Quantum Matched Filtering—Signal Processing in the Quantum Age

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ABSTRACT

Optimal quantum control theory identifies the quantum equivalent of a matched filter, which maximizes the signal-to-noise ratio, enabling exploitation of extremely high sensitivity of quantum sensors to detect known signals of interest. This article describes a Johns Hopkins University Applied Physics Laboratory (APL) team's work in this field.

INTRODUCTION

Quantum systems are extremely sensitive to external fields, making them ideal for sensing weak signals. Promising candidates for quantum sensors include defects in diamond or SiC (silicon carbide), SQUID (superconducting quantum interference device)-based sensors, atomic sensors, and others (see, e.g., Ref. 1). These systems are also candidates for building quantum bits (qubits), the elementary component for information processing in quantum computers. A variety of sensing techniques have been developed to estimate either the magnitude or phase of a signal using qubits as the sensing platform. For example, Ramsey interferometry[2] allows for estimation of magnetic field amplitude with sensitivity limited by the free-evolution dephasing time of the qubit, which can be enhanced through optimal control methods.[3]

Here, we formulate the classical detection problem but in the context of a quantum sensor: is the incoming time-varying signal sensed by the qubit just noise, or is it signal plus noise? This task has been studied extensively in the field of classical decision theory.[4] In contrast to traditional quantum sensing protocols that seek to accurately estimate a signal parameter (e.g., the amplitude or phase), this work focuses on identifying control protocols that optimally discriminate between the presence or absence of a signal with known spectrum in the presence of background noise.

METHODS AND RESULTS

In the presence of an external signal and noise, the coherence of a qubit decays exponentially. This coherence decay causes a change to the probability of a binomial measurement outcome that can be observed in the lab. This difference can be amplified by quantum control [denoted by $\Omega(t)$]. This notional detection scheme is shown in Figure 1.

Detection Protocol

The quantum circuit for the detection protocol is shown in Figure 2a and can be described in four steps: (1) Initialize in a quantum superposition state. (2) Evolve for time $t = t_{\text{opt}}$ in the presence of the background and control. Here, t_{opt} is chosen depending on the signal, noise, and control to maximize the likelihood ratio by maximizing the difference in decays between the signal present and absent cases. (3) Undo the quantum superposition. (4) Measure. Record outcome as 0 or 1. Repeat steps 1–4 N_{shots} times.

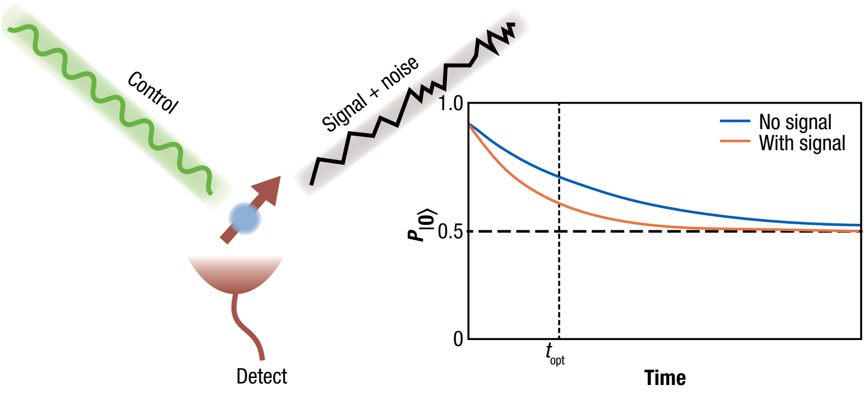

Figure 1. Notional detection scheme. The schematic figure shows a detection experiment using a single-qubit/two-level system as a detector. The plot shows an example output for detection probabilities. The optimal time for detection is at $t = t_{opt}$.

Optimization for Detection

The optimal detector requires the control protocol that maximizes the difference between signal present and absent cases. This is determined by a two-step procedure: (1) Optimize over control trajectories to obtain $\Omega_{opt}(t)$ for detection at a particular time t. (2) Optimize over different times to obtain the optimal detection time t_{opt}.

Results

The signal and background noise are classical Gaussian stochastic processes, with zero mean and power spectrum denoted by $S_s(\omega)$ and $S\eta(\omega)$, respectively; see Figure 2b. α denotes the signal-to-noise power ratio (SNR), and the signal is chosen in the regime of low SNR, $\alpha << 1$. Using what is known as the second cumulant approximation (SCA),[5] we analytically identify the optimal control for white background noise—spin-locking; see Figure 2c, in red. This corresponds to constant control at the frequency of signal's maximum, $\Omega(t) = \Omega_0$, (see Figure 2, b and c). We verify the performance of this protocol and other common schemes by numerical simulation. Figure 2d shows the signal showing agreement with the SCA. We compare spin-locking with two well-known sensing protocols (see Figure 2c): (1) Carr–Purcell–Meiboom–Gill (CPMG) pulse sequence, where $\Omega(t)$ is given by a series of equidistant π-pulses (where π refers to a unitless measure of the pulse area) separated by free evolution periods of duration π/Ω_0; and (2) Ramsey interferometry, where $\Omega(t) = 0$. Figure 2e shows that spin-locking performs the

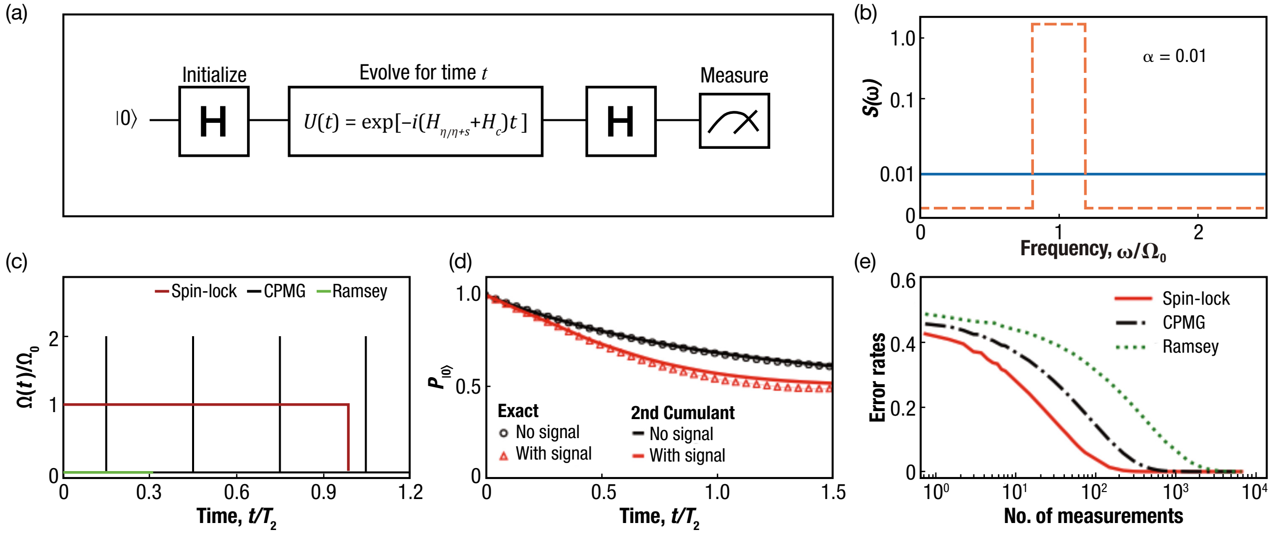

Figure 2. Results of our work. (a) Detection protocol. (b) Power spectral density (normalized) for the background noise (blue) and the signal (orange). (c) Different control protocols for sensing spin-locking, CPMG, and Ramsey. (d) Outcome probabilities $P_{|0\rangle}(t)$ in the presence (red) and absence (black) of signal. Points are from exact numerical simulations, and the solid line is the approximate result from SCA. (e) Equal error rates in detection as a function of the number of shots for different control protocols.

best: given an error rate, it requires fewer measurements to identify the presence of the signal.

The detection scheme can be used to identify signals in electromagnetic fields with the bandwidth only limited by the frequency range of the control drive. For spin-lock driving, experimental practicalities such as saturation and drive-power limitations likely limit this to about 10–100 MHz for SiC quantum sensors. On the other hand, CPMG-type control allows for much higher detection bandwidth.

OUTLOOK

There are several directions for future work. Multi-axis control needs to be explored to identify more robust protocols for detection. Another possibility is to consider cases where the signal or noise is non-Gaussian and/or nonstationary. Finally, we have yet to consider the role of multiple qubits and entanglement, which may provide an enhancement beyond what available classical techniques offer.

CONCLUSIONS

This work analyzed the performance of different control schemes for detecting a signal and shows that a spin-lock drive is nearly optimal for detecting a signal in certain noise environments. This work opens up an exciting use case for currently available quantum sensor hardware. Furthermore, as both the solution and analysis were heavily motivated by classical signal processing, there is much untapped potential in future application of these classical techniques to the quantum sensing domain.

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