Preserving quantum coherence using optimized open-loop control techniques

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Abstract: We describe experimental and theoretical studies of open-loop quantum control techniques known as dynamical decoupling (DD) for the suppression of decoherence-induced errors in quantum systems. Our experiments on trapped atomic ion qubits demonstrate that it is possible to optimize the construction of DD sequences for a given noise power spectral density. Studies of novel sequences derived analytically or through numerical optimization – while maintaining fixed control resources – demonstrate large gains in our ability to preserve quantum coherence in arbitrary noise environments.

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1. Introduction to dynamical decoupling

From quantum computation to medical imaging, the ability to precisely and coherently control quantum mechanical systems is of fundamental importance in realizing a new generation of technologies. Unfortunately, quantum systems are susceptible to environmental fluctuations, leading to a phenomenon known as decoherence, in which the "quantumness" of the system under test becomes lost. We are thus motivated to develop control techniques capable of correcting for errors that inevitably creep into such a system. However, fundamental limitations provided by quantum mechanics – particularly the fact that the process of projective measurement destroys a quantum system – greatly restrict the applicable control-theoretic concepts in a quantum coherent setting.

Open-loop techniques that do not rely upon measurement feedback to reach a desired outcome are well suited to applications in quantum control. One such technique useful for suppressing decoherence-induced errors is known as dynamical decoupling (DD) [1]. In DD, a series of parity-reversing control pulses is applied to a quantum system in order to effectively time-reverse the accumulation of error probability due to unwanted environmental coupling.

The most familiar historical antecedent for modern DD is the spin echo from nuclear magnetic resonance, in which the deleterious effects of sample inhomogeneities can be repeatedly time-reversed by chaining together a series of "π" control pulses with a precisely defined interpulse spacing. Such a sequence, known (in a particular instance) as Carr-Purcell-Meiboom-Gill multipulse spin echo (CPMG), can easily be translated to a single-particle setting. As such CPMG has found an important role in quantum informatic experiments for the suppression of decoherence.

Under CPMG application, the cancellation of decoherence is perfect if the unwanted environmental coupling is stationary on the time scale of the experiment. However, meeting this condition is not generally possible, and in a noisy environment characterized by an arbitrary power spectral density, $S(\omega)$, the ability of CPMG to suppress decoherence breaks down as spectral components with frequencies comparable to or larger than the inverse pulse spacing appear.

Recent theoretical work [2] has shown that it is possible to mitigate the effects of high-frequency noise without additional resources in a DD sequence, *simply by modifying the relative pulse spacings*. Using the theoretical construct of the "filter function," which describes how a particular DD pulse sequence will suppress noise, Uhrig and collaborators derived a new sequence designed for specific noise environments dominated by high-frequency spectral components. Numerical simulations showed that this sequence – later dubbed "UDD" – provided many tens of dB in error suppression in an Ohmic environment with a sharp cutoff ($S(\omega) \propto \omega\ \Theta(\omega_C - \omega)$). These theoretical results were strongly motivational for our experimental studies of optimized dynamical decoupling techniques.

2. Experimental dynamical decoupling using trapped ions

Quantum two-level systems, known as qubits (quantum bits), may be realized in a number of technologies and used for fundamental tests of quantum mechanics and experimental studies of quantum control. We employ ${}^{9}Be^{+}$ ion crystals in a Penning trap for studies of dynamical decoupling techniques with exceedingly high operational and measurement

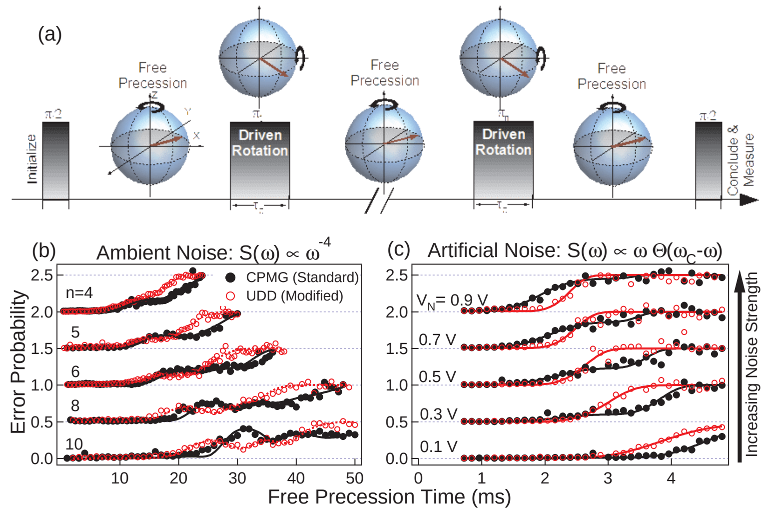

Fig. 1. Dynamical decoupling demonstrated using trapped ions. (a) Generalized sequence construction for n pulses. (b) Sequence performance as a function of n. Traces offset from zero for clarity. A value of 0.5 corresponds to complete decoherence. (c) Sequence performance in artificial Ohmic noise. Here n = 6, $\omega_C/2\pi$ = 500 Hz.

fidelities. Our qubit transition is an electron-spin-flip with energy splitting of ∼124 GHz, which is controlled using a home-built quasi-optical microwave system.

Figure 1 demonstrates our ability to suppress dephasing (a particular form of decoherence) errors due to classical noise through the application of DD pulse sequences [3, 4]. Employing an ability to engineer the noise environment in order to force our trapped ion qubits to mimic the dynamics of qubits realized in other technologies, we find strong agreement between experimental data and theoretical predictions for qubit coherence. Further, we show that in noise environments dominated by high-frequency spectral components, the novel UDD sequence outperforms standard CPMG in suppressing error and prolonging qubit coherence. These results validate a large – and growing – body of theoretical literature on dynamical decoupling sequence optimization.

3. Local sequence optimization

It is often difficult to precisely observe or predict all relevant spectral components of the environmental $S(\omega)$, making appropriate DD sequence selection challenging. In order to overcome this limitation, and to extend the optimization ideas developed by Uhrig to incorporate all relevant parameters (including nonzero pulse duration and total free-precession time), we have developed and experimentally demonstrated local optimization of dynamical decoupling pulse sequences, yielding significant benefits over the best previously known sequences. We use measurement feedback and a multidimensional search algorithm to determine optimized sequences in the absence of any direct operator knowledge of the noise environment's spectral characteristics [3].

Additionally, we derive a novel analytic condition that we enforce on the sequence filter function in order to yield a single suite of sequences providing near-optimal error suppression in any arbitrary noise environment parameterized only by a high-frequency cutoff [5]. We show via numerical simulation and experimental measurements that the resulting sequences perform comparably to CPMG in low-frequency noise environments, while giving significant benefits over UDD in the presence of high-frequency-dominated spectra.

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