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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 2003 a total of 24 manuscripts have been prepared, most of which have already been published in leading international journals or have been posted in the public domain (including 4 in Phys. Rev. Lett.). The results and achievements of this project have been presented in 23 talks, lectures and posters at scientific conferences in different countries, including Europe, USA, Japan, Brasil and Russia. 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).

Among the highlight results obtained in the frame of this project in 2003 we stress:

(a) the development of new quantum algorithms for efficient simulation of classical chaotic dynamics, for simulation of dynamical localization in the regime of quantum chaos and Anderson metal-insulator transition in disordered systems with quadratic speedup; an experimental NMR implementation of the quantum algorithm for dynamical localization is planned in the group of D.Cory at MIT;

(b) universal laws have been established for fidelity decay in quantum computations in presence of random errors and static imperfections; these laws have been tested in numerical simulations for quantum Fourier transform, quantum wavelet algorithms and newly developed algorithms; we have shown that static imperfections lead to a faster decay of fidelity in comparison with random errors in quantum gates;

(c) we have found that there are two regimes of entanglement evolution in a realistic quantum computer hardware with residual couplings between qubits: entanglement is preserved in the integrable regime with small couplings and drops significantly above the quantum chaos threshold; we have established a relation between statistical relaxation induced by classical chaos and concurrence decay in a quantum algorithm for chaotic dynamics; in parallel with the results obtained by P.Shor, we have shown that strong superadditivity of the entanglement of formation follows from its additivity; with the help of the quantum trajectories method we have demonstrated that the transfer of entanglement along a long qubit chain can be realized in presence of a noisy dissipative environment;

(d) we have developed optimum measurement strategies for the extraction of information coded in quantum wave functions (using similarities with MP3 sound compression codes) and showed that qubit measurements in a quantum algorithm for dynamical localization give a transition between localized and delocalized regimes;

(e) in the direction of the development of quantum error correcting codes we have constructed a family of one detected jump-error correcting quantum codes and determined the optimal redundancy, encoding and recovery as well as general properties of these codes.

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)

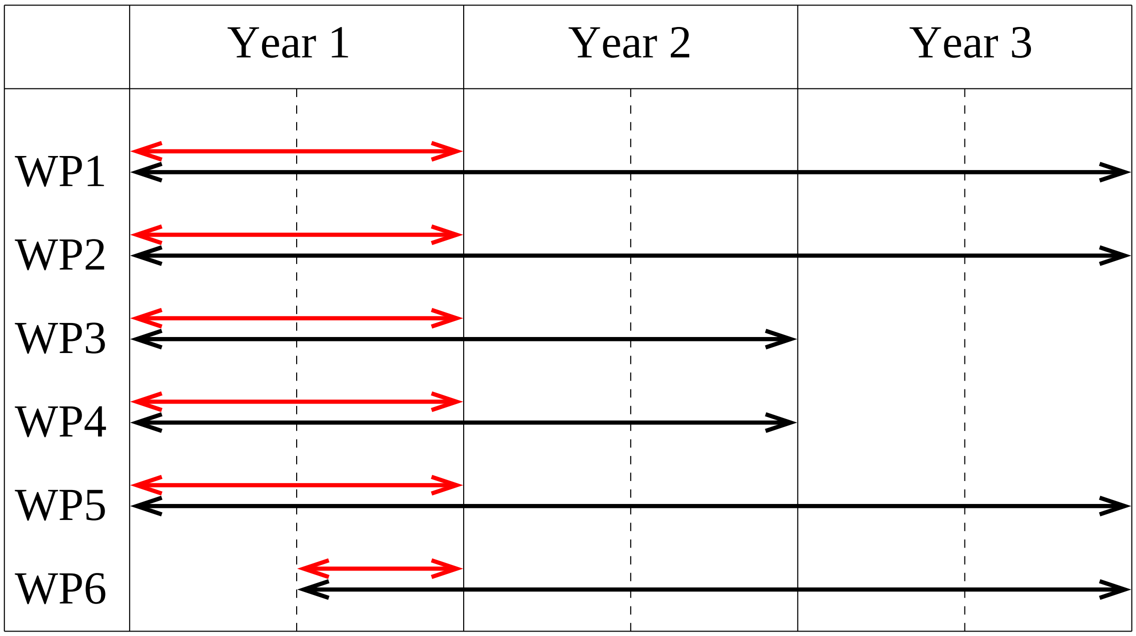

Fig.1. Gantt chart for workpackages: black arrows represent the work to be done and red/gray arrows the work accomplished.

Workpackage progress reports are listed in Appendix A, publications are listed in Appendix B, the list of EDIQIP talks and posters is presented in Appendix C. A detailed list of EDIQIP deliverables is given in Appendix D. A selection of deliverables (all papers accepted for publication in Phys. Rev. Lett. in 2003 and a selection of other papers) 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 (terminated after 12 months)

D7: Static Imperfection Time Scales for QIP (to be completed after 24 months)

D8: Decoherence Time Scales for QIP (to be 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) and (d) described in the Executive Summary and give their global description below.

(a1) Starting from the famous work of Lorenz in 1963, it has been realized that the dynamics of many various dissipative systems converges to so-called strange attractors. These objects are characterized by fractal dimensions and chaotic unstable dynamics of individual trajectories. They appear in nature in very different contexts, including applications to turbulence and weather forecast, molecular dynamics, chaotic chemical reactions, multimode solid state lasers and complex dynamics in ecological systems and physiology. The efficient numerical simulation of such dissipative systems can therefore lead to many important practical applications. We have shown that dissipative classical dynamics converging to a strange attractor can be simulated on a quantum computer. Such quantum computations allow to investigate efficiently the small scale structure of strange attractors, yielding new information inaccessible to classical computers. Even if the dynamics on the attractor is unstable, dissipative and irreversible, a realistic quantum computer can simulate it in a reversible way, and, already with 70 qubits, will provide access to new informations unaccessible for modern supercomputers. This opens new possibilities for quantum simulations of various dissipative processes in nature. [Ref. [1] in Appendix B]

(a2) We have built quantum algorithms enabling to find Poincaré recurrence times and periodic orbits of classical dynamical systems. It has been shown that exponential gain compared to classical algorithms can be reached for a restricted class of systems, for example the Arnold cat map. Quadratic gain can be achieved for a larger set of dynamical systems. The simplest cases can be implemented with small number of qubits. [Ref. [12]]

(a3) We have shown that a quantum computer operating with a small number of qubits can simulate the dynamical localization of classical chaos in a system described by the quantum sawtooth map model. The quantum evolution of the system is computed efficiently up to a time $t \geq \ell$, and then the localization length ℓ can be obtained with accuracy ν by means of order $1/\nu^2$ computer runs, followed by coarse grained projective measurements on the computational basis. This quantum algorithm gives a quadratic speedup compared to known classical algorithms. The group of D.Cory at MIT plans the experimental implementation of this algorithm on an NMR-based quantum computer. Future experimental implementation with an ion-trap quantum computer are discussed with R.Blatt (Innsbruck). [Ref. [3]] We also developed other algorithms to simulate quantum chaos in a mixed phase space and proposed a convenient method for computation of coarse-grained Wigner function. [Ref. [21]]

(a4) We have proposed a quantum algorithm for simulation of the Anderson metal-insulator transition in disordered lattices. In the vicinity of the critical point the algorithm gives a quadratic speedup in computation of diffusion rate and localization length, comparing to the known classical algorithms. We have shown that the Anderson transition can be detected on quantum computers with $7-10$ qubits. [Ref. [10]]

(b1) The effects of external decoherence modeled with fluctuating random errors in quantum gates have been investigated for a broad range of newly developed quantum algorithms, including algorithms for strange attractors [Ref. [1]], quantum Fourier transform, quantum kicked rotator and Wigner functions [Ref. [4]], quantum wavelet algorithms [Ref. [6]], quantum sawtooth and tent maps [Refs. [15] and [21]]. A universal law has been established, according to which the quantum computation of complex dynamics with fidelity higher than some threshold (e.g. 90%) can be performed for a total number of quantum gates N_g given by the relation $N_g \approx 5/\epsilon^2$, where ϵ is the amplitude of random errors in quantum gate rotations. This law has been tested numerically with up to 28 qubits. We note that this is the world record for numerical simulations of quantum algorithms in presence of imperfections.

(b2) We have studied numerically the effects of static imperfections (residual inter-qubit couplings and one-qubit energy shifts) on the accuracy of quantum algorithms simulating quantum chaos, dynamical localization, Anderson transition and quantum wavelet transforms. [Refs. [2], [3], [6], [10] and [21]] In these numerical simulations with up to 21 qubits we have determined empirical dependence for accuracy bounds as a function of imperfection strength in quantum computations of localization length, critical point of Anderson transition, and quantum wavelets. To determine the accuracy bounds in the limit of more than few tens of qubits, we developed a new approach based on the Wigner-Dyson random matrix theory applied to quantum computation of complex dynamics in presence of static imperfections. The theoretical predictions have been tested and confirmed in extensive numerical simulations of a quantum algorithm for quantum chaos with variation of a scaling function by ten orders of magnitude. The theory developed determines the time scales for reliable quantum computations in absence of the quantum error correction codes. These time scales are related to the Heisenberg time, the Thouless time, and the decay time given by Fermi's golden rule which are well known in the context of mesoscopic systems. This universal law shows that static imperfections lead to a faster fidelity decay compared to the effects of random errors in quantum gates. The results obtained for fidelity decay in realistic quantum computations have close links with the investigations of Loschmidt echo decay in the regime of quantum chaos carried out by Como node.

(b3) We illustrate the general theory described in previous point (b2) on a concrete example of the quantum tent map [Ref. [21]]. The quantum algorithm for this dynamics performs one map iteration in approximately $n_g \approx (9/2)n_q^2$ elementary quantum gates for a vector of size $N = 2^{n_q}$, where n_q is the number of qubits. This map generates chaotic or integrable dynamics in the quasi-classical limit. The developed new approach based on the random matrix theory gives the fidelity decay in the form

$$f(t) = \exp\left[-\left(\frac{t}{t_c} + \frac{2t^2}{\sigma t_c t_H}\right)\right],$$

where t is measured in number of map iterations, $t_c \approx 1/(\epsilon^2 n_g^2 n_q)$ and $t_H = 2^{n_q}$, where ϵ is the dimensionless strength of static imperfections and σ is the relative measure for chaotic component in the Poincaré cross section. This equation determines the time scale t_f of reliable quantum computation with fidelity $f > 0.9$:

$$t_f \approx t_c/10 = 1/(10\epsilon^2 n_q n_g^2)\ ;\ N_g \approx 1/(10\epsilon^2 n_q n_g)$$

for $t_{\rm H} > t_c$ so that $\epsilon > \epsilon_{ch} = 2^{-n_q/2}/(n_g\sqrt{n_q})$. Here, $N_g = t_f n_g$ is the total number of gates which can be performed with fidelity $f > 0.9$. In this regime the static errors act in a way similar to random noise errors even if their effect is stronger due to coherent accumulation of static errors inside a certain interval of the algorithm (one map iteration for the tent map). Indeed, for random errors in quantum gates we have

$$t_f \approx t_r/10 \approx 5/(\epsilon^2 n_g)\ ;\ N_g \approx 5/\epsilon^2.$$

Even if the dependence of N_g on ϵ is the same for random errors and static imperfections, the dependence on n_q is rather different. This difference should play an important role for the quantum error correction codes which allow to perform the fault-tolerant quantum computation for the random error rate $p_r \sim \epsilon^2 < 10^{-4}$. The fact that for random errors N_g is independent of n_q while for static imperfections N_g drops strongly with n_q should significantly decrease the threshold for fault-tolerant quantum computation in presence of static imperfections.

For $t_c < t_{\rm H}$ or $\epsilon < \epsilon_{ch} = 2^{-n_q/2}/(n_g\sqrt{n_q})$ the time scale t_f is given by the relation

$$t_f \approx 0.2\sqrt{t_c t_{\rm H}} \approx 2^{n_q/2}/(5\varepsilon n_g\sqrt{n_q}) \ ; \ N_g \approx 2^{n_q/2}/(5\varepsilon\sqrt{n_q}).$$

In this regime the effect of static imperfections is absolutely different from random noise errors. This regime may be dominant for up to 10 - 15 qubits. However, in the limit of large $n_q \gg 10$ it appears only in the limit of very small static imperfections and should not be very important for quantum computers with few tens of qubits.

The transition from the one regime to the other takes place for

$$\epsilon > \epsilon_{ch} = 2^{-n_q/2}/(n_g\sqrt{n_q}) \ .$$

From the physical point of view this border can be interpreted as the quantum chaos border above which the static imperfections start to mix the energy levels of ideal quantum algorithm. The fact that this border drops exponentially with the number of qubits n_q has been discussed in [Ref. [2]] for a quantum algorithm for complex dynamics. Above ϵ_{ch} the effect of static imperfections becomes somewhat similar to random errors.

The above results for the time scales of reliable quantum computation are based on the random matrix theory and are universal for algorithms which simulate a complex dynamics, *e.g.* an evolution in the regime of quantum chaos. However, it is important to keep in mind that there are other types of algorithms where the evolution is rather regular, *e.g.* the Grover algorithm or integrable dynamics. In such cases the asymptotic dependence of $t_{\rm H}$ on n_q should be studied in more detail.

(c1) We have studied the dynamics of the pairwise entanglement in a qubit lattice in the presence of static imperfections, and characterized three different regimes: (i) the perturbative regime, in which the entanglement is stable against imperfections, (ii) the crossover regime, in which the imperfections degrade the concurrence of an initially entangled pair but can also drive a significant entanglement generation, and (iii) the ergodic regime, in which a pair of qubits becomes entangled with the rest of the lattice and therefore the concurrence of the pair drops to zero. We stress two important points of our findings from the point of view of quantum computation. First of all, the pairwise entanglement is destroyed above a coupling strength which is only weakly dependent on the size of the quantum computer. Second, there is a broad crossover region in which the computer imperfections can be used to create a significant amount of pairwise entanglement. [Ref. [9]] This research was done in collaboration with the IST-SQUBIT2 project (R.Fazio, Pisa).

(c2) We have studied analytically and numerically the behavior of quantum entanglement in a quantum computer operating an efficient algorithm for quantum chaos. Our results show that in an ideal algorithm the entanglement decays exponentially with the diffusive relaxation rate induced by classical chaos. This decay goes down to a residual level which drops exponentially with the number of qubits n_q, being inversely proportional to the square root of the conductance. The residual entanglement is destroyed by decoherence, whose effective rate grows exponentially with the number of qubits. [Ref. [5]]

(c3) The additivity of both the entanglement of formation and the classical channel capacity is known to be a consequence of the strong superadditivity conjecture. We have shown that, conversely, the strong superadditivity conjecture follows from the additivity of the entanglement of formation; this means that the two conjectures are equivalent and that the additivity of the classical channel capacity is a consequence of them. [Ref. [7]] Independently, the same results with additional generalizations have been obtained by P. Shor.

(c4) We have studied the fidelity of quantum teleportation for the situation in which quantum logic gates are used to provide the long distance entanglement required in the protocol, and where the effect of a noisy environment is modeled by means of a generalized amplitude damping channel. Our results demonstrate the effectiveness of the quantum trajectories approach, which allows the simulation of open systems with a large number of qubits (up to 24). This shows that the method is suitable for modeling quantum information protocols in realistic environments. [Ref. [16]]

(d1) We have studied numerically how a sound signal stored in a quantum computer can be recognized and restored with a minimal number of measurements in presence of random quantum gate errors. A method developed uses elements of MP3 sound compression and allows to recover human speech and sound of complex quantum wavefunctions. An example is available at the website http://www.quantware.ups-tlse.fr/qaudio [Ref. [13]] The results of this work were highlighted in the electronic journal Newsfactor, see the webpage http://www.newsfactor.com/perl/story/22456.html

(d2) We have studied numerically the effects of measurements on dynamical localization in the kicked rotator model simulated on a quantum computer. Contrary to the previous studies, which showed that measurements induce a diffusive probability spreading, our results demonstrate that localization can be preserved for repeated single-qubit measurements. We have detected a transition from a localized to a delocalized phase, depending on the system parameters and on the choice of the measured qubit. [Ref. [14]]

(e1) We have studied quantum error-correcting codes that exploit additional information about the locations of the errors. This information is obtained by continuously monitoring the system. Errors caused by the resulting nonunitary dynamics are corrected passively by embedding the error-correcting codes in a decoherence-free subspace. To construct such codes, we have established connections to the design theory. The numerical simulations for quantum memory and Grover's algorithm demonstrate that the jump codes discussed can stabilize quantum systems even in the case of imperfect detection and recovery operations. [Refs. [22]-[24]]. This research is done in collaboration with the IST-QIPC project represented by Th.Beth (Karlsruhe).

2.2. Work schedule for 2004

The results obtained in the first 12 months represent a good step towards realization of tasks described in the Workpackages WP3-WP4. We developed the techniques to take into account dissipative decoherence effects in Ref. [16] and we are planning to apply them for realization of tasks WP3-WP4. The studies of decoherence effects in the quantum baker's map, which has been implemented experimentally with NMR-based quantum computers in the group of D.Cory at MIT, are also planned in the frame of workpackage WP3. 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.

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 D (it contains only Deliverables applicable for the report period). Also Appendix B gives the total List of EDIQIP publications 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 D1 - Project Presentation

The report on the Deliverable D1 is presented at 30.06.2003. Project presentation is available at the EDIQIP web page http://www.quantware.ups-tlse.fr/EDIQIP/

3.2. Deliverable D2 - Dissemination/Use Plan

The report on the Deliverable D2 is presented at 30.06.2003. Dissemination/Use Plan describes the optimal way for realisation of project workpackages and promotion of the obtained results.

3.3. Deliverable D3 - Periodic Report

The report on the Deliverable D3 is presented at 30.06.2003. It describes the current status of scientific research progress in the frame of EDIQIP project.

3.4. Deliverable D4 - Quantum Chaos Algorithms

This scientific Deliverable D4 is done and it is presented in the publications Refs. [1-6],[8],[14],[15],[17],[18],[20],[21] given in the Appendix B. The Issue date is 31.12.2003. The description of the scientific results for Deliverable D4 is given in Sections 1.0 and 2.1. Deliverable D4 in the form of selected publications is given in Annex S.

3.5. Deliverable D5 - Annual Report

This is the annual report on the Deliverable D5 presented at 07.01.2004. 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/

3.6. Deliverable D7 - Static Imperfections Time Scales for QIP

This scientific Deliverable D7 is in the working stage. The results obtained for Deliverable D7 are presented in the publications Refs. [2],[3],[6],[9],[10],[19],[21] given in the Appendix B. The description of the scientific results for Deliverable D7 is given in Sections 1.0 and 2.1. A part of Deliverable D7 in the form of selected publications is given in Annex S. Issue date 31.12.2003, due date 31.12.2004.

3.7. Deliverable D8 - Decoherence Time Scales for QIP

This scientific Deliverable D8 is in the working stage. The results obtained for Deliverable D8 are presented in the publications Refs. [1],[4],[5],[6],[15],[16],[18],[21],[22],[23],24] given in the Appendix B. The description of the scientific results for Deliverable D8 is given in Sections 1.0 and 2.1. A part of Deliverable D8 in the form of selected publications is given in Annex S. Issue date 31.12.2003, due date 31.12.2004.

3.8. 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. [3],[7],[10-13] given in the Appendix B. 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 31.12.2003, due date 31.12.2005.

3.9. 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. [1],[3],[13],[16],[21-24] given in the Appendix B. 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 31.12.2003, due date 31.12.2005.

4. Project Management

The first meeting of the consortium has been organized at 7 - 14 July, 2002 during the international Quantware workshop held in Toulouse in the frame of collaboration of coordinator (UPS) with the american research program in quantum computing supported by NSA/ARDA/ARO. The workshop took place in Toulouse during 1 - 14 July, 2002. It attracted 5 americans and about 15 european participants, and was supported by funds available at UPS independently from the EDIQIP project.

After that, short coordinating meetings took place during the EU-QIPC workshop at Dublin (September 2002) and the EU meeting at Bad Nauheim (March 2003).

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 21 talks at international conferences held in Europe, USA, Japan, Russia and Brasil. The obtained results have been presented at the quantum program review of ARO/NSA/ARDA by D.L.Shepelyansky and G.Casati in August 2003. These gives significant promotion of ITS-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 two other QIPC projects (groups of R.Fazio and Th.Beth). Two nodes (Toulouse and Como) participate in the US quantum computing program ARO/NSA/ARDA. This allowed to have regular visits of american scientists working in the field of quantum information to Toulouse and Como (*e.g.* D.Averin (Stony Brook), I.Deutsch (New Mexico, USA), J.Emerson (MIT)).

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)
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 2003 Toulouse node attracted to the EDIQIP research project EU post-docs Dr.S.Bettelli and Dr.M.Terraneo (linked to the RTN project QTRANS) 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 and a diploma student, D.Rossini.

6. Information Dissemination

As mentioned in the Executive summary, during the report period 24 manuscripts have been posted in the public domain and published in high quality scientific journals. The results have been presented in 21 talks and 2 posters at scientific schools and conferences in Europe, USA, Japan, Russia and Brasil. The sheer amount of high level publications is matched by their highest quality and impact. As mentioned in the Executive summary, 3 manuscripts are published and 1 is accepted to publication in Phys. Rev. Lett. Some results have been highlighted by the electronic journal Newsfactor.com 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.

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 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 24 manuscripts are opened to free public access and published in leading international journals. They include 4 manuscripts published or accepted to Phys. Rev. Lett., 3 manuscripts in collaboration with other QIPC projects. The results are presented on 23 international conferences and workshops in Europe, USA, Japan, Russia and Brasil. The results obtained [Ref. [13]] are highlighted by the electronic journal Newsfactor.com. 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 saw-tooth 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 the model of noisy gates with random unitary rotations by uncorrelated angles [Refs. [1,4,6,15,18,21-24]]. This gives the number of quantum gates which can be performed with high fidelity at given strength of random errors in quantum gates. The numerical tests of analytical theory are done with up to 28 qubits for the newly developed quantum algorithms for strange attractor [1], the Wigner function in the kicked rotator model [Ref. [4]], the quantum Fourier and wavelet transforms [Refs. [4,5]], the quantum saw-tooth and tent maps [Refs. [15,21]]. The sensitivity of entanglement to this type of decoherence is analyzed in [Refs. [5,18]] on the example of the quantum algorithm for the saw-tooth map and it is shown that the residual level of entanglement is exponentially sensitive to such errors. The properties of the entanglement echo are studied in [Ref. [18]] and it is shown that its decay is characterized by the same time scale as for the fidelity decay. The dissipative models of decoherence are started to be developed on the basis of quantum trajectories method in [Ref. [16]]. The first results have shown that the quantum teleportation remains stable in respect to non-unitary errors.

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

Various numerical codes have been developed to simulate the algorithms discussed in WP3 in the presence of static residual couplings between qubits as well as static energy shifts in the level spacings for individual qubits. The developed codes allow us to simulate the quantum sawtooth and tent maps in the presence of static imperfections with up to 30 qubits. [Refs. [2],[3],[6],[9],[10],[19],[21]] Actual numerical simulations were done with up to 21 qubits. Quantum chaos border for an operating quantum computer is determined, giving the threshold for mixing of quantum eigenstates and phase transition in the level spacing statistics; this threshold drops exponentially with the number of qubits. [Ref. [2]] The numerical studies of fidelity decay induced by static imperfections were performed for the quantum sawtooth and tent maps [Refs. [2],[3],[21]], the quantum wavelet transform [Ref. [6]], the Anderson metal-insulator transition in disordered materials [Ref. [10]]. It is shown that the shift of the critical point of the Anderson transition scales polynomially with the number of qubits and the strength of static imperfections. [Ref. [10]] We developed a new approach based on the Wigner-Dyson random matrix theory, which determines the time scale for reliable quantum computation in the presence of static imperfections in absence of the quantum error-correction codes. The universal law shows that static imperfections lead to a faster fidelity decay compared to the effects of random errors in quantum gates. [Ref. [21]] We have studied the behavior of entanglement in a realistic quantum computer hardware with residual couplings between qubits and demonstrated that the pairwise entanglement is preserved in the integrable regime with small couplings and drops significantly above the quantum chaos threshold. [Ref. [9]]

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

We have shown that dissipative classical dynamics converging to a strange attractor can be simulated on a quantum computer. Such quantum computations allow to investigate efficiently the small scale structure of strange attractors, yielding new information inaccessible to classical computers. [Ref. [1]] We have built quantum algorithms enabling to find Poincaré recurrence times and periodic orbits of classical dynamical systems. It has been shown that exponential gain compared to classical algorithms can be reached for a restricted class of systems, for example the Arnold cat map. [Ref. [12]] We have developed a quantum algorithm which is able to simulate the problem of dynamical localization of quantum chaos and showed that it gives a quadratic speedup compared to known classical algorithms. [Ref. [3]] The group of D.Cory at MIT plans the experimental implementation of this algorithm on an NMR-based quantum computer. We also developed other algorithms to simulate the quantum chaos in a mixed phase space and proposed a convenient method for computation of coarse-grained Wigner function. [Ref. [21] We have proposed a quantum algorithm for simulation of the Anderson metal-insulator transition in disordered lattices. In the vicinity of the critical point the algorithm gives a quadratic speedup in computation of diffusion rate and localization length, comparing to the known classical algorithms. We have shown that the Anderson transition can be detected on quantum computers with $7-10$ qubits. [Ref. [10]] We developed a numerical code which implements the model of the wavelet kicked rotator and allows to study numerically the effects of random errors and static imperfections for the quantum wavelet transform. [Ref. [6]] The effects of measurements on dynamical localization simulated by a quantum algorithm have been investigated in [Ref. [14]]. We have detected a transition from a localized to a delocalized phase, depending on the system parameters and on the choice of the measured qubits. In parallel with the results obtained by P.Shor we have shown that strong superadditivity of the entanglement of formation follows from its additivity. [Ref. [7]]

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 numerical codes in standard programming languages (Fortran, C, C++) have been developed, that allowed to simulate effects of imperfections for the quantum algorithms described in the Workpackages WP3, WP4 and WP5. The numerical simulations with noisy random errors in quantum gates were performed with 28 qubits, for the quantum algorithm simulating a strange attractor [Ref. [1]]. This represents the world record for numerical simulations of quantum algorithms with imperfections. The effects of static imperfections have been simulated with up to 21 qubits for the quantum algorithms for sawtooth and tent maps, kicked rotator model, dynamical and Anderson localization [Refs. [2], [3], [4], [10], [21]]. The effects of dissipative environmental errors on quantum teleportation have been studied on the basis of developed numerical codes with quantum trajectories approach. The transfer of entanglement was demonstrated numerically on a scale of 24 qubits in a quantum computer with linear architecture suitable for ion traps experiments [Ref. [16]]. A numerical code has been developed to study how a sound signal stored in a quantum computer can be recognized and restored with a minimal number of measurements in presence of random quantum gate errors. The developed method uses elements of MP3 sound compression and adapt them to quantum treatment of sound [Ref. [13]]. The numerical simulations for quantum memory and Grover's algorithm demonstrate the ability of detected-jump-error-correction quantum codes to stabilize quantum computations even in the case of imperfect detection and recovery operations [Refs. [22]-[24]].

Appendix B - List of EDIQIP Publications

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

[11] B.Georgeot et D.L.Shepelyansky, *Les ordinateurs quantiques affrontent le chaos*, to appear in Images de la Physique 2003 [quant-ph/0307103] (D11).

[12] B.Georgeot, *Quantum computing of Poincaré recurrences and periodic orbits*, to appear in Phys. Rev. A [quant-ph/0307233] (D11).

[13] J.W.Lee, A.D.Chepelianskii and D.L.Shepelyansky, *Treatment of sound on quantum computers*, submitted to Eur. Phys. J. D [quant-ph/0309018] (D11,D12).

[14] M.Terraneo and D.L.Shepelyansky, *Dynamical localization, measurements and quantum computing*, to appear in Phys. Rev. Lett. [quant-ph/0309192] (D4).

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

[16] 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).
[17] 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, to appear in Lecture Notes in Physics, Springer-Verlag [quant-ph/0307165] (D4).
[18] D.Rossini, G.Benenti and G.Casati, *Entanglement echoes in quantum computation*, submitted to Phys. Rev. Lett. [quant-ph/0309146] (D4,D8).
[19] W.-G.Wang, G.Casati and B.Li, *Stability of quantum motion: beyond Fermi-golden-rule and Lyapunov decay*, submitted to Phys. Rev. Lett. [quant-ph/0309154] (D7).
[20] G.Benenti, G.Casati and G.Strini, *Principles of quantum computation and information*, Volume I, to be published by World Scientific, Singapore (2003) (D4).
[21] K.M.Frahm, R.Fleckinger and D.L.Shepelyansky, *Quantum chaos and random matrix theory for fidelity decay in quantum computations with static imperfections*, submitted to Eur. Phys. J. D [quant-ph/0312120] (D4,D7,D8,D12).
[22] 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).
[23] 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).
[24] 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

[1] Invited lecture D.L.Shepelyasnky: *Quantum algorithms for complex dynamics*, at Euroworkshop *Quantum computers: nanoscopic implementation*, 10-21 February, 2003, ISI, Villa Gualino, Torino, Italy.
[2] Invited talk D.L.Shepelyansky: *Les ordinateurs quantiques affrontent le chaos*, Journée de Physique pour l'Istitut de Mathématiques, Calcul et conrôle quantiques, 25 April 2003, Paris.
[3] Invited talk D.L.Shepelyansky: *Quantum computation: entanglement, chaos and decoherence*, Workshop on Quantum Chaos and Localisation, 24-25 May 2003, Warsaw, Poland.
[4] Invited talk D.L.Shepelyansky: *Quantum algorithms in presence of imperfections*, ARO/NSA/ARDA meeting *Theory in Quantum Computing*, Harper's Ferry, West Virginia, 9-10 June 2003.
[5] Invited talk D.L.Shepelyansky: *Quantum computation: entanglement and chaos*, NATO Advanced Research Workshop *Quantum chaos: theory and applications*, Como, Italy, 17-21 June 2003.
[6] Invited talk D.L.Shepelyansky: *Imperfection effects in quantum computation*, at Quantum computing program review organized by ARO/NSA/ARDA, 18-23 August 2003, Nashville, TN, USA.

[7] Invited talk D.L.Shepelyasnky: *Chaos and quantum computation*, at the Conference *Kolmogorov's legacy in physics: one century of chaos, turbulence and complexity*, ICTP, Trieste, Italy, 15-17 September 2003.
[8] Invited talk D.L.Shepelyansky: *Chaos and realistic quantum computation*, at *Fundamentals of solid state quantum information processing*, Lorentz Center, Leiden, The Netherlands, 8-12 December 2003.
[9] Invited talk B.Georgeot: *Quantum computation and quantum chaos*, at International Conference *Inhomogeneous Random Systems*, Université de Cergy Pontoise, France, 28-29 January, 2003.
[10] Poster S.Bettelli: *Quantum algorithms for complex dynamics in presence of imperfections*, 4th European QIPC Workshop, Oxford, UK, 13-17 July, 2003.
[11] Invited talk G.Casati: *Fidelity decay and correlation functions in classical and quantum systems*, at International conference on *Dynamical Chaos in Classical and Quantum Physics*, Budker Institute of Nuclear Physics, Novosibirsk, Russia 4-9 August, 2003.
[12] Invited talk G.Casati: *Quantum chaos and quantum computers*, at Quantum computing program review organized by ARO/NSA/ARDA, 18-23 August 2003, Nashville, TN, USA.
[13] Invited talk G.Casati: *Quantum Computing of Complex Systems: Dynamical Localization*, at Int. conference on *Quantum information, quantum computation and nanotechnology*, Waseda University, Tokyo, Japan, 29-31 October 2003.
[14] Invited talk G.Casati: *Decay of fidelity in classically chaotic and integrable systems*, at International Conference *Quantum Information*, Tokyo University of Science, Tokyo, Japan, 1-3 November, 2003.
[15] Invited talk G.Casati: *On the stability of quantum motion under system's perturbations*, at International Conference *Quantum Information*, International Institute for Advanced Studies, Kyoto, Japan, 5-7 November, 2003.
[16] Invited talk G.Casati: *Fidelity decay and entanglement echo*, at Pan American Advanced Institute on "The Physics of Information" Buzios, Brasil, 4-9 december, 2003.
[17] Invited talk G.Benenti: *Localization and entanglement in quantum computing of complex systems*, at International Conference *Quantum Information*, Tokyo University of Science, Tokyo, Japan, 1-3 November, 2003.
[18] Invited talk G.Benenti: *Stability of quantum computation in a noisy environment: a quantum trajectories approach*, at International Conference *Quantum Information*, International Institute for Advanced Studies, Kyoto, Japan, 5-7 November, 2003.
[19] Poster G.G.Carlo: *Quantum trajectories and quantum information: teleportation in a noisy environment*, 4th European QIPC Workshop, Oxford, UK, 13-17 July, 2003.
[20] Contributed talk A.A.Pomeransky: *Strong superadditivity of the entanglement of formation follows from its additivity*, Madeira Math Encounters XXV "Quantum information, Control and Computing", Madeira, Spain, 1-11 October 2003.
[21] Invited talk R.Schack: *Unknown quantum operations*, at International Conference on *Quantum Theory: Reconsideration of Foundations 2*, Växjö University, Sweden, June 2003.
[22] Invited talk R.Schack: *Unknown quantum operations: A de Finetti representation theorem*, at Workshop on *Quantum Information Processing (QIP 2003)*, Mathematical Sciences Research Institute (MSRI), Berkeley, USA.

[23] Contributed talk G.Alber: *Dynamics of Nonlinear Maps for Quantum Information Processing*, at Annual Meeting of the German Physical Society (DPG), 25 March 2003.

Appendix D - 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 B).

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**	**Classifi-cation**	**Due Date**	**Issue Date**
D1	1.0	Project Presentation	R	Pub.	6	30.06.2003
D2	1.0	Dissemination/Use Plan	R	Int.	6	30.06.2003
D3	1.0	Periodic Report	R	Int.	6	30.06.2003
D4	1.0	Quantum Chaos Algorithms Publications: Refs. [1],[2],[3], [4],[5],[6],[8],[14],[15], [17],[18],[20],[21]	R	Pub.	12	31.12.2003
D5	1.0	Annual Report	R	Int.	12	07.01.2004

Del. No.	Revision	Title	Type	Classification	Due Date	Issue Date
D7	1.0	Static Imperfections Time Scales for QIP Publications: Refs. [2],[3],[6], [9],[10],[19],[21]	R	Pub.	24	31.12.2003
D8	1.0	Decoherence Time Scales for QIP Publications: Refs. [1],[4],[5], [6],[15],[16],[18], [21],[22],[23],[24]	R	Pub.	24	31.12.2003
D11	1.0	New Quantum Algorithms for Physical Problems Publications: Refs. [3],[7],[10], [11],[12],[13]	R	Pub.	36	31.12.2003
D12	1.0	Numerical Simulator of Decoherence/Imperfection Effects Publications: Refs. [1],[3],[13], [16],[21],[22],[23],[24]	R	Pub.	36	31.12.2003

Appendix E - 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 B are marked as R1,R2,...,R24. 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] (R1); (D4,D8,D12).

[2] 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] (R3); (D4,D7,D11,D12).

[3] 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] (R5);(D4,D8).

[4] 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] (R6); (D4,D7,D8).

[5] A.A.Pomeransky, *Strong superadditivity of the entanglement of formation follows from its additivity*, Phys. Rev. A **68**, 032317 (2003) [quant-ph/0305056] (R7); (D11).

[6] S.Montangero, G.Benenti and R.Fazio, *Dynamics of entanglement in quantum computers with imperfections*, Phys. Rev. Lett. **91**, 187901 (2003) [quant-ph/0307036] (R9); (D7).

[7] A.A.Pomeransky and D.L.Shepelyansky, *Quantum computation of the Anderson transition in presence of imperfections*, to appear in Phys. Rev. A [quant-ph/0306203] (R10); (D7,D11).

[8] B.Georgeot, *Quantum computing of Poincaré recurrences and periodic orbits*, to appear in Phys. Rev. A [quant-ph/0307233] (R12); (D11).

[9] J.W.Lee, A.D.Chepelianskii and D.L.Shepelyansky, *Treatment of sound on quantum computers*, submitted to Eur. Phys. J. D [quant-ph/0309018] (R13); (D11,D12).

[10] M.Terraneo and D.L.Shepelyansky, *Dynamical localization, measurements and quantum computing*, to appear in Phys. Rev. Lett. [quant-ph/0309192] (R14); (D4).

[11] 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] (R16); (D8,D12).

[12] K.M.Frahm, R.Fleckinger and D.L.Shepelyansky, *Quantum chaos and random matrix theory for fidelity decay in quantum computations with static imperfections*, submitted to Eur. Phys. J. D [quant-ph/0312120] (R21); (D4,D7,D8,D12).

[13] 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] (R22); (D8,D12).