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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 2005 a total of 29 manuscripts (including 3 PRL) 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 20 talks, lectures and posters at scientific conferences in different countries, including Europe, Japan, Korea and Mexico. 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. This dissemination has been especially enhanced by the organization of an International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos* organized in Varenna in July 2005 (directors G.Casati, D.Shepelyansky and P.Zoller). This School attracted enormous number of students from all over the world (near 75 students participated in the work of the School, about 120 applications had been received, the number of students was in fact restricted by the hall capacities; see the web site: http://scienze-como.uninsubria.it/benenti/varenna2005.html). The dissemination will be additionally enhanced by the coming up Trimester at the Institute Henri Poincaré, Paris, on *Quantum Information, Computation and Complexity*, in Jan-Apr 2006 (directors Ph.Grangier, M.Santha and D.Shepelyansky; see the web site: http://www.quantware.ups-tlse.fr/IHP2006). At the moment about 130 participants are registered for the Trimester. The QIPC Review meeting will be a part of this Trimester.

Among the highlight results obtained in the frame of this project in 2005 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. These effects are investigated in [10] for the the all-silicon quantum computer in presence of magnetic field gradient, recently proposed by the Yamamoto group in Phys. Rev. Lett. **89**, 017901 (2002). The results obtained in [10] determine the stable and quantum chaos regimes in the quantum computer hardware identified as a function of magnetic field gradient and dipole-dipole

couplings between qubits on a square lattice. It is shown that a strong magnetic field gradient leads to suppression of quantum chaos.

(b) New quantum algorithms are developed in [7] and [8]. They allow to simulate on quantum computers a delocalization transition in small-world models which now became very popular in the community of statistical mechanics since they describe reliably links in human society, internet, publication data bases etc. It is shown that the developed quantum algorithms will give at minimum a polynomial gain in such systems. A quantum algorithm for intermediate quantum maps is constructed and tested numerically in [8]. The accuracy of these algorithms in presence of realistic errors is also analyzed. In [25] we generalize the reversible map algorithms (quantum as well as classical, e.g. baker's map) to the case of irreversible time evolutions. This case has been treated by exploiting the similarity to the problem of Bayesian updating.

(c) The theory of quantum trajectories is applied to simulate the effects of quantum noise sources induced by the dissipative environment on the quantum chaos algorithm (quantum sawtooth map) [4] and the Grover quantum search algorithm [12]. We study the models that generalizes single qubit noise channel like amplitude damping to the many-qubit situation. The effects of dissipative decoherence on dynamical localization are carefully analyzed in [4]. This regime is close to a currently running experiment in the group of David Cory at MIT with NMR-based quantum computation of dynamical localization. A generic decay law for fidelity decay and Grover probability decay are obtained [4,12]. The rate of the decay is proportional to the number of qubits in a quantum computer and a one-qubit decay rate. This result is in agreement with findings of last year obtained for teleportation and the quantum baker's map and hence give the universal decay law for dissipative decoherence. Thus, the number of gates N_g that can be reliably implemented without quantum error correction drops only polynomially with the number of qubits, $N_g \propto 1/n_q$. In the case of static imperfections $N_g \propto 1/n_q^5$ and therefore the static imperfections may play a very significant role.

The effects of dissipative decoherence on dynamical localization in the quantum sawtooth map have been recently tested experimentally by the group of D.Cory at MIT on a 3-qubit NMR-based quantum computer (quant-ph/0512204). In agreement with the results of Ref. [4] experiments show that dynamical localization has certain stability in respect to dissipative decoherence and static imperfections. We note that this quantum algorithm had been developed by Toulouse-Como nodes and was studied in Ref. [4] and Refs. [4,16] (Appendix B2) and Refs. [2,3,5] (Appendic B3).

The effect of a dissipative environment on cold atoms transport in laser fields is analyzed in [6,9]. The phenomenon of the Ehrenfest explosion of a quantum wave packet is found in [6], while the quantum synchronization phenomenon is described in [9].

(d) Deterministic environment and measurement models are analyzed in [5]. It is shown that in a regime of quantum chaos a deterministic detector can realize a projective measurements with the rate determined by the Lyapunov exponent which characterizes the classical chaotic dynamics. The links between classical dynamical chaos and quantum dephasing for the Loschmidt echo and fidelity are established in [16]. Effects of noise on quantum purification are determined in [17]. A quantitative measure of interference is proposed in [11]. Ref. [26] studies decoherence and entropy increase for different coarse-grainings of the quantum baker's map. Ref. [26] identifies, in the framework of the

decoherent histories formalism, those coarse-grainings that lead to the smallest entropy increase, i.e., those coarse-grainings that lead to the most predictable classical evolution.

(e) A general quantum error correction method PAREC was presented last year being capable of correcting coherent errors originating from static residual inter-qubit couplings in a quantum computer [3]. As a major result of this year in this direction we show that it could be demonstrated that the error correcting properties of the PAREC method could be increased significantly [28]. For this purpose we developed a new dynamical decoupling scheme which is based on embedding a deterministic decoupling scheme into the stochastic PAREC method. This way it is possible to combine the advantages of both methods and to increase the suppression of undesired perturbations of quantum systems significantly even for long interaction times. The stabilizing properties of one-error correcting jump codes under realistic non-ideal conditions are analyzed in [27].

(f) The Quantware Library with quantum numerical recipes is created in the frame of EDIQIP project. It allows to simulate realistic quantum computations with about 20 - 30 qubits. The Library is publicly available via the web site given in [29].

The obtained results allow us to develop a deep understanding of decoherence and imperfection effects during quantum information processing. They 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)

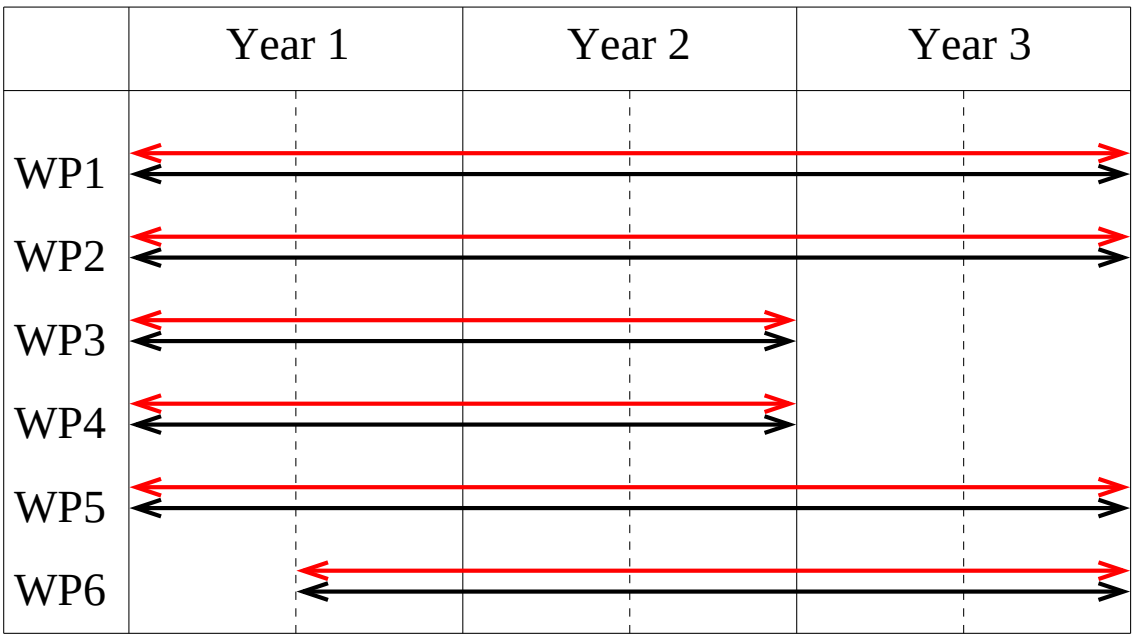

Fig.1. Gantt chart for workpackages: black arrows represent the work to be done and red/gray arrows the work accomplished.

Workpackage progress reports are listed in Appendix A, publications are listed in Appendix B (Appendix B1: papers published or submitted during 2005; Appendix B2: papers published in journals in 2004), the list of EDIQIP talks and posters is presented in Appendix C. A detailed list of EDIQIP deliverables is given in Appendix E. A selection of deliverables is bundled in Annex S (the selection list is given in Appendix F).

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 (completed after 36 months)

D12: Numerical Simulator of Decoherence/Imperfection Effects (completed after 36 months)

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

(a1) In Ref. [10], we present numerical and analytical studies of a quantum computer proposed by the Yamamoto group in Phys. Rev. Lett. **89**, 017901 (2002). The stable

and quantum chaos regimes in the quantum computer hardware are identified as a function of magnetic field gradient and dipole-dipole couplings between qubits on a square lattice. It is shown that a strong magnetic field gradient leads to suppression of quantum chaos. In the Yamamoto group proposal the qubits are spin-halves nuclei (e.g. isotopes ^{29}Si) placed on a 2D lattice on a surface of a crystalline solid matrix (e.g. of spin-0 ^{28}Si nuclei). A magnetic field gradient is assumed to be applied in the plane of the lattice to allow address qubits individually. At present large gradients can be realized experimentally and thousands of qubits can be addressed. In addition to qubit frequency gradient there are also dipole-dipole couplings between qubits typical of liquid-state NMR. These two elements, frequency gradient and dipole-dipole couplings between qubits, also appear in other proposals of quantum computers: e.g. for trapped polar molecules in electric field with gradient and trapped-ion spin molecules with magnetic gradient. Therefore the investigation of generic properties of such systems is important for future experimental implementations. The results obtained in [10] determine the stable and quantum chaos regimes in the quantum computer hardware identified as a function of magnetic field gradient and dipole-dipole couplings between qubits on a square lattice. The critical strength of dipole-dipole couplings, above which the quantum chaos sets in, is proportional to the magnetic field gradient and inversely proportional to the square-root of the number of qubits. The rate for the onset of quantum chaos is also determined. For typical experimental parameters (e.g. ^{29}Si and lattice constant $b = 1.9$Å) the quantum hardware is in the stable regime at magnetic field gradient $g \approx 2$ T/μm for $n_q = 100$ qubits and at $g \approx 20T/\mu m$ for $n_q = 10^4$ qubits. These values can be realized with modern experimental methods.

(b1) Recently, much attention has been attracted to the study of small-world networks. They have been shown to describe social and biological networks, Internet connections, airline flights and other complex networks. In such systems, it is possible to go from a given point to any other through only a small number of links. Well-established classical models have been proposed and analyzed by statistical methods. The study of quantum networks with the same property has started only recently, showing that these systems present interesting features related to quantum transport, delocalization and fast diffusion.

In the paper [7], we study a quantum small-world network with disorder and show that the system exhibits a delocalization transition. A quantum algorithm is built up which simulates the evolution operator of the model in a polynomial number of gates for exponential number of vertices in the network. The total computational gain is shown to depend on the parameters of the network and a larger than quadratic speed-up can be reached. We also investigate the robustness of the algorithm in presence of imperfections.

(b2) In Ref. [8] we study quantum maps displaying spectral statistics intermediate between Poisson and Wigner-Dyson. It is shown that they can be simulated on a quantum computer with a small number of gates, and efficiently yield information about fidelity decay or spectral statistics. We study their matrix elements and entanglement production, and show that they converge with time to distributions which differ from random matrix predictions. A randomized version of these maps can be implemented even more economically, and yields pseudorandom operators with original properties, enabling for example to produce fractal random vectors. These algorithms are within

reach of present-day quantum computers.

(b3) There exist quantum algorithms for a number of reversible maps, quantum as well as classical, notably those studied in the past by both the RHUL and Toulouse groups. In Ref. [25] we study a generalization of these algorithms to irreversible time evolutions. If the time evolution maps between states that represent probability distributions, i.e., states with real coefficients, it can typically be phrased in terms of Bayesian updating. In these terms, the initial state is known as the prior, and the final state as the posterior. The updating procedure takes the form of a quantum algorithm that prepares an n-qubit quantum register in the state representing the posterior distribution. Depending on how the prior distribution is given, Ref. [25] describes two efficient implementations, one probabilistic and one deterministic, of such an algorithm in the standard model of a quantum computer. Ref. [25] thus provides a partial solution of the problem of modeling irreversible physical evolution on a quantum computer.

In addition Ref. [24] is a much expanded version of a 4-page summary version posted last year and contains a new detailed error and computational resources analysis. In general, a physical simulation problem consists of three parts: (i) the preparation of the initial state, (ii) the time evolution, and (iii) the readout. Ref. [24] gives a detailed general solution to (i) by describing a quantum algorithm to prepare an arbitrary pure state of a register of a quantum computer with fidelity arbitrarily close to 1. 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.

(c1) 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. [4] using the methods of quantum trajectories we investigate the effects of dissipative decoherence in a quantum computer algorithm simulating dynamics in various regimes of quantum chaos including dynamical localization, quantum ergodic regime and quasi-integrable motion. As an example we use the quantum sawtooth algorithm which can be implemented in a polynomial number of quantum gates. It is shown that the fidelity of quantum computation decays exponentially with time and that the decay rate is proportional to the number of qubits, number of quantum gates and per gate dissipation rate induced by external decoherence. In the limit of strong dissipation the quantum algorithm generates a quantum attractor which may have complex or simple structure. We also compare the effects of dissipative decoherence with the effects of static imperfections. This comparison shows that static imperfections lead to more rapid drop of fidelity than in the case of dissipative decoherence.

At present the group of D.Cory (MIT) works on implementation of this quantum algorithm on NMR-based quantum computer with 3 qubits to simulate dynamical localization of quantum chaos (first results are available at quant-ph/0512204).

(c2) The methods of quantum trajectories are also applied to the Grover algorithm

in [12] with up to 16 qubits. The obtained results are in agreement with the dependence found for the quantum sawtooth map in [4] and the quantum baker's map (Ref. [15] in App. B2). This means that the decay rate relation according to which the total decay rate $\Gamma \approx n_q \Gamma_1$, where Γ_1 is one-qubit decay rate, gives a universal description of dissipative decoherence in various quantum algorithms. Therefore it is possible to compare the three classes of quantum errors considered in this project (noisy unitary errors, static imperfections and dissipative decoherence). The comparison shows that the most rapid decrease of fidelity, and thus the accuracy of quantum computation, is produced by static imperfections.

(c3) Quantum simulation is a particular instance of quantum computation, in which a quantum system is simulated by another, for which the level of control is much higher. Therefore, it is foreseen that optical lattices will be used as efficient quantum simulators to shed light in unsolved many-body problems in condensed-matter physics. This expectation has been confirmed by the experimental observation of the superfluid to insulator transition in an optical lattice. In the frame of the EDIQIP project we have shown that the class of problems for which optical lattices could be useful simulators also includes complex dissipative quantum dynamical systems. Cold atoms exposed to time-dependent standing waves of light already proved to be an ideal test bed to explore the features of the quantum dynamics of nonlinear systems. They allowed the experimental investigation of several important physical phenomena, such as dynamical localization, quantum resonances, chaos assisted tunneling, directed transport, Zeno and anti-Zeno effects, and decoherence. The laser field can create 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). Furthermore, the parameters of the optical potential can be chosen at will, through an appropriate choice of the laser field configuration. In this way both symmetric and asymmetric optical potentials are created. Optical lattices appear then as the ideal system to generate models for the Hamiltonian motion of particles in a periodic potential. Moreover, dissipative friction forces can be produced by techniques such as Doppler cooling, so that also non-Hamiltonian dissipative dynamics can be investigated.

Using the method of quantum trajectories we study [2] a quantum chaotic dissipative system which exhibits directed transport (also known as ratchet effect), appearing for particles in a pulsed asymmetric potential in the presence of a dissipative environment. The directed transport emerges 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. The impact of noise on these results is also considered and the robustness of our ratchet model is demonstrated. These studies give better understanding of quantum information transport in presence of dissipative decoherence. Moreover they allow us to test the efficiency of the quantum trajectories approach, which promise to become the main tool for the simulation of quantum information processing in realistic environments.

We also use the quantum trajectories approach to investigate the stability of quantum chaotic motion in open systems. The quantum dynamics of chaotic Hamiltonian systems is characterized by an exponentially fast spreading of the quantum wave packet.

The spreading rate is given by the Lyapunov exponent, which measures the rate of exponential instability of classical chaotic motion. This implies that the classical concept of trajectory becomes meaningless after the so-called Ehrenfest time scale. This time scale is logarithmically short in the effective Planck constant of the system. This conclusion is no longer valid in an open system. We show [6] that the coupling to a dissipative environment can restore the true chaos typical of classical mechanics, characterized by positive Kolmogorov-Sinai entropy and exponential divergence of nearby trajectories. We show that, for strong dissipation, the quantum wave function in the phase space collapses onto a compact packet which follows classical chaotic dynamics and whose area is proportional to the Planck constant. In contrast, at weak dissipation the exponential instability of Hamiltonian quantum dynamics up to the Ehrenfest time scale dominates and leads to the Ehrenfest explosion of a quantum wave packet. The transition from collapse to explosion takes place when the dissipation time scale exceeds the Ehrenfest time.

We also consider quantum simulation in Josephson junction circuits. In particular, we show [14] that the quantum kicked rotator model can be realized in a periodically driven superconducting nanocircuit. A study of the fidelity would allow the experimental investigation of exponential instability of quantum motion inside the Ehrenfest time scale, chaotic diffusion and quantum dynamical localization. We propose and experimental setup to measure the fidelity and discuss the impact of different noise sources.

In Ref. [9] using the methods of quantum trajectories we study numerically a quantum dissipative system with periodic driving which exhibits synchronization phenomenon in the classical limit. The model allows to analyze the effects of quantum fluctuations on synchronization and establish the regimes where the synchronization is preserved in a quantum case (quantum synchronization). Our results show that at small values of Planck constant $\hbar$ the classical devil's staircase remains robust with respect to quantum fluctuations while at large $\hbar$ values synchronization plateaus are destroyed. Quantum synchronization in our model has close similarities with Shapiro steps in Josephson junctions and it can be also realized in experiments with cold atoms.

(d1) The long-standing problem of quantum measurement has recently gained a renewed interest due to its relevance for quantum information processing. Indeed, one of the requirements for the physical implementation of quantum computation is the ability to readout a single two-level quantum system (qubit). This problem has been solved in ion-trap quantum computation using quantum jump detection. In solid-state implementations, the single-qubit measurement is very challenging and has been widely discussed. Moreover, various readout schemes have been experimentally realized, for instance by the groups of D. Esteve (Saclay), J.E. Mooij (Delft) and Nakamura (NEC, Japan).

A detector can be seen as a complex quasi-classical object coupled to a quantum system. It is therefore interesting to investigate the dynamical evolution of concrete system-detector models. We discuss in [5] a deterministic model of detector coupled to a two-level system (a qubit). The detector is a quasi-classical object whose dynamics is described by the kicked rotator Hamiltonian. We show that in the regime of quantum chaos the detector acts as a chaotic bath and induces decoherence of the qubit. We discuss the dephasing and relaxation rates and demonstrate that the main features of single-qubit decoherence due to a heat bath can be reproduced by our fully deterministic

dynamical model. Moreover, we show that, for strong enough qubit-detector coupling, the dephasing rate is given by the rate of exponential instability of the detector's dynamics, that is, by the Lyapunov exponent of classical motion. Finally, we discuss the measurement in the regimes of strong and weak qubit-detector coupling. For the case of strong coupling the detector performs a measurement of the up/down state of the qubit. In the case of weak coupling, due to chaos, the dynamical evolution of the detector is strongly sensitive to the state of the qubit. However, in this case it is unclear how to extract a signal from any measurement with a coarse-graining in the phase space on a size much larger than the Planck cell.

(d2) The relation between classical dynamical chaos and quantum dephasing is still an open important problem, potentially relevant also for the prospects of quantum computation. In order to elucidate this problem, we consider in [16] the quantum Loschmidt echo or fidelity. This quantity is a measure of the stability of quantum motion under perturbations and its behavior has been already extensively investigated in different parameter regimes and in relation to the nature of the corresponding classical motion as well as a standard tool to explore the stability of quantum computation. We discuss the dephasing induced by the internal classical chaotic motion in the absence of any external environment. We relate the dephasing to the decay of the quantum Loschmidt echo which, in the semiclassical limit, is expressed in terms of an appropriate classical correlation function. Our results are derived analytically for the example of a nonlinear driven oscillator and then numerically confirmed for the kicked rotor model.

(d3) A central problem of quantum communication is how to reliably transmit quantum information through a noisy quantum channel. The carriers of information (the qubits) unavoidably interact with the external world, leading to phenomena such as decoherence and absorption. In particular, if a member of a maximally entangled EPR (Einstein-Podolsky-Rosen) pair is transmitted from a sender (known as Alice) to a receiver (Bob) through a quantum channel, then noise in the channel can degrade the amount of entanglement of the pair. This problem is of primary importance for entanglement-based quantum cryptography, in protocols such as E91 (Ekert, 1991).

Entanglement purification techniques exist. In particular, they have been applied to quantum cryptography and a quantum privacy amplification (QPA) iterative protocol was proposed, that eliminates entanglement with an eavesdropper by creating a small number of nearly perfect (pure) EPR states out of a large number of partially entangled states. This protocol is based on the so-called LOCC, that is on local quantum operations (quantum gates and measurements performed by Alice and Bob on their own qubits), supplemented by classical communication.

Under realistic conditions, the quantum operations themselves are unavoidably affected by errors and introduce a certain amount of noise. We study in [17] the stability under quantum noise effects of the quantum privacy amplification protocol for the purification of entanglement in quantum cryptography. We assume that the E91 protocol is used by two communicating parties (Alice and Bob) and that the eavesdropper Eve uses the isotropic Bužek-Hillery quantum copying machine to extract information. Entanglement purification is then operated by Alice and Bob by means of the quantum privacy amplification protocol and we present a systematic numerical study of the impact of all possible single-qubit noise channels on this protocol. We find that both the qualitative

behavior of the fidelity of the purified state as a function of the number of purification steps and the maximum level of noise that can be tolerated by the protocol strongly depend on the specific noise channel. These results provide valuable information for experimental implementations of the quantum privacy amplification protocol.

(d4) In Ref. [11] we introduce an interference measure which allows to quantify the amount of interference present in any physical process that maps an initial density matrix to a final density matrix. In particular, the interference measure enables one to monitor the amount of interference generated in each step of a quantum algorithm. We show that a Hadamard gate acting on a single qubit is a basic building block for interference generation and realizes one bit of interference, an "i-bit". We use the interference measure to quantify interference for various examples, including Grover's search algorithm and Shor's factorization algorithm. We distinguish between "potentially available" and "actually used" interference, and show that for both algorithms the potentially available interference is exponentially large. However, the amount of interference actually used in Grover's algorithm is only about 3 i-bits and asymptotically independent of the number of qubits, while Shor's algorithm indeed uses an exponential amount of interference.

(d5) In continuation of our work on decoherence for chaotic quantum maps Ref. [26] studies decoherence and entropy increase for different coarse-grainings of the quantum baker's map. Ref. [26] identifies, in the framework of the decoherent histories formalism, those coarse-grainings that lead to the smallest entropy increase, i.e., those coarse-grainings that lead to the most predictable classical evolution. We find that these are exactly those coarse-grainings that correspond to the natural representation of the map on a quantum register. The quantum baker's map is the first chaotic map that has been successfully implemented on a three-qubit NMR quantum computer. Due to its simplicity, it may well be the first chaotic map to be implemented on larger quantum computers. The quantum baker's map has a natural representation on a quantum register, i.e., a string of qubits, on which it acts in a way that corresponds closely to classical symbolic dynamics. We exploit this correspondence in our analytical calculations.

(e) In Ref. [3] a general error correcting method has been developed for overcoming the 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.

We have continued to explore the error correcting properties of our recently developed stochastic decoupling method PAREC in Ref. [28]. As a major result it could be demonstrated that the error correcting properties of the PAREC method could be increased significantly. For this purpose we developed a new dynamical decoupling scheme which is based on embedding a deterministic decoupling scheme into the stochastic PAREC method. This way it is possible to combine the advantages of both methods and to increase the suppression of undesired perturbations of quantum systems significantly even for long interaction times. As a first application the stabilization of a quantum mem-

ory was discussed which is perturbed by one-and two-qubit interactions. Compared to already existing deterministic decoupling methods this embedding procedure does not require any major additional computational effort and it is well suited for stabilizing quantum memories and quantum algorithms against coherent inter-qubit couplings.

In addition, we have further explored the stabilizing properties of one-error correcting jump codes under realistic non-ideal conditions Ref. [27]. For this purpose the quantum algorithm of the quantum tent-map was decomposed into a particular universal set of Hamiltonian quantum gates which ensures perfect correction of spontaneous decay processes under ideal circumstances even if they occurred during a gate operation. Within this framework we developed an entanglement gate which is capable of entangling any two logical qubits of different one-error correcting code spaces. With the help of this gate simultaneous spontaneous decay processes affecting physical qubits of different code spaces could be corrected. As a consequence decoherence could be suppressed significantly.

(f) The Quantware Library is now freely open 24 hours a day, 7 days a week, all over a year for public all over the world at the web site: http://www.quantware.ups-tlse.fr/QWLIB/ . It gives Quantum Numerical Recipes (numerical codes) to simulate realistic quantum computations in presence of static imperfections, noisy errors in quantum gates and dissipative decoherence. It may run computations with about 20 - 30 qubits and various quantum algorithms.

2.2. Work schedule

The results obtained in the 36 months perform all tasks described in the Workpackages WP1-WP6.

The theoretical studies of decoherence effects in the quantum sawtooth map are now studied experimentally with NMR-based quantum computers in the group of D.Cory at MIT (quant-ph/0512204). Benjamin Lévi, who finished his PhD thesis in Toulouse, now became postdoc in the group of D. Cory at MIT and works in this direction. Software codes have been developed to simulate various effects of imperfections and decoherence and error-correction. They are now available to the public.

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 D10 - Periodic Report

The report on the Deliverable D10 is presented at 30.06.2005. It describes the current status of scientific research progress in the frame of EDIQIP project.

3.2. Deliverable D11 - New Quantum Algorithms for Physical Problems

This scientific Deliverable D11 is completed and it is presented in the publications Refs. [1],[7],[8],[13],[18],[19],[20],[22],[23],[24],[25],[26],[27],[28] given in the Appendix B1. The Issue date is 31.12.2005. The description of the scientific results for Deliverable D11 is given in Sections 1.0 and 2.1. Deliverable D11 in the form of selected publications is given in Annex S.

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

This scientific Deliverable D12 is completed and it is presented in the publications Refs. [2],[3],[4],[5],[6],[9],[10],[11],[12],[16],[17],[28],[29] given in the Appendix B1. The Issue date is 31.12.2005. The description of the scientific results for Deliverable D11 is given in Sections 1.0 and 2.1. Deliverable D12 in the form of selected publications is given in Annex S.

3.4. Deliverable D13 - Technical Implementation Plan

The technical implementation plan in the form of the Deliverable D13 is presented at 03.01.2005. It describes the technical implementation plan of EDIQIP project.

3.5. Deliverable D14 - Annual Report

This is the annual report on the Deliverable D14 presented at 03.01.2005. It describes the status of scientific research progress in the frame of EDIQIP project and gives the description of Deliverables achieved. It is available at the EDIQIP web page
http://www.quantware.ups-tlse.fr/EDIQIP/

3.6. Deliverable D15 - Final Report

The final report in the form of the Deliverable D15 is presented at 03.01.2005. It describes the final 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/

4. Project Management

The consortium members met in various combinations on several occasions during 2005: QIPC meeting at Innsbruck (February), Como - Varenna (July), Toulouse (October - November), TUD Darmstadt (November, December).

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 20 talks at international conferences held in Europe, Japan, Korea and Mexico. This gives significant promotion of IST-FET QIPC project.

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

4.2. Project Collaborations

There are 4 joint publications of EDIQIP members (Refs. [2], [3], [5], [6] in Appendix B1). The project collaborations include joint publications with partners of another QIPC project (group of R.Fazio). Two nodes (Como and Toulouse) participated in organization of E.Fermi Summer School in Varenna (2005). Two nodes (Toulouse and Como) participated 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, e.g. group of D.Cory (MIT) and group of D.Averin (Stony Brook).

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, till mid Jan 2005, 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 - to Sept 2005, responsible D.L.Shepelyansky)
Darmstadt: N/A
Como: Dr. Gabriel Carlo (country of origin is Argentina, till Dec 2005, responsible G.Casati)
Como: Dr. Antonio D'Arrigo (country of origin is Italy, 1 month in 2005, responsible G.Casati)
London: Dr. Andrei N. Soklakov (country of origin is Belarus, till end June 2005, responsible R.Schack)

In addition, in 2005 Toulouse node attracted to the EDIQIP research project CNRS postdoc Dr. O. Giraud (till September 2005 as post-doc CNRS and as CNRS researcher from Oct 2005). Como node attracted as ARO/NSA/ARDA post-docs, Dr. C.Mejía-Monasterio and Dr. Antonio D'Arrigo. Toulouse node had close collaboration with senior researcher Dr. O.V.Zhirov from Budker Institute of Nuclear Physics, Novosibirsk, Russia.

At the end of the EDIQIP project Dr. Jae-Weon Lee continues as post-doc at KIAS, Seoul, S.Korea; Dr. J.Lages got permanent position as researcher (MC) at university at Besancon, FR; Dr. G. Carlo got researcher position at CEA at Bouenos-Aires, Argentina; Dr. A. D'Arrigo is post-doc in Italy; Dr. A.Soklakov works at a bank in UK.

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 (1/1/2005-31/12/2005) 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	0	0	10	10	0	0	0	0	0	0	8	8	0	0	9	9	0	0	27	27
WP4	0	0	6	6	0	0	0	0	0	0	12	12	0	0	4	4	0	0	22	22
WP5	2	2	6	6	0	0	0	0	3	3	5	5	5	5	12	12	10	10	23	23
WP6	10	7.5	14	14	0	0	0	0	9	10	11	11	1	1	5	5	20	18.5	30	30
Total	12	9.5	36	36	0	0	0	0	12	13	36	36	6	6	30	30	30	28.5	102	102

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	0.4	0.4	1	1	0.4	0.4	1	1	0.4	0.4	1	1	0.4	0.4	1	1	1.6	1.6	4	4
WP2	0.4	0.4	1	1	0.4	0.4	1	1	0.4	0.4	1	1	0.4	0.4	1	1	1.6	1.6	4	4
WP3	0	0	8	8	0	0	4	4	0	0	6	6	0	0	7	7	0	0	25	25
WP4	0	0	6	6	0	0	4	4	0	0	12	12	0	0	4	4	0	0	26	26
WP5	2	2	6	6	2	2	6	6	3	3	5	5	5	5	12	12	12	12	29	29
WP6	10	10	14	14	1	1	2	2	9	9	11	11	1	1	5	5	21	21	32	32
Total	12.8	12.8	36	36	3.8	3.8	18	18	12.8	12.8	36	36	6.8	6.8	30	30	36.2	36.2	120	120

7. Information Dissemination

As mentioned in the Executive summary, during the report period 29 papers have been posted in the public domain and published in high quality scientific journals. The results have been presented in 20 talks and posters at scientific schools and conferences in Europe, Japan, Korea, and Mexico. The sheer amount of high level publications is matched by their highest quality and impact. 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.

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 particular, the consortium members have contributed to the organization of the following events:

- International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos* (Varenna, Italy, 5-15 July 2005).
  Directors: G. Casati (Como), D.L. Shepelyansky (Toulouse), P. Zoller (Innsbruck), Scientific Secretary: G. Benenti (Como).
  Webpage: http://scienze-como.uninsubria.it/benenti/varenna2005.html
  The School has dealt with the following topics: introduction to quantum computing, quantum logic, information and entanglement, quantum algorithms, error-correcting codes for quantum computation, quantum measurements and control, quantum communication, quantum optics, cold atoms and Bose-Einstein condensates for quantum information, quantum computing with solid state devices, theory and experiments for superconducting qubits, quantum algorithms and quantum chaos, effects of decoherence and imperfections for quantum information processing.
  The School has been attended by 70 students from all over the world. Many of them came from groups supported by the FET-QIPC programme of European Union.

- Workshop on *Noise and Instabilities in Quantum Mechanics* (Trieste, Italy, 3-7 October 2005).
  Directors: G. Casati (Como), S. Lloyd (MIT), G.J. Milburn (Qeensland), Local Organizers: G. Benenti and G. Carlo (Como).
  Webpage available at the ICTP website: http://www.ictp.it/
  The workshop has been focused on the following topics: quantum noise in open quantum systems, entanglement and decoherence, fidelity of quantum motion and quantum to classical correspondence, noise control in quantum computation, entanglement and critical phenomena, quantum information processing with cold atoms in ion traps and with Bose-Einstein condensates in optical lattices.
  This conference has attracted 73 participants from all over the word and given the opportunity to many PhD students or postdocs to present their results in short oral talks and in the poster session which followed the short oral presentations.

- Conference on *Quantum Mechanics and Quantum Computation*, Vietri sul Mare, Italy, 18-20 March, 2005.

Organizers: G. Casati (Como) and S. Pascazio (Bari).
Webpage: http://www.ba.infn.it/∼pascazio/vietri_programma.html
The Conference has focused on topics such as quantum optics and quantum information, experimental implementations of quantum communication protocols, quantum information with Bose-Einstein condensates, measures of entanglement, quantum measurements, quantum noise. The conference has attracted about 70 participants.

- The Programme on *Quantum information, computation and complexity* at the Institut Henri Poincaré, Paris, 4 Jan - 7 April, 2006 is now in the final preparation stage.
  Organizers: Ph.Grangier, M.Santha and D.Shepelyansky
  Webpage: http://www.quantware.ups-tlse.fr/IHP2006/ About 120 participants plan to participate from all over the world.

A further contribution to the dissemination of knowledge has been the publication of Refs. [13,18-20]: while Ref. [18] addresses a wide range of physicists (as in the style of the broadly distributed Europhysics News), Ref. [19] discusses the links between quantum computation and chaos in the recently published Enciclopedia of Condensed Matter Physics. Finally, Refs. [13,20], to be published in the Proceedings of the "E. Fermi" Varenna School on *Quantum Computers, Algorithms and Chaos*, give a review of the results obtained in the study of the effects of decoherence and chaos on the stability of quantum computation. Many of these results were obtained in the frame of the EDIQIP project.

Courses on Quantum Information are given to students at universities at UPS, Como, RHUL, TUD by the participants of the EDIQIP project. In Como, based on these lectures, a two volume book on *Principles of Quantum Computation and Information*, written by G. Benenti, G. Casati and G. Strini, has been nearly completed. The first volume has been published in 2004 and the second one will be published in summer 2006. This book also presents many of the results obtained within the EDIQIP project.

8. Updated Dissemination and Use Plan

8.1. Overview

Deliverable D11: New Quantum Algorithms for Physical Problems for QIP is completed after 36 months of the contract. It provides the newly developed quantum algorithms for various physical problems with complex dynamics. The results are presented in the publications given in Appendix B1 (Refs. [1],[7],[8],[13],[18],[19],[20],[22],[23],[24],[25],[26]), [27],[28]), Appendix B2 (Refs. [1],[2],[3],[4],[11],[16],[19],[23],[24]) and Appendix B3 (Refs. [3],[7]).

Deliverable D12: Numerical Simulator of Decoherence and Imperfections for QIP is completed after 36 months of the contract. It represents an ensemble of quantum numerical recipes which allow to simulate realistic quantum computations in presence of decoherence and imperfections on classical computers (public access is avail-

able via the web site http://www.quantware.ups-tlse.fr/QWLIB/). Such numerical simulations allow to test effects of decoherence and imperfections with up to 20 - 30 qubits. The results are presented in the publications given in Appendix B1 (Refs. [2],[3],[4],[5],[6],[9],[10],[11],[12],[16],[17],[28],[29]), Appendix B2 (Refs. [4],[7], [9],[10], [11],[15],[23],[24]) and Appendix B3 (Refs. [1],[3],[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 2006. 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.

The results of the project will be presented at the Programme "Quantum Information, Computation and Complexity" at the Institut Henri Poincaré, Paris, during 4 Jan - 7 April, 2006. The information about the Programme is available at the website http://www.quantware.ups-tlse.fr/IHP2006/

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. [2],[3],[4],[5],[6],[9],[10],[11],[12],[16],[17],[28],[29]), Appendix B2 (Refs. [4],[7],[9],[10].[11],[15],[23].[24]) and Appendix B3 (Refs. [1],[3],[10], [12],[13], [14]). The codes are publicly available at the web page http://www.quantware.ups-tlse.fr/QWLIB/.

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, or in ion-trap based quantum computations of R.Blatt group at Innsbruck. At present the group of D. Cory, MIT performs quantum algorithm for dynamical localization in the quantum sawtooth map which had been proposed in Toulouse-Como (quant-ph/0512204).

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 reports for 2003, 2004 and 2005 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 29 manuscripts are opened to free public access and published in leading international journals. They include 4 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, Japan, Korea and Mexico. 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*, vols. I and II, by G. Benenti, G. Casati and G. Strini (World Scientific, Singapore). Promotion of EDIQIP results to broad public is given in Refs. [18,19]. The nodes are inter-connected via the web site www.quantware.ups-tlse.fr/EDIQIP. Future promotion of the obtained results is assured by the organization of an International School of Physics Enrico Fermi on *Quantum Computers, Algorithms and Chaos*, hold in 2005 in Varenna and the Semester at Institute Henri Poincaré, Paris, on *Quantum Information, Computation and Complexity*, in Jan-Apr 2006. Other organized events are listed in Sec.7.

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

WP3 is completed and reported in 2004.

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

WP4 is completed and reported in 2004.

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. [1,7,8,13,18,19,20,22,23,24,25,26,27,28].
The simulation of information spreading in small-world systems is studied in [7]. We study a quantum small-world network with disorder and show that the system exhibits a delocalization transition. A quantum algorithm is built up which simulates the evolution operator of the model in a polynomial number of gates for exponential number of vertices in the network. The total computational gain is shown to depend on the parameters of the network and a larger than quadratic speed-up can be reached. In Ref. [8] we study quantum maps displaying spectral statistics intermediate between Poisson and Wigner-Dyson. It is shown that they can be simulated on a quantum computer with a small number of gates, and efficiently yield information about fidelity decay or spectral statistics. In Ref. [25] we study a generalization of algorithms to irreversible time evolutions. If the time evolution maps between states that represent probability distributions, i.e., states with real coefficients, it can typically be phrased in terms of Bayesian updating. Ref. [25] describes two efficient implementations, one probabilistic and one deterministic, of such an algorithm in the standard model of a quantum computer. Ref. [26] studies decoherence and entropy increase for different coarse-grainings of the quantum baker's map. Ref. [26] identifies, in the framework of the decoherent histories formalism, those coarse-grainings that lead to the smallest entropy increase, i.e., those coarse-grainings that lead to the most predictable classical evolution. It is shown [28] that the error correcting properties of the PAREC method [3] could be increased significantly. For this purpose we developed a new dynamical decoupling scheme which is based on embedding a deterministic decoupling scheme into the stochastic PAREC method. The results obtained for new quantum algorithms for physical systems have been reported in Refs. [1],[7],[8],[13],[18],[19],[20],[22],[23],[24],[25],[26]), [27],[28] (year 2005), in Refs. [1],[2],[3],[4],[11],[16],[19],[23],[24] (year 2004) and in Refs. [3],[7] (year 2003). These research results complete the tasks of WP5.

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. [2,3,4,5,6,9,10,11,12,16,17,28,29]. 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 16 qubits for the quantum algorithm simulating the quantum sawtooth map [4] and the Grover algorithm [12]. Effects of static imperfections of Yamamoto group quantum computer proposal have been studied in [10] with up to 18 qubits. Numerical simulation of dissipative quantum dynamics is described in [2,6,9]. Computer codes for the improved PAREC method were developed in Ref. [28], that allowed to test the method with up to 10 qubits and to reach a significant fidelity increase. The results obtained for numerical simulator of decoherence and imperfection effects have been reported in Refs. [2],[3],[4],[5],[6],[9],[10],[11],[12],[16],[17],[28],[29] (year 2005), in Refs. [4],[7], [9],[10], [11],[15],[23],[24] (year 2004) and in Refs. [1],[3],[10],[12],[13],[14] (year 2003). The codes are publicly available at the web site http://www.quantware.ups-tlse.fr/QWLIB/. These research results complete the tasks of WP6.

Appendix B1 - List of EDIQIP Publications (2005)

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

[1] M. Terraneo, B. Georgeot and D.L. Shepelyansky, *Quantum computation and analysis of Wigner and Husimi functions: toward a quantum image treatment*, Phys. Rev. E **71**, 066215 (2005) [quant-ph/0412123] (D11).

[2] G.G. Carlo, G. Benenti, G. Casati and D.L. Shepelyansky *Quantum ratchets in dissipative chaotic systems*, Phys. Rev. Lett. **94**, 164101 (2005) [cond-mat/0407702] (D8,D12).

[3] O. Kern, G. Alber and D. L. Shepelyansky, *Quantum error correction of coherent errors by randomization*, Eur. Phys. J. D **32**, 153 (2005) [quant-ph/0407262] (D7,D8,D12)

[4] J.W.Lee and D.L.Shepelyansky, *Quantum chaos algorithms and dissipative decoherence with quantum trajectories*, Phys. Rev. E **71**, 056202 (2005) [quant-ph/0501120] (D12).

[5] J.W.Lee, D.V.Averin, G.Benenti and D.L.Shepelyansky, *Model of a deterministic detector and dynamical decoherence*, Phys. Rev. A **72**, 012310 (2005) [quant-ph/0501153] (D12).

[6] G.Carlo, G.Benenti and D.L.Shepelyansky, *Dissipative quantum chaos: transition from wave packet collapse to explosion*, Phys. Rev. Lett. **95**, 164101 (2005) [quant-ph/0503081] (D12).

[7] O.Giraud, B.Georgeot and D.L.Shepelyansky, *Quantum computing of delocalization in small-world networks*, Phys. Rev. E **72**, 036203 (2005) [quant-ph/0504188] (D11).

[8] O.Giraud and B.Georgeot, *Intermediate quantum maps for quantum computation* , Phys. Rev. A **72**, 042312 (2005) [quant-ph/0504230] (D11).

[9] O.V.Zhirov and D.L.Shepelyansky, *Quantum synchronization*, Eur. Phys. J. D (to appear) [cond-mat/0507029] (D12).

[10] J.Lages and D.L.Shepelyansky, *Suppression of quantum chaos in a quantum computer hardware*, submitted to Phys. Rev. E [cond-mat/0510392] (D12).

[11] D.Braun and B.Georgeot, *A quantitative measure of interference*, to appear in Phys. Rev. A [quant-ph/0510159] (D12).

[12] O.V.Zhirov and D.L.Shepelyansky, *Dissipative decoherence in the Grover algorithm*, Eur. Phys. J. D (to appear) [quant-ph/0511010] (D12).

[13] B.Georgeot, *Quantum algorithms and quantum chaos*, to be published in the Proceedings of the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005 (D11).

[14] S. Montangero, A. Romito, G. Benenti and R. Fazio, *Chaotic dynamics in superconducting nanocircuits*, Europhys. Lett. **71**, 893 (2005) [cond-mat/0407274] (D8).

[15] C. Mejía-Monasterio, G. Benenti, G.G. Carlo and G. Casati, *Entanglement across a transition to quantum chaos*, Phys. Rev. A **71**, 062324 (2005) [quant-ph/0410246] (D7).

[16] V.V. Sokolov, G. Benenti and G. Casati, *Quantum dephasing and decay of classical correlation functions in chaotic systems*, preprint quant-ph/0504141, submitted to Phys. Rev. Lett. (D12).

[17] G. Benenti, S. Felloni and G. Strini, *Effects of single-qubit quantum noise on entanglement purification*, preprint quant-ph/0505177, to be published in Eur. Phys. J. D (D12).

[18] G. Benenti and G. Casati, *Quantum computers: Where do we stand?*, Europhysics News **36/1**, 16 (2005) (D11).
[19] G. Casati and G. Benenti, *Quantum computation and chaos*, in *Enciclopedia of Condensed Matter Physics*, edited by G. Bassani, G. Liedl and P. Wyder (Elsevier Science, Oxford, United Kingdom, 2005) (D11).
[20] G.Benenti and G. Casati, *Quantum chaos, decoherence and quantum computation*, to be published in the Proceedings of the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005 (D11).
[21] W.-G. Wang, G.Casati, B. Li and T. Prosen, *Uniform semiclassical approach to fidelity decay*, Phys. Rev. E **71**, 037202 (2005) [quant-ph/0407040] (D7).
[22] A. Scherer and A. N. Soklakov, *Initial states and decoherence of histories*, J. Math. Phys. **46**, 042108 (2005) (D11).
[23] A. N. Soklakov and R. Schack, *State preparation based on Grover's algorithm in the presence of global information about the state*, Optics and Spectroscopy **99**, 211 (2005) (D11).
[24] A. N. Soklakov and R. Schack, *Efficient state preparation for a register of quantum bits*, (quant-ph/0408045 expanded version), to appear in Phys. Rev. A (D11).
[25] A.N. Soklakov and R. Schack, *Bayesian updating of a probability distribution encoded on a quantum register*, submitted to Phys. Rev. A (quant-ph/0511216) (D11).
[26] A. Scherer, A. N. Soklakov and R. Schack, *Classical predictability and coarse-grained evolution of the quantum baker's map*, submitted to Phys. Rev. D (quant-ph/0511215) (D11).
[27] O. Kern, G. Alber, *Suppressing decoherence of quantum algorithms by jump codes*, Eur. Phys. J. D **36**, 241 (2005) (D7,D8,D11).
[28] O. Kern, G. Alber, *Controlling quantum systems by embedded dynamical decoupling schemes* Phys. Rev. Lett. **95**, 250501 (2005) (quant-ph/0506038) (D11,D12).
[29] Quantware Library: *Quantum numerical recipes* (numerical codes for realistic quantum simulations created in the frame of EDIQIP project), publicly available at the EDIQIP web site http://www.quantware.ups-tlse.fr/QWLIB/ (D12)

Publications [1-3], [14,15], [21-24] were included in the EDIQIP publication list of the 2004 report as preprints.

Appendix B2 - List of EDIQIP Journal 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] G. Benenti, G. Casati and G. Strini, *Principles of quantum computation and information*, Volume I: Basic concepts (World Scientific, Singapore, 2004) (D4).

[19] 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).
[20] 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).
[21] 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).
[22] G. Alber and T. Walther, Thema Forschung **1**, 44 (2004), Quanteninformationsverarbeitung - Prüfstein für IT-Sicherheit (D8).
[23] 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).
[24] 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).

Appendix B3 - 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 (2005)

[1] Contributed talk D.L. Shepelyansky: *Quantum computation in presence of imperfections and decoherence*, EU IST-FET QIPC Program Review, Innsbruck, AU, 14 - 16 February 2004.
[2] Invited talk D.L. Shepelyansky: *Quantum chaos and realistic quantum computations* at the International KIAS-KAIST Workshop *Quantum information science*, Seoul, South Kirea, August 22 - 24, 2005.
[3] Invited talk G. Benenti: *Quantum simulation of dissipative chaotic systems: Quantum ratchets and Ehrenfest explosion*, at the conference *Quantum Mechanics and Quantum Computation*, Vietri sul Mare, Italy, 18-20 March, 2005.
[4] Invited lectures G. Benenti: *Quantum chaos, decoherence and quantum computation*, at the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005.
[5] Invited talk G.G. Carlo: *Quantum noise in algorithms and transport*, at the Workshop on *Noise and Instabilities in Quantum Mechanics*, Trieste, Italy, 3-7 October, 2005.
[6] Invited talk V.V. Sokolov: *Dephasing and quantum-classical correspondence in the decay of the Loschmidt echo*, at the Workshop on *Noise and Instabilities in Quantum Mechanics*, Trieste, Italy, 3-7 October, 2005.
[7] Invited talk G. Casati: *Quantum chaotic dissipative ratchets*, at the International Conference on *Aspect of quantum chaotic scattering*, Max Planck Institute, Dresden, Germany, 8-11 March 2005.

[8] Invited talk G. Casati: *Chaos and Fourier law in classical and quantum mechanics*, at the 2nd workshop on *Quantum Chaos*, Varsaw, Poland, 19-22 May 2005.
[9] Invited talk G. Casati: *Fidelity decay and quantum dephasing*, at Max Planck Institute for Complex Systems, Dresden, Germany, 26-29 September 2005.
[10] Invited talk G. Casati: *Classical dynamical chaos and quantum dephasing*, at the International Conference *Are there quantum jumps?*, Losinij, Slovenia, 5-10 September 2005.
[11] Invited talk G. Casati: *Quantum chaos, fidelity decay and decoherence*, at the International Conference on *New Trends in Quantum Mechanics: Fundamental Aspects and Applications*, Palermo, Italy, 11-13 November 2005.
[12] Poster presentation O. Kernand G.Alber: *Quantum algorithms and quantum maps – implementation and error correction* at *Quantum physics of nature*, Workshop in Vienna, Austria, 20 - 26 May 2005.
[13] Poster presentation O. Kern and G.Alber: *Quantum algorithms and quantum maps – implementation and error correction* at *Quantum information processing*, Workshop of the Deutsche Forschungsgemeinschaft, Bad Honnef, Germany, 2 - 3 June 2005.
[14] Oral presentation O. Kern: *Combinating random and cyclic decoupling technique* at *Quantum Computers, Algorithms and Chaos*, International "Enrico Fermi" School, Varenna, Italy 5 - 15 July 2005.
[15] Invited lectures B.Georgeot: *Quantum algorithms and quantum chaos*, at the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005.
[16] Invited talk B.Georgeot: *Quantum computing of Poincare recurrences and periodic orbits*, at the 9th International Conference on Squeezed States and Uncertainty Relations, Besancon, France, 3-7 May 2005.
[17] Invited talk B.Georgeot: *Quantum computing for physics research*, at X International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2005), Zeuthen, Germany, 22-27 May, 2005.
[18] Contributed talk B.Georgeot: *Quantum maps for quantum computation*, at ERATO conference on quantum information science (EQIS 2005), Tokyo, Japan, 26-31 August, 2005.
[19] Contributed talk B.Georgeot: *Realistic quantum computation*, at SQUBIT-2 - RS-FQubit - EuroSQIP Workshop, Karlsruhe, Germany, 12-14 October, 2005.
[20] Invited talk B.Georgeot: *Quantum chaos and quantum computation*, at workshop *Energy relaxation versus phase relaxation in many-body systems*, Centro Internacional de Ciencias, Cuernavaca, Mexique, 30 October - 5 November, 2005.

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
D10	1.0	Periodic Report	R	Int.	30	30.06.2005
D11	1.0	New Quantum Algorithms for Physical Problems Publications: Refs. [1],[7],[8],[13] [18],[19],[20],[22].[23] [24],[25],[26],[27],[28]	R	Pub.	36	31.12.2005
D12	1.0	Numerical Simulator of Decoherence/Imperfection Effects Publications: Refs. [2],[3],[4],[5], [6],[9],[10],[11] [12],[16],[17],[28],[29]	R	Pub.	36	31.12.2005
D13	1.0	Tech. Implem. Plan	R	Int.	36	03.01.2006
D14	1.0	Annual Report	R	Int.	36	03.01.2006
D15	1.0	Final Report	R	Int.	36	03.01.2006

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 D11,D12.

[1] J.W.Lee and D.L.Shepelyansky, *Quantum chaos algorithms and dissipative decoherence with quantum trajectories*, Phys. Rev. E **71**, 056202 (2005) [quant-ph/0501120] (R4); (D12).

[2] J.W.Lee, D.V.Averin, G.Benenti and D.L.Shepelyansky, *Model of a deterministic detector and dynamical decoherence*, Phys. Rev. A **72**, 012310 (2005) [quant-ph/0501153] (R5); (D12).

[3] G.Carlo, G.Benenti and D.L.Shepelyansky, *Dissipative quantum chaos: transition from wave packet collapse to explosion*, Phys. Rev. Lett. **95**, 164101 (2005) [quant-ph/0503081] (R6); (D12).

[4] O.Giraud, B.Georgeot and D.L.Shepelyansky, *Quantum computing of delocalization in small-world networks*, Phys. Rev. E **72**, 036203 (2005) [quant-ph/0504188] (R7); (D11).

[5] O.Giraud and B.Georgeot, *Intermediate quantum maps for quantum computation* , Phys. Rev. A **72**, 042312 (2005) [quant-ph/0504230] (R8); (D11).

[6] J.Lages and D.L.Shepelyansky, *Suppression of quantum chaos in a quantum computer hardware*, submitted to Phys. Rev. E [cond-mat/0510392] (R10); (D12).

[7] O.V.Zhirov and D.L.Shepelyansky, *Dissipative decoherence in the Grover algorithm*, Eur. Phys. J. D (to appear) [quant-ph/0511010] (R12); (D12).

[8] G. Benenti, S. Felloni and G. Strini, *Effects of single-qubit quantum noise on entanglement purification*, preprint quant-ph/0505177, to be published in Eur. Phys. J. D (R17); (D12).

[9] A.N. Soklakov and R. Schack, *Bayesian updating of a probability distribution encoded on a quantum register*, submitted to Phys. Rev. A (quant-ph/0511216) (R25); (D11).

[10] O. Kern, G. Alber, *Controlling quantum systems by embedded dynamical decoupling schemes* Phys. Rev. Lett. **95**, 250501 (2005) (quant-ph/0506038) (R28); (D11,D12).