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Precision Bounds for Characterising Quantum Measurements

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Quantum measurements, alongside quantum states and processes, form a cornerstone of quantum information processing. The precise characterisation of this triad—of states, processes, and measurements—underpins how well quantum devices used across computation, communication, and sensing platforms can be calibrated, benchmarked, and ultimately trusted. However, while state and process characterisation benefit from rigorous theoretical foundations that guide the optimal estimation strategies and set performance benchmarks, the precise characterisation of quantum measurements lacks a similar theoretical grounding. This asymmetry is not just of fundamental concern but also has practical implications; for instance, despite several experimental demonstrations of quantum detector tomography, there is no clear guideline yet on the optimal probing strategy or the best precision attainable in this task.

In this work, we resolve this asymmetry by introducing a comprehensive framework for detector estimation that links the parameter information content of measurements to the ultimate precision with which they may be characterised. By identifying a fundamental quantum limit to the information that can be extracted from a measurement—termed the detector quantum Fisher information—we determine the precision limit for detector tomography and the optimal probing strategies that attain this benchmark. Our framework is applied to physically motivated examples and validated through a provably-optimal detector estimation experiment on a superconducting platform, demonstrating relevance and robustness for current quantum detector technologies.

More broadly, our formalism presents a dual perspective to the well-studied problem of quantum state estimation, while also highlighting unique aspects of detector analysis, such as scaling advantages, that differ from state estimation. This development connects and completes the triad of high-precision state, process, and detector tomography, thereby advancing quantum information theory with wide-ranging implications for emerging technologies reliant on precisely calibrated measurements.

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