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Quantum Annealing with Anneal Path Control: Application to 2-SAT Problems with Known Energy Landscapes

Ting-Jui Hsu[1], Fengping Jin[1], Christian Seidel[2], Florian Neukart[3], Hans De Raedt[4] and Kristel Michielsen[1,5,*]

[1] *Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, D-52425 Jülich, Germany.*
[2] *Volkswagen Data:Lab, Munich, Germany.*
[3] *Volkswagen Group of America, San Francisco, USA.*
[4] *Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, NL-9747AG Groningen, The Netherlands.*
[5] *RWTH Aachen University, D-52056 Aachen, Germany.*

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Abstract. We study the effect of the anneal path control per qubit, a new user control feature offered on the D-Wave 2000Q quantum annealer, on the performance of quantum annealing for solving optimization problems by numerically solving the time-dependent Schrödinger equation for the time-dependent Hamiltonian modeling the annealing problems. The anneal path control is thereby modeled as a modified linear annealing scheme, resulting in an advanced and retarded scheme. The considered optimization problems are 2-SAT problems with 12 Boolean variables, a known unique ground state and a highly degenerate first excited state. We show that adjustment of the anneal path control can result in a widening of the minimal spectral gap by one or two orders of magnitude and an enhancement of the success probability of finding the solution of the optimization problem. We scrutinize various iterative methods based on the spin floppiness, the average spin value, and on the average energy and describe their performance in boosting the quantum annealing process.

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*Corresponding author. *Email addresses:* `k.michielsen@fz-juelich.de` (K. Michielsen), `ting-jui.hsu@rwth-aachen.de` (T.-J. Hsu), `F.Jin@fz-juelich.de` (F. Jin), `chr_seidel@quantentunnel.de` (C. Seidel), `florian.neukart@vw.com` (F. Neukart), `h.a.de.raedt@rug.nl` (H. De Raedt)

1 Introduction

Quantum annealing is a quantum version of classical simulated annealing [1], using quantum fluctuations instead of thermal fluctuations, to explore the energy landscape of an optimization problem [2]. This approach has received enormous interest in the last two decades [3–14] and is regarded as a second model of quantum computing, which is quite distinct to the gate-based model of quantum computing [15].

A recent overview of theoretical work on adiabatic quantum computation (annealing) in closed systems described by various types of Hamiltonians, thereby discussing, among many other issues, universality and quantum speedup, is given in Ref. [16]. Because of the ongoing academic discussions about the universality and hypothetical quantum speedup for different types of Hamiltonians and because in practice, it is not straightforward to build devices that are described by the desired Hamiltonian, the efforts to implement quantum annealing in physical systems for the purpose of actual problem solving are rather limited compared to those for building gate-based quantum information processors.

Since 1999, D-Wave Systems Inc. [17] manufactures quantum annealers as integrated circuits of superconducting qubits that can be described by the Ising model in the transverse field on a Chimera lattice [18]. This type of quantum annealer was designed for solving quadratic unconstrained binary optimization problems. Since D-Wave Systems installed its first commercial system in 2010, the D-Wave quantum processor doubles in size almost every two years and each new generation of machines comes with new user control features. Their current processor has more than 2000 qubits. This makes the D-Wave 2000Q machine an interesting system for researchers to explore, test and utilize it for all kinds of optimization and machine learning problems [19–30].

The latest D-Wave quantum annealer, the D-Wave 2000Q comes with an increased user control over the anneal path by means of two new features. The Anneal Offset feature allows a user to advance or delay the annealing path of individual qubits and the Anneal Pause & Ramp feature allows a user to first introduce a pause in the annealing process at a given point in time and of a certain duration and then rapidly quench the transverse field. The potential of the Anneal Offset feature, which amounts to tuning the transverse field on an individual qubit basis, has been demonstrated for a 24-qubit system [24] and for an integer factoring circuit [25]. In Ref. [25], it was shown that it gives a remarkable improvement over baseline performance, making the computation more than 1000 times faster in some cases. The Anneal Pause & Ramp feature has been used in a study of the three-dimensional transverse Ising model [26].

How these user control features influence the quantum dynamics of the system and affect the performance of solving problems is not well-understood. As mentioned in Ref. [25], determining an optimal set of anneal offsets for a given optimization problem is difficult. In Ref. [24], a heuristic algorithm, similar to the one described in Ref. [19], is used to control the anneal offset. The goal of the present work is (1) to get more insight in the relation between controlling the quantum dynamics of the system by an anneal offset