Engineered Quantum Noise: Characterization by Noise Spectroscopy and Suppression by Dynamical Decoupling

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Abstract. Quantum coherence inevitably undergoes irreversible transformations over certain time-scales due to the omnipresent environmental interferences. This process, known as decoherence, is a fundamental threat to quantum computation as well as quantum communication. Hence, preserving quantum information against decoherence is an important area of current research. Our work is an attempt towards a better study of decoherence by subjecting the system qubits to engineered quantum noise, characterizing the artificial decoherence, and its supression using dynamical decoupling.

Keywords: Quantum noise, artificial decoherence, noise spectral density, dynamical decoupling.

1 Introduction

An important challenge in experimental quantum information studies is preserving the quantum information encoded in the form of quantum coherences [1, 2]. A quantum register, due to inevitable interactions with its environment, gradually looses the coherence in an irreversible process known as decoherence. Since most of the quantum technologies are based on manipulating quantum coherences, preserving them against decoherence is an important, but a challenging task.

Various techniques have already been explored for this purpose. These include encoding quantum information in decoherence-free subspaces (DFS) [3], post-processing by quantum error correction [4], and dynamical decoupling (DD) [5, 6]. Recently DD has received significant attention because of its versatility. Unlike the other techniques, DD does not require extra qubits, and moreover, it can be combined with other quantum gates leading to fault tolerant quantum computation [7].

One way of studying decoherence involves subjecting the system qubits to engineered quantum noise and characterizing the artificial decoherence. Our present work has three parts: (i) introducing artificial decoherence using engineered quantum noise, (ii) characterizing the spectral density of the artificial decoherence, and (iii) using DD to preserve quantum information by suppressing the artificial decoherence.

In the following, we describe experimental studies on introducing artificial decoherence, its characterization, and finally its suppression by using dynamical decoupling.

2 Engineered Quantum Noise

We consider a closed two qubit system - $CHCl_3$ - as our NMR quantum information processor, with the subsystems ^{1}H and ^{13}C forming the two qubits. We treat the qubit ^{1}H as the system qubit of interest (S) and the qubit ^{13}C as the environment qubit (E). We consider a purely dephasing Hamiltonian $\mathcal{H}$ given by $\mathcal{H} = \pi(\nu_S \sigma_z^S + \nu_E \sigma_z^E + \frac{\Omega}{2}\sigma_z^S \sigma_z^E)$, where σ_z's are the Pauli spin operators, ν_S and ν_E are the resonance frequencies of the system qubit and the environment qubit respectively and Ω is the coupling between them. It is apparent that the evolution of the total system under $\mathcal{H}$ is unitary. However, the subsystem ^{1}H may loose some part of useful information (in our case phase information) upon interacting with the environment qubit. By randomly perturbing the environment qubit by an external field, the relative phases of the basis states of the system qubit gets randomized leading to phase decoherence [8]. In NMR, rotaions are realized by radio-frequency pulses. We generated random pulses with small random angles ϵ_m and random phases ϕ_m. The kick operator acting on the environment qubit is of the form $\mathcal{K}_m = \exp\left(-i\epsilon_m \sigma_{\phi_m}^E\right)$.

We chose the initial system qubit state to be $\rho^S(0) = (1-p_S)I/2 + p_S\sigma_x$ and the initial environment qubit to be $\rho^E(0) = (1-p_E)I/2 + p_E\sigma_z$, where I is the identity, p_S and p_E are the spin polarizations. The kicks were applied on the environment qubit and we measured the characteristic decay constant T_2 of the system qubit. We studied the coherence of the system qubit at various kicks rates The study shows the decrease of T_2 values with increase in kick rates indicating the presence of induced decoherence.

After having acheived control over this artificial noise, we measured the spectral density of the noise which provides information about the noise content. In order to measure the spectral density of this artificial noise, we followed the technique given by [9]. This involved applying a large number of equally spaced π-pulses on the system qubit with τ being the time interval between the two π-pulses. The spectral density ($\mathcal{S}_d$) is a function of the frequency $\omega = \pi/\tau$ and is given by [9]: $\mathcal{S}_d(\omega) = \pi^2 T_2(\omega)/4$. Experiments were performed at a constant kick rate of 50 kicks/ms for various ω values by changing τ. The resulting spectral density profile is shown in Fig. 1. The triangles indicate the experimental results obtained by the above method in the absence of artificial decoherence (without applying kicks on the environment qubit) and the stars and dots indicate the experimental results

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obtained in the presence of artificial decoherence (with kicks on the environment qubit) for two different kick angles. The data clearly reveals the enhanced features in the spectral density profile in the case of artificial decoherence.

As a next step, we considered suppressing such a noise by a CPMG dynamical decoupling (DD) sequence [5]. We measured T_2 of the system for various kick rates when the system qubit is subjected to a rapid sequence of periodic π pulses while, simultaneously subjecting the environment qubit to kicks. The results are shown in Fig. 2.

3 Figures

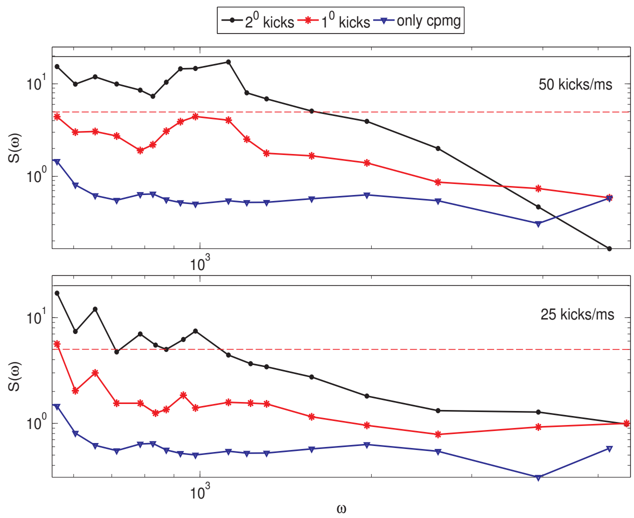

Figure 1: Spectral density distribution in the absence (triangles) and presence (stars and dots) of engineered noise.

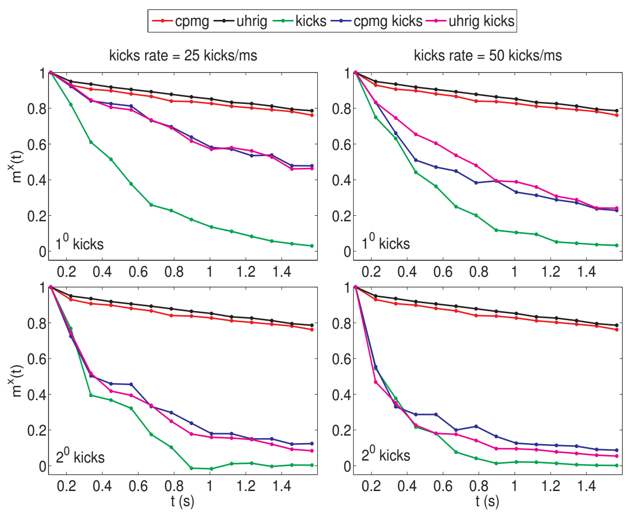

Figure 2: Evolution of transverse Magnetization for various kicks rates and kick angles. The comparision of decay of magnetization of the system with only DD, with kicks and with DD and kicks are shown. The left and right column corresponds to a kick rate of 25 and 50 kicks/ms.

4 Conclusions

We described experimental studies on the use of artificial noise to study decoherence. To introduce the noise, we exploited an ancilla qubit interacting with a system qubit. In a particular case that we considered, the system and ancilla qubits were coupled by indirect spin-spin interaction. Randomizing the ancilla spin state by external perturbations lead to the phase decoherence in system qubit. We measured the spectral density of the quantum noise which, is helpful not only in understanding the effect of standard DD sequences, but also in designing optimized DD sequences. We then studied the spectral densities before and after applying the perturbations revealing the effect of the artificial noise. Further we applied standard DD sequences to suppress the effect of the noise and preserve quantum coherences. We reported the results of these experiments carried out using nuclear magnetic resonance techniques, which may provide insights into mechanisms of decoherence and in designing efficient schemes of dynamical decoupling.

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