - EDIQIP Workpackage Progress Reports

WP1: Project Management

Workpackage number: WP1
Start date or starting event: month 0
Participant number: 1 (3,4,2)

Objectives

The workpackage **WP1** is devoted to the management of the project, organization of the communication flow within the consortium, meetings of consortium members and periodic reports.

Summary of work

The required periodic progress reports and annual report for 2003 and 2004 are presented in time. Scientific collaboration between nodes is realized via joint meetings, visits between nodes and electronic communication.

WP2: Dissemination of scientific results

Workpackage number: WP2
Start date or starting event: month 0
Participant number: 1 (3,4,2)

Objectives

The objective is to provide easy public access to the scientific results obtained within the project and establish collaborations with other researchers in the QIPC field.

Summary of work

During the report period 33 manuscripts are opened to free public access and published in leading international journals. They include 2 joint publications between different EDIQIP nodes and 1 manuscript in collaboration with other QIPC projects. The results are presented on international conferences and workshops in Europe, USA, Japan, Korea, Mexico and Belarus. The results obtained [Ref. [7]] became the first highlight paper of the European Journal of Physics D in 2004. The results of the project are also presented in the broadly distributed book published by consortium members and entitled *Principles of quantum computation and information*, vol. I, by G. Benenti, G. Casati and G. Strini (World Scientific, Singapore) (Ref. [22]). Two PhD theses had been defended in the frame of the research lines of EDIQIP project (see Refs. [32],[33] and Appendix D). The nodes are inter-connected via the web site www.quantware.ups-tlse.fr/EDIQIP. Future promotion of the obtained results will be assured by the organization of an International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos*, to be held in 2005 in Varenna and the Semester at Institute Henri Poincaré, Paris, on *Quantum Information, Computation and Complexity*, in Jan-Apr 2006.

WP3: Decoherence Models for QIP

Workpackage number: WP3
Start date or starting event: month 0
Participant number: 1 (4,3,2)

Objectives

The main objective is to determine the decoherence time scales and their dependence on system parameters, for quantum computers simulating simple efficient quantum algorithms already developed by consortium members (quantum baker's map, quantum sawtooth map). These maps are particularly interesting for the first generation of quantum computers, since their rich dynamics can be explored with less than ten qubits.

Summary of work

The decoherence time scales are determined in models of dissipative decoherence using the method of quantum trajectories, which allows to investigate quantum evolution for density matrix with up to 22 qubits. The results are presented in Ref. [15]. They give the dissipative rates for non-unitary noise and provide the number of quantum gates which can be performed with high fidelity for a given qubit-environment coupling. The numerical simulations were performed for the teleportation protocol and the baker's map with up to 22 qubits. In Ref. [19] we test the effects of dissipative decoherence on the dynamics of cold atoms in laser fields. The laser field creates effective kicked potential implementing the kicked rotator model, which has been realized by the groups of M.Raizen (Texas), d'Arcy et al. (Oxford), Amman et al. (Auckland) and Ringot et al. (Lille). Using the method of quantum trajectories we study a quantum chaotic dissipative ratchet appearing for particles in a pulsed asymmetric potential in the presence of a dissipative environment. These studies give better understanding of quantum information transport in presence of dissipative decoherence. In Ref. [26] we have formulated and proved a necessary and sufficient condition for decoherence of fine-grained histories for arbitrary finite-dimensional maps. We prove that fine-grained histories of arbitrary length decohere for all classical initial states if and only if the unitary evolution preserves classicality of states (using a natural formal definition of classicality). In [27,28], we generalize the results of [26] in two complementary ways. Ref. [27] provides a version of our decoherence criterion in the case of arbitrary coarse-grainings. Furthermore, we show in [27] that decoherence of arbitrarily long histories for a fixed projective partition, and for all initial states that are naturally induced by the projective partition, implies decoherence for arbitrary initial states. In [28] we make a first step towards a generalization of the results in [27,28] to the case of approximate decoherence.
The results obtained for unitary decoherence and noise have been reported in the publications in Refs. [6,7,10,11,12,17,21,29,30,32,33] (this year) and Refs. [1,4,5,6,12,13,14] (previous year, see Appendix B2). Together with this year results for dissipative decoherence reported in Refs. [15,19,26,27,28] and in Ref. [10] of previous year, they give the complete picture of decoherence effects in quantum algorithms simulated on realistic quantum computers. These research results complete the tasks of WP3.

WP4: Effects of Residual Inter-Qubit Interactions for QIP

Workpackage number: WP4
Start date or starting event: month 0
Participant number: 3 (1,4,2)

Objectives

The main objective of this workpackage is to study the effects of imperfections inside a quantum processor which is isolated from the environment. Indeed, the absence of external decoherence does not mean that the quantum processor will operate properly. Static internal imperfections due to inter-qubit residual couplings can strongly modify the ideal quantum register represented by noninteracting many-body (multi-qubit) states of ideal qubits.

Summary of work

During the previous year, the universal scaling law was established for fidelity decay induced by static imperfections inside the quantum computer, which simulates algorithms for complex quantum dynamics. This year we have investigated the effects of static imperfections for integrable quantum Grover algorithm (Refs. [9,10]). It was shown that static imperfections give a much stronger reduction of fidelity compared to the case of noisy unitary quantum errors [10]. In Ref. [9] we have presented extensive numerical and analytical studies which establish the global stability diagram of reliable operability of the Grover algorithm in presence of static imperfections. Numerical tests are done with up to 16 qubits. We have shown that the Grover algorithm remains robust against static imperfections inside a well defined domain and determined the dependence of algorithm efficiency on the imperfection strength. The properties of fidelity decay and quantum entanglement in presence of static imperfections are also investigated in Refs. [18,20,32,33]. The information entropy of quantum mechanical states is analyzed in Ref. [8].
A general quantum error correction method is presented which is capable of correcting coherent errors originating from static residual inter-qubit couplings in a quantum computer [30]. It is based on a randomization of static imperfections in a many-qubit system by the repeated application of Pauli operators which change the computational basis. This Pauli-Random-Error-Correction (PAREC)-method eliminates coherent errors produced by static imperfections and increases significantly the maximum time over which realistic quantum computations can be performed reliably. Furthermore, it does not require redundancy so that all physical qubits involved can be used for logical purposes.
The results obtained for static imperfections have been reported in the publications in Refs. [1,7,8,9,10,18,20,30,32,33] (this year) and Refs. [2,3,6,9] (previous year, see Appendix B2). All together they give the complete picture of static imperfection effects in quantum algorithms simulated on realistic quantum computers. These research results complete the tasks of WP4.

WP5: New Quantum Algorithms for Physical Systems

Workpackage number: WP5
Start date or starting event: month 0
Participant number: 4 (1,3,2)

Objectives

The simulation of physical phenomena is a key area in which quantum computers are expected to become useful long before they will become capable to solve large-scale factorization problems. The main objective of this workpackage is the development of new efficient quantum algorithms for the simulation of important physical models, both quantum and classical.

Summary of work

The new quantum algorithms for simulation of physical systems are obtained in Refs. [11,23,24,25,31,32,33].
The simulation of complex quantum systems on a quantum computer is studied for the kicked Harper model [11]. This model describes the motion of electrons in a magnetic field on a two-dimensional solid-state lattice. This well-known system has a rich variety of dynamical behavior depending on parameters, displays interesting phenomena such as fractal spectra, mixed phase space, dynamical localization, anomalous diffusion, or partial delocalization. Three different quantum algorithms are presented and analyzed, enabling to simulate efficiently the evolution operator of this system with different precision using different resources. We identify transport or spectral quantities which can be obtained more efficiently on a quantum computer than on a classical one. In most cases, a polynomial gain compared to classical algorithms is obtained, which can be quadratic or less depending on the parameter regime.
In Ref. [31] we study quantum algorithms obtaining phase space distributions like Wigner and Husimi functions. Different quantum algorithms are envisioned to build these functions, and compared with the classical computation. Different procedures to extract more efficiently information from the final wave function of these algorithms are studied, including coarse-grained measurements, amplitude amplification and measure of wavelet-transformed wave function. The results show that the use of the quantum wavelet transform allows to lower dramatically the number of measurements needed, but at the cost of losing a lot of information.
In Refs. [23-25] we consider the state preparation problem in the case that the Hilbert space dimension of the quantum register is so large that listing the complex coefficients of the state is impractical. In these Refs., we describe a quantum algorithm to prepare an arbitrary pure state of a register of a quantum computer with fidelity arbitrarily close to 1. Our algorithm is based on Grover's quantum search algorithm. For sequences of states with suitably bounded amplitudes, the algorithm requires resources that are polynomial in the number of qubits. Such sequences of states occur naturally in the problem of encoding a classical probability distribution in a quantum register.

WP6: Numerical Simulator of Decoherence and Imperfection Effects

Workpackage number: WP6
Start date or starting event: month 6
Participant number: 1 (3,4,2)

Objectives

The main objective of this workpackage is to develop a package of numerical codes which simulate the decoherence and imperfection effects considered in WP3 and WP4 and implement them to the new quantum algorithms developed in WP5. Using these codes, it will be possible to carry out extensive numerical simulations of quantum information processing for important physical and mathematical problems with up to 30 qubits using modern supercomputers. This will allow us to detect the regions of stability for operability of quantum processors as a function of imperfection strength and parameters of the models simulated by quantum algorithms. Quantum error correction codes will be tested with these algorithms.

Summary of work

The further development of numerical codes in standard programming languages (Fortran, C, C++) has been done in Refs. [9,10,11,15,19,30,31,32,33]. These codes allowed to simulate effects of imperfections for the quantum algorithms described in the Workpackages WP3, WP4 and WP5. The numerical simulations with dissipative decoherence were performed with up to 22 qubits for the quantum algorithm simulating the quantum baker's map [15]. Dissipation effects on the quantum information transport can be studied with the codes developed in Ref. [19]. The effects of static imperfections have been simulated with up to 16 qubits for the quantum Grover algorithm with the numerical codes developed in Refs. [9-10]. The codes for static imperfection effects and noisy errors in quantum algorithms for the kicked Harper model were developed in Ref. [11]. Computer codes for the random Pauli error correction method were developed in Ref. [30], that allowed to test the method with up to 10 qubits and reach the fidelity increase by two orders of magnitude.

Appendix B1 - List of EDIQIP Publications (2004)

Scientific deliverables are marked by D4,D7,D8,D11,D12.

[1] A.A.Pomeransky and D.L.Shepelyansky, *Quantum computation of the Anderson transition in the presence of imperfections*, Phys. Rev. A **69**, 014302 (2004) [quant-ph/0306203] (D11,D7).

[2] B.Georgeot and D.L.Shepelyansky, *Les ordinateurs quantiques affrontent le chaos*, (in French, *Images de la Physique 2003-2004*, CNRS Edition, pp. 17-23) [quant-ph/0307103] (D11).

[3] B.Georgeot, *Quantum computing of Poincare recurrences and periodic orbits*, Phys. Rev. A **69**, 032301 (2004) [quant-ph/0307233] (D11).

[4] J.W.Lee, A.D.Chepelianskii and D.L.Shepelyansky, *Treatment of sound on quantum computers*, Proceedings of ERATO Conference on Quantum Information Science 2004, Tokyo, pp. 91-92 (2004); and *Applications of quantum chaos to realistic quantum computations and sound treatment on quantum computers*, in *Noise and information in nanoelectronics, sensors, and standards II* Proceedings of SPIE Eds. J.M.Smulko, Y.Blanter, M.I.Dykman, L.B.Kish, v.5472, pp.246-251 (2004) [quant-ph/0309018] (D11,D12).

[5] M.Terraneo and D.L.Shepelyansky, *Dynamical localization and repeated measurements in a quantum computation process*, Phys. Rev. Lett. **92**, 037902 (2004) [quant-ph/0309192] (D4).

[6] S.Bettelli, *A quantitative model for the effective decoherence of a quantum computer with imperfect unitary operations*, Phys. Rev. A **69**, 042310 (2004) [quant-ph/0310152] (D4,D8).

[7] K.M.Frahm, R.Fleckinger and D.L.Shepelyansky, *Quantum chaos and random matrix theory for fidelity decay in quantum computations with static imperfections*, Eur. Phys. J. D **29**, 139 (2004) [highlight paper of the issue] [quant-ph/0312120] (D4,D7,D8,D12).

[8] A.Stotland, A.A.Pomeransky, E.Bachmat and D.Cohen, *The information entropy of quantum mechanical states*, Europhys. Lett. **67**, 700 (2004) [quant-ph/0401021] (D7).

[9] A.A.Pomeransky, O.V.Zhirov and D.L.Shepelyansky, *Phase diagram for the Grover algorithm with static imperfections*, Eur. Phys. J. D **31**, 131 (2004) [quant-ph/0403138] (D7,D12).

[10] A.A.Pomeransky, O.V.Zhirov and D.L.Shepelyansky, *Effects of decoherence and imperfections for quantum algorithms*, Proceedings of ERATO Conference on Quantum Information Science 2004, Tokyo, pp. 171-172 (2004) [quant-ph/0407264] (D7,D8,D12).

[11] B.Levi and B.Georgeot, *Quantum computation of a complex system: the kicked Harper model*, Phys. Rev. E **70**, 056218 (2004) [quant-ph/0409028] (D7,D8,D11,D12).

[12] D. Rossini, G. Benenti and G. Casati, *Entanglement Echoes in Quantum Computation* Phys. Rev. A **69**, 052317 (2004) [quant-ph/0309146] (D4,D8).

[13] W.-G. Wang, G. Casati and B. Li *Stability of Quantum Motion: Beyond Fermi-golden-rule and Lyapunov decay*, Phys. Rev. E **69**, 025201 (2004) [quant-ph/0309154] (D7).

[14] G. Casati and S.Montangero, *Measurement and Information Extraction in Complex Dynamics Quantum Computation* in *Decoherence and Entropy in complex Systems*, H.-T. Elze Ed., Lectures Notes in Physics Vol. 633, Springer-Verlag, Berlin 2004 [quant-ph/0307165] (D4).

[15] G.G. Carlo, G. Benenti, G. Casati and C. Mejía-Monasterio, *Simulating noisy quantum protocols with quantum trajectories*, Phys. Rev. A **69**, 062317 (2004) [quant-ph/0402102] (D8,D12).
[16] G. Benenti, G. Casati and S. Montangero, *Quantum computing and information extraction for dynamical quantum systems*, Quantum Information Processing **3**, 273 (2004) [quant-ph/0402010] (D11).
[17] D. Rossini, G. Benenti and G. Casati, *Classical versus quantum errors in quantum computation of dynamical systems*, Phys. Rev. E **70**, 056216 (2004) [quant-ph/0405189] (D8).
[18] W.-G. Wang, G.Casati, B. Li and T. Prosen, *Uniform semiclassical approach to fidelity decay*, submitted to Phys. Rev. Lett. [quant-ph/0407040] (D7).
[19] G.G. Carlo, G. Benenti, G. Casati and D.L. Shepelyansky *Quantum ratchets in dissipative chaotic systems*, submitted to Phys. Rev. Lett. [cond-mat/0407702] (D8,D12).
[20] C. Mejía-Monasterio, G. Benenti, G.G. Carlo and G. Casati, *Entanglement across a Transition to Quantum Chaos*, submitted to Phys. Rev. A [quant-ph/0410246] (D7).
[21] S. Montangero, A. Romito, G. Benenti and R. Fazio, *Chaotic dynamics in superconducting nanocircuits*, submitted to Phys. Rev. Lett. [preprint cond-mat/0407274] (D8).
[22] G. Benenti, G. Casati and G. Strini, *Principles of quantum computation and information*, Volume I: Basic concepts (World Scientific, Singapore, 2004) (D4).
[23] A. N. Soklakov and R. Schack, *Efficient state preparation for a register of quantum bits*, submitted to Phys. Rev. Lett. [quant-ph/0408045] (D11).
[24] A. N. Soklakov and R. Schack, *State preparation based on Grover's algorithm in the presence of global information about the state*, to appear in Optics and Spectroscopy [quant-ph/0411010] (D11).
[25] A. N. Soklakov and R. Schack, *Hypothesis elimination on a quantum computer*, in Quantum Communication, Measurement and Computing (QCMC'04), edited by Stephen M. Barnett (AIP Press, Melville, NY, 2004), p. 151 [quant-ph/0412025] (D11).
[26] A. Scherer, A. N. Soklakov and R. Schack, *A simple necessary decoherence condition for a set of histories*, Phys. Lett. A **326**, 307 (2004) [quant-ph/0401132] (D8).
[27] A. Scherer and A. N. Soklakov, *Initial states and decoherence of histories*, submitted to Journal of Mathematical Physics [quant-ph/0405080] (D8).
[28] A. Scherer and A. N. Soklakov, *Decoherence properties of arbitrarily long histories*, in Quantum Communication, Measurement and Computing (QCMC'04), edited by Stephen M. Barnett (AIP Press, Melville, NY, 2004), p. 417 [quant-ph/0412024] (D8).
[29] G. Alber and T. Walther, Thema Forschung **1**, 44 (2004), Quanteninformationsverarbeitung - Prüfstein für IT-Sicherheit (D8).
[30] O. Kern, G. Alber and D. L. Shepelyansky, *Quantum error correction of coherent errors by randomization*, to be published in Eur. Phys. J. D [quant-ph/0407262] (D7,D8,D12).
[31] M. Terraneo, B. Georgeot and D.L. Shepelyansky, *Quantum computation and analysis of Wigner and Husimi functions: toward a quantum image treatment*, submitted to Phys. Rev. E [quant-ph/0412123] (D11).
[32] A. Pomeransky, *Entanglement and imperfections in quantum computation* (in French), PhD thesis at Univ. P. Sabatier, Toulouse, France (2004)

(available at http://www.quantware.ups-tlse.fr/theses.html) (D7,D8,D11,D12).
[33] B. Lévi, *Computation of quantum systems by realistic quantum computers* (in French), PhD thesis at Univ. Paris VII, France (2004)
(available at http://www.quantware.ups-tlse.fr/theses.html) (D7,D8,D11,D12).

Publications [1-7], [12], [14] and [22] were included in the EDIQIP publication list of the 2003 report as preprints.

Appendix B2 - List of EDIQIP Journal Publications (2003)

Scientific deliverables are marked by D4,D7,D8,D11,D12.

[1] M.Terraneo, B.Georgeot and D.L.Shepelyansky, *Strange attractor simulated on a quantum computer*, Eur. Phys. J. D **22**, 127 (2003) [quant-ph/0203062] (D4,D8,D12).
[2] G.Benenti, G.Casati, S.Montangero and D.L.Shepelyansky, *Statistical properties of eigenvalues for an operating quantum computer with static imperfections*, Eur. Phys. J. D **22**, 285 (2003) [quant-ph/0206130] (D4,D7).
[3] G.Benenti, G.Casati, S.Montangero and D.L.Shepelyansky, *Dynamical localization simulated on a few qubits quantum computer*, Phys. Rev. A **67**, 052312 (2003) [quant-ph/0210052] (D4,D7,D11,D12).
[4] B.Levi, B.Georgeot and D.L.Shepelyansky, *Quantum computing of quantum chaos in the kicked rotator model*, Phys. Rev. E **67**, 046220 (2003) [quant-ph/0210154] (D4,D8).
[5] S.Bettelli and D.L.Shepelyansky, *Entanglement versus relaxation and decoherence in a quantum algorithm for quantum chaos*, Phys. Rev. A **67**, 054303 (2003) [quant-ph/0301086] (D4,D8).
[6] M.Terraneo and D.L.Shepelyansky, *Imperfection effects for multiple applications of the quantum wavelet transform*, Phys. Rev. Lett. **90**, 257902 (2003) [quant-ph/0303043] (D4,D7,D8).
[7] A.A.Pomeransky, *Strong superadditivity of the entanglement of formation follows from its additivity*, Phys. Rev. A **68**, 032317 (2003) [quant-ph/0305056] (D11).
[8] R.Livi, S.Ruffo and D.L.Shepelyansky, *Le cheminement de Kolmogorov de l'integrabilite au chaos et au-dela*, p.15-45, Eds. R.Livi et A.Vulpiani, in *L'heritage de Kolmogorov en physique* (Belin, Paris, (2003)) (in French); *Kolmogorov pathways from integrability to chaos and beyond*, Eds. R.Livi and A.Vulpiani, in *The Kolmogorov legacy in physics* (Lecture Notes in Physics, Springer, Berlin (2003)) (D4).
[9] S.Montangero, G.Benenti and R.Fazio, *Dynamics of entanglement in quantum computers with imperfections*, Phys. Rev. Lett. **91**, 187901 (2003) [quant-ph/0307036] (D7).
[10] G.G.Carlo, G.Benenti and G.Casati, *Teleportation in a noisy environment: a quantum trajectories approach*, Phys. Rev. Lett. **91**, 257903 (2003) [quant-ph/0307065] (D8,D12).
[11] G.Casati and S.Montangero, *Measurement and information extraction in complex dynamics quantum computation*, in Proceedings of First International Workshop DICE (Decoherence, Information, Complexity and Entropy), Piombino, Italy, 2002, Ed. H.-

T. Elze, Lecture Notes in Physics, Vol. 633 (2003), p. 341 Springer-Verlag [quant-ph/0307165] (D4).
[12] G.Alber, Th.Beth, Ch.Charnes, A.Delgado, M.Grassl, M.Mussinger, *Detected-jump-error-correcting quantum codes, quantum error designs, and quantum computation*, Phys. Rev. A **68**, 012316 (2003) [quant-ph/0208140] (D8,D12).
[13] Th.Beth, Ch.Charnes, M.Grassl, G.Alber, A.Delgado, M.Mussinger, *A New Class of Designs Which protect against Quantum Jumps*, Designs, Codes and Cryptography **29**, 51 (2003) (D8,D12).
[14] G.Alber, M.Mussinger, A.Delgado, *Quantum information processing and error correction with jump codes*, in *Quantum Information Processing*, edited by Th. Beth and G. Leuchs (Wiley-VCH, Berlin, 2003) (D8,D12).

Appendix C - List of EDIQIP Talks and Posters (2004)

[1] Contributed talk D.L. Shepelyansky: *Quantum computation in presence of imperfections and decoherence*, EU IST-FET QIPC Program Review, Bratislava, SK, 16 - 18 February 2004.
[2] Invited talk D.L. Shepelyansky: *Quantum algorithms in presence of imperfections* at the International workshop *Quantum entanglement - from error correction to secure key distribution*, Waldemar-Peterson Haus, Hirschegg, Austria, 30 March - 2 April 2004.
[3] Invited talk D.L. Shepelyansky: *Quantum computation of complex dynamics in presence of imperfections* at NATO Advanced Research Workshop *Decoherence, entanglement and information protection in complex quantum systems*, Ecole de Physique Les Houches, France, 25 - 30 April 2004.
[4] Invited talk D.L. Shepelyansky: *Applications of quantum chaos to realistic quantum computations and sound treatment on quantum computers*, SPIE Conference 5472 *Noise and information in nanoelectronics*, Maspalamos, Gran Canaria, Spain, 25 - 28 May 2004.
[5] Poster presentation D.L. Shepelyansky: *Effects of decoherence and imperfections for quantum algorithms* at ERATO Conference on Quantum Information Science 2004, Tokyo, Japan, 4 September 2004.
[6] Poster presentation D.L.Shepelyansky and B.Georgeot: *Quantum computation in presence of imperfections*, ARO Quantum Computing Program Review (Orlando (FL, USA)), August 16-20, 2004.
[7] Contributed talk K. Frahm: *Universal regime of fidelity decay in realistic quantum computations*, Quantum information and Decoherence in Nanosystems (39th Rencontres de Moriond, La Thuile, Italy), January 25 - February 1, 2004.
[8] Invited talk B. Georgeot: *Quantum chaos and quantum computing* at *Quantum Chaos and its applications to mesoscopic physics*, Focus Program, APCTP, Pohang, Korea, July.
[9] Poster presentation J.W. Lee: *Quantum algorithms and decoherence with quantum trajectory methods*, 5th European QIPC Workshop, Rome, Italy, 20th-22th September 2004.

[10] Contributed talk B. Georgeot: *Quantum computation of chaotic systems*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 december, 2004.
[11] Contributed talk D. Braun: *Entanglement from coupling to a common heat bath*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 December, 2004.
[12] Contributed talk J. Lages: *Decoherence by a chaotic many-spin bath*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 December, 2004.
[13] Contributed talk J. Lages: *Decoherence by a chaotic many-spin bath*, GDR 2426 *Physique Quantique Mésoscopique*, Aussois, France, 6-9 December, 2004.
[14] Invited talk K. Frahm: *Quantum computation and quantum chaos with random matrix theory*, GDR 2426 *Physique Quantique Mésoscopique*, Aussois, France, 6-9 December, 2004.
[15] Invited talk G. Casati: *Quantum computation of dynamical systems*, at the conference *Problemi Attuali di Fisica Teorica*, Vietri sul Mare, Italy, 2-7 April, 2004.
[16] Invited talk G. Casati: *On the stability of quantum motion*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.
[17] Invited talk G. Casati: *Classical and quantum fidelity decay and correlation functions in dynamical systems*, *Complexity in science and society*, Education Center of Ancient, Olympia, Greece, July 19-26, 2004.
[18] Contributed talk G. Casati: *Quantum computing and quantum chaos*, ARO Quantum Computing Program Review (Orlando (FL, USA)), August 16-20, 2004.
[19] Invited talk G. Casati: *On the stability of quantum motion*, *Quantum Chaos in the 21st century*, Cuernavaca, Mexico, august 18-25, 2004.
[20] Invited talk G. Casati: *Quantum-classical correspondence in perturbed chaotic systems*, Second International Workshop DICE 2004, Piombino, Italy September 1-4, 2004.
[21] Invited talk G. Casati: *Quantum-classical correspondence in perturbed chaotic systems*, School and Workshop on Quantum Entanglement, Decoherence, Information, and Geometrical Phases in Complex Systems, Abdus Salam International Centre for theoretical Physics, Trieste, Italy November 1-5, 2004.
[22] Invited talk G. Benenti: *Quantum computing of dynamical quantum systems: Information extraction and noise effects*, at the conference *Problemi Attuali di Fisica Teorica*, Vietri sul Mare, Italy, 2-7 April, 2004.
[23] Invited talk G. Benenti: *Quantum computing of dynamical quantum systems: Information extraction and noise effects*, at the annual meeting of the Italian Physical Society, Brescia, Italy, 20-25 September, 2004.
[24] Contributed talk G. Benenti: *Quantum ratchets in dissipative chaotic systems*, at the annual meeting of the MIUR project *Fault tolerance, control and stability in quantum information processing*, Torino, Italy, 11-12 November, 2004.
[25] Invited talk R. Schack: *From Degrees of Belief to Quantum Process Tomography*, One-day conference on "Probability in Quantum Mechanics", Centre for Philosophy of Natural and Social Science, LSE, London, UK, February 2004.
[26] Invited talk R. Schack: *The frequency operator in quantum mechanics*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.

[27] Invited talk R. Schack: *A de Finetti Representation Theorem for Quantum Process Tomography*, nternational Symposium on Entanglement, Information and Noise, Krzyzowa/Kreisau, Poland, June 2004.
[28] Invited talk R. Schack: *Bayesian Approach to Quantum Probability*, Twentyfourth International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering (MaxEnt'04), Max Planck Institute for Plasma Physics (IPP), Garching, Germany, July 2004.
[29] Invited talk A. Soklakov: *Algorithm for encoding probability distributions in quantum states*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.
[30] Poster presentation A. Soklakov: *Encoding probability distributions in quantum states*, 7th International Conference on Quantum Communication, Measurement, and Computing (QCMC), University of Strathclyde, UK, July 2004.
[31] Poster presentation A. Soklakov: *Quantum state preparation via Grover iterations*, 5th European QIPC Workshop, Rome, Italy, 20th-22th September 2004.
[32] Contributed talk G. Alber and O. Kern: *Quantum computation with jump codes under non-ideal conditions*, Annual meeting of the German Physica Society (DPG) in Munich, 22-26 March 2004.
[33] Contributed talk B. Georgeot: *Quantum computation of chaotic systems*, Second Feynman Festival, Maryland, USA, August 20-25, 2004.

Appendix D - List of PhD theses

[1] Andrei Pomeransky, Thesis of Universite Paul Sabatier (supported by ARO/NSA/ARDA): *Entanglement and imperfections in quantum computation.*
Jury:
V.Akulin (examinator, LAC, Orsay),
B.Georgeot (co-director, LPT, Toulouse),
K.Frahm (president, LPT, Toulouse),
J.-L.Pichard (referee, CEA, Saclay),
R.Schack (EDIQIP referee, RHUL, London),
D.Shepelyansky (director, LPT, Toulouse).
Defended at LPT, IRSAMC, Univ. P.Sabatier, Toulouse, October 22, 2004.
[2] Benjamin Lévi, Thesis of Universite Paris VII: *Computation of quantum systems by realistic quantum computers.*
Jury:
G.Alber (EDIQIP examinator, TUD, Darmstadt),
D.Feinberg (referee, CNRS Grenoble),
B.Georgeot (director, LPT, Tlse),
Ph.Lafarge (president, Paris VII),
D.Shepelyansky (examinator, LPT, Tlse),
D.Weinmann (referee, CNRS Strasbourg).
Defended at LPT, IRSAMC, Univ. P.Sabatier, Toulouse, November 9, 2004.

Appendix E - List of EDIQIP Deliverables

In the following deliverables table we provide, for each scientific deliverable, the related scientific publications (titles and publications details on these references are given in Appendix B1).

DELIVERABLES TABLE

Project Number: IST-2001-38869
Project Acronym: EDIQIP
Title: Effects of Decoherence and Imperfections for Quantum Information Processing

Del. No.	**Revision**	**Title**	**Type**	**Classification**	**Due Date**	**Issue Date**
D6	1.0	Periodic Report	R	Int.	18	30.06.2004
D7	1.0	Static Imperfections Time Scales for QIP Publications: Refs. [1],[7],[8], [9],[10],[11],[13],[18], [20],[30],[32],[33]	R	Pub.	24	31.12.2004
D8	1.0	Decoherence Time Scales for QIP Publications: Refs. [6],[7],[10], [11],[12],[15],[17], [19],[21],[26],[27] [28],[29],[30],[32],[33]	R	Pub.	24	31.12.2004
D9	1.0	Annual Report	R	Int.	24	07.01.2005
D11	1.0	New Quantum Algorithms for Physical Problems Publications: Refs. [1],[2],[3],[4] [11],[16],[23] [24],[25],[31]	R	Pub.	36	31.12.2004
D12	1.0	Numerical Simulator of Decoherence/Imperfection Effects Publications: Refs. [4],[7],[9],[10], [11],[15],[19],[30] [32],[33]	R	Pub.	36	31.12.2004

Appendix F - List of EDIQIP Selected Publications for Deliverables

The selected EDIQIP publications for Deliverables are given in the Annex S (printed version, available upon request). Here we give only the list of them. Publications in the total publication list from Appendix B1 are marked as R1,R2,...,R24. Scientific deliverables are marked by D4,D7,D8,D11,D12.

[1] A.A.Pomeransky, O.V.Zhirov and D.L.Shepelyansky, *Phase diagram for the Grover algorithm with static imperfections*, Eur. Phys. J. D **31**, 131 (2004) [quant-ph/0403138] (R9); (D7,D12).

[2] B.Levi and B.Georgeot, *Quantum computation of a complex system: the kicked Harper model*, Phys. Rev. E **70**, 056218 (2004) [quant-ph/0409028] (R11); (D7,D8,D11,D12).

[3] G.G. Carlo, G. Benenti, G. Casati and C. Mejía-Monasterio, *Simulating noisy quantum protocols with quantum trajectories*, Phys. Rev. A **69**, 062317 (2004) [quant-ph/0402102] (R15); (D8,D12).

[4] G. Benenti, G. Casati and S. Montangero, *Quantum computing and information extraction for dynamical quantum systems*, Quantum Information Processing **3**, 273 (2004) [quant-ph/0402010] (R16); (D11).

[5] G.G. Carlo, G. Benenti, G. Casati and D.L. Shepelyansky *Quantum ratchets in dissipative chaotic systems*, submitted to Phys. Rev. Lett. [cond-mat/0407702] (R19); (D8,D12).

[6] C. Mejía-Monasterio, G. Benenti, G.G. Carlo and G. Casati, *Entanglement across a Transition to Quantum Chaos*, submitted to Phys. Rev. A [quant-ph/0410246] (R20); (D7).

[7] A. N. Soklakov and R. Schack, *Efficient state preparation for a register of quantum bits*, submitted to Phys. Rev. Lett. [quant-ph/0408045] (R23); (D11).

[8] A. Scherer, A. N. Soklakov and R. Schack, *A simple necessary decoherence condition for a set of histories*, Phys. Lett. A **326**, 307 (2004) [quant-ph/0401132] (R26); (D8).

[9] O. Kern, G. Alber and D. L. Shepelyansky, *Quantum error correction of coherent errors by randomization*, to be published in Eur. Phys. J. D [quant-ph/0407262] (R30); (D7,D8,D12).

[10] M. Terraneo, B. Georgeot and D.L. Shepelyansky, *Quantum computation and analysis of Wigner and Husimi functions: toward a quantum image treatment*, submitted to Phys. Rev. E [quant-ph/0412123] (R31); (D11).