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

Swathi S. Hegde and T. S. Mahesh

Department of Physics and NMR Research Center,
Indian Institute of Science Education and Research, Pune 411008, India

1 Abstract

An important challenge in experimental quantum information studies is preserving the quantum information encoded in the form of quantum coherences [1, 2]. A quantum coherence 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. 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 briefly explain these three parts.

To introduce quantum noise, we exploit an ancilla qubit (called *environment* 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. Then we utilize the procedure described by Cory and coworkers [8] to introduce artificial noise. This involves applying a series of kicks (small rotations of random phases and angles) on the environment qubit. These perturbations on the environment qubit randomizes it's spin state leading to phase decoherence in system qubit. We measure the spectral density of the quantum noise which provides information about the frequency distribution of the noise and is helpful not only in understanding the effect of standard DD sequences, but also in designing optimized DD sequences. In order to characterize spectral density we utilize the procedure proposed independently by Yuge et al [9] and Alvarez et al [10]. The procedure involves applying a series of uniformly distributed π pulses (called CPMG sequence) which has a sinc-like filter-function. In the limit of large number of pulses, the filter function mimics a delta function, and samples a particular noise frequency. The frequency ω of this delta peak depends on the duration τ between the π pulses: $\omega = \pi/\tau$. The amplitude of the noise $S(\omega)$ at this frequency can be determined by measuring the decay constant T_2 of the coherence: $S(\omega) = (\pi^2/4)T_2$. By repeating the experiments with different τ values, we can scan the desired range of frequencies and can obtain the profile of $S(\omega)$. Then we studied the spectral densities before and after applying the kicks revealing the effect of the artificial noise. Further we applied standard DD sequences to suppress the effect of the artificial noise and preserve quantum coherences. Here we report the results of these experiments carried out using nuclear magnetic resonance techniques.

2 Engineered Quantum Noise

We consider a closed two qubit system - $CHCl_3$ - as our NMR quantum information processor, with the subsystems ^1H and ^{13}C forming the two qubits. We treat the qubit ^1H 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 resonant 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 ^1H 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 with $\epsilon_m = [0^0, 1.125^0]$ and $\phi_m = [0^0, 360^0]$. 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 $\rho^S(0) = (1 - p_S)1/2 + p_S\sigma_x$ and the initial environment qubit to be $\rho^E(0) = (1 - p_E)1/2 + p_E\sigma_z$, where 1 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 and is shown in Fig. 1a. The study shows the decrease of T_2 values with increase in kick rates indicating the presence of induced decoherence.

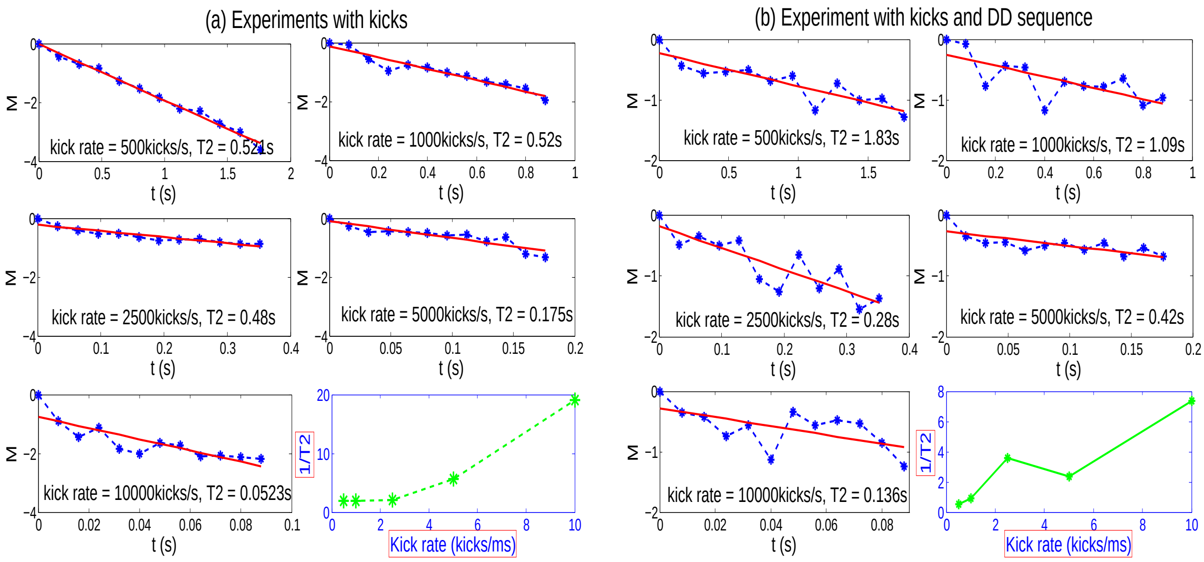

Figure 1: Experiments with kicks (a) and with kicks and DD sequence (b). The first five subplots in each of the figures are magnetization (M) verses evolution times (t). The last subplot in each of the figures represents $1/T_2$ as a function of kicks rate. The comparison between (a) and (b) shows the effect of DD sequence on the system undergoing artificial decoherence.

After having acheived control over this artificial noise, we measured the spectral density of

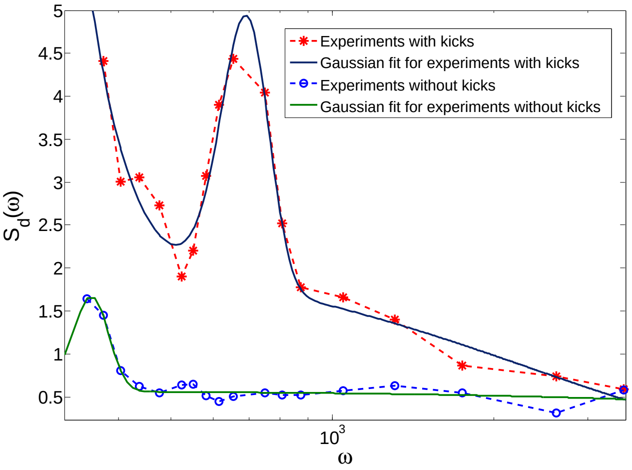

Figure 2: Spectral Density distribution of the engineered noise.

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. 2. The circles 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 indicate the experimental results obtained in the presence of artificial decoherence (with kicks on the environment qubit). 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. 1b. The comparison of the two figures reveals the efficiency of DD sequence in suppressing the artificial decoherence.

3 Conclusions

We described experimental studies on introducing artificial decoherence, its characterization, and finally its suppression using dynamical decoupling. These results can provide insights into mechanisms of decoherence and in designing efficient schemes of dynamical decoupling.

References

[1] **Michael A. Neilsen and Isaac L. Chuang**, *Quantum Computation and Quantum Information(Cambridge: Cambridge University Press) (2000)*

[2] **Viola L and Lloyd S**, *Phy. Rev. A.* ***58****, 2733 (1998)*

[3] **Daniel A. Lidar and K. Birgitta Whaley**, *arXiv:quant-ph/0301032*, (2003)

[4] **J. Preskill**, *Proc. R. Soc. A.* ***454****, 385 (1998)*

[5] **S. Meiboom and D. Gill**, *Rev. Sci. Instrum,* ***29****, 688 (1958)*

[6] **Gotz S. Uhrig**, *Phy. Rev. Lett.* ***98****, 100504 (2007)*

[7] **Hui Khoon Ng, Daniel A. Lidar and John Preskill**, *arXiv:0911.3202*, (2011)

[8] **G. Teklemariam, E. M. Fortunato, C. C. Lopez, J. Emerson, Juan Pablo Paz, T. F. Havel and D. G. Cory**, *Phy. Rev. A.* ***67****, 062316 (2003)*

[9] **Tatsuro Yuge, Susumu Sasaki and Yoshiro Hirayama**, Phys. Rev. Lett. **107**, 170504 (2011).

[10] **Gonzalo A. Alvarez and Dieter Suter**, Phys. Rev. Lett. **107**, 230501 (2011).