Optimizing quantum sensors to their ultimate precision limits

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Abstract. Precise probing of quantum systems is one of the key to progress in diverse quantum technologies. We explore the ability of a qubit-probe to characterize unknown parameters of its environment. By resorting to quantum estimation theory, we analytically find the ultimate bound on the precision of estimating key parameters of a broad class of ubiquitous environmental noises which the qubit may probe. We provide the optimized dynamical control on the qubit-probes to achieve this maximal accuracy on the estimation [1-5] in diverse scenarious when it serves as a thermometers [3] and sensors for imaging or monitoring biological process [4-5].

Keywords: quantum sensing, dynamical control of open quantum systems, quantum information, MRI

1 Enhanced precision bound of low-temperature quantum thermometry via dynamical control

High-precision low-temperature thermometry is a challenge for experimental quantum physics. We consider a thermometer modeled by a dynamically-controlled multilevel quantum probe in contact with a bath and show that dynamical control of the quantum probe can dramatically increase the maximum accuracy bound of low-temperatures estimation. As opposed to the diverging relative error bound at low temperatures in conventional quantum thermometry, periodic modulation of the probe allows for low-temperature thermometry with temperature-independent relative error bound.

2 Quantum sensing to push the resolution limits in Magnetic Resonance Imaging

Extracting quantitative microstructure information of living tissue by non-invasive imaging is an outstanding challenge for understanding disease mechanisms. Magnetic Resonance Imaging (MRI) is a promising and widely used technique to pursue this goal, but still provides low resolution to reveal microstructure details.

2.1 Precision limits of tissue microstructure characterization by Magnetic Resonance Imaging. We derive the ultimate precision limits for obtaining microstructure information with MRI techniques by probing water-molecule diffusion. We show that currently available MRI pulse sequences can be optimized to attain the ultimate precision limits per measurement, and therefore the number of measurements and the total acquisition time may be drastically reduced compared to the present state of the art.

2.2 Non-invasive quantitative imaging of selective microstructure-sizes with magnetic resonance

We report on a method to produce images of filtered microstructure-sizes based on selective probing of nuclear-spin dephasing induced by the molecular diffusion within specific tissue-compartments. The microstructure-size filter relies on suitable dynamical control of nuclear spins that sense magnetization "decay-shifts" rather than the commonly used spin-echo decay-rates. The feasibility and performance of the method are illustrated with proof-of-principle experiments and simulations on typical size-distributions of white-matter in the mouse brain.

These results are expected to open new avenues towards unravelling diagnostic information by quantitative MRI.

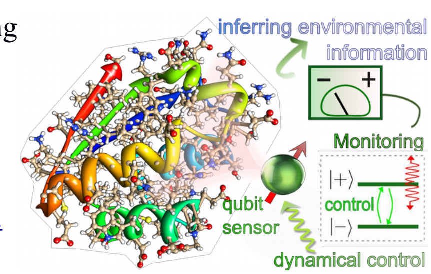

Figure 1 Schematic Quantum sensing.

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