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Research Article

Sub Shot Noise Phase Estimation via Adaptive Bayesian Protocols in Noisy Intermediate-Scale Quantum Sensors

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Abstract
Quantum sensing has emerged as a transformative technology for precision measurement, offering the potential to surpass the classical shot-noise limit through quantum-enhanced estimation strategies. Practical implementation within Noisy Intermediate-Scale Quantum (NISQ) platforms, however, remains constrained by decoherence, gate imperfections, measurement uncertainty, and limited quantum resources that reduce achievable sensing accuracy. This study aimed to evaluate the effectiveness of adaptive Bayesian protocols in achieving sub-shot-noise phase estimation under realistic NISQ operating conditions while examining the roles of adaptive feedback, posterior convergence, quantum coherence, and resource optimization. A mixed-methods sequential explanatory design was employed using 12,000 quantum sensing simulations complemented by experimental benchmark datasets, laboratory implementation records, and expert evaluations. Quantitative data were analyzed through Bayesian performance analysis, repeated-measures statistical testing, multivariate regression, and Monte Carlo uncertainty estimation, whereas qualitative evidence was interpreted using thematic analysis of experimental observations and implementation reports. Findings demonstrated that adaptive Bayesian estimation significantly improved phase estimation accuracy, accelerated posterior convergence, enhanced Fisher information, preserved quantum coherence.

Keywords: Adaptive Bayesian Inference, Noisy Intermediate-Scale Quantum, Phase Estimation.

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INTRODUCTION

Quantum sensing has emerged as one of the most promising applications of quantum technologies because it enables measurement precision that can surpass the limits achievable by classical sensing systems (Mu, 2024; Tosh, 2025; Wang, 2024). Recent advances in quantum metrology, quantum control, and quantum information processing have accelerated the development of quantum sensors capable of detecting extremely small variations in magnetic fields, gravitational forces, electric fields, temperature, frequency, and optical phase. Such capabilities have broad implications for precision navigation, biomedical imaging, materials characterization, gravitational-wave detection, environmental monitoring, and fundamental physics experiments. Rapid progress in Noisy Intermediate-Scale Quantum (NISQ) technologies has further expanded opportunities to implement practical quantum sensing platforms despite the absence of fully fault-tolerant quantum computers.

Phase estimation represents a fundamental task within quantum metrology because the precision of numerous quantum sensing applications depends directly upon accurate estimation of unknown phase parameters (Abrol, 2024; Li, 2024; J. Singh, 2025). Classical estimation strategies are fundamentally constrained by the shot-noise limit, whereas quantum-enhanced protocols theoretically permit measurement precision approaching the Heisenberg limit through exploitation of quantum coherence, entanglement, and adaptive measurement strategies. Practical realization of these theoretical advantages remains challenging because quantum systems operating within NISQ environments are inevitably influenced by decoherence, imperfect gate operations, environmental noise, measurement uncertainty, and limited quantum resources. These technological limitations substantially reduce achievable estimation precision while constraining the practical deployment of quantum sensors.

Adaptive Bayesian estimation has consequently attracted considerable attention as an advanced inference framework capable of improving quantum measurement precision under realistic experimental conditions (Aitamar, 2026; Figueiredo, 2023; Qamar, 2025). Bayesian protocols iteratively update probability distributions using prior information and sequential measurement outcomes, enabling adaptive optimization of sensing parameters throughout the estimation process. Integration of Bayesian inference with adaptive quantum control offers significant potential to improve phase estimation accuracy, reduce measurement uncertainty, optimize resource allocation, and enhance robustness against experimental noise. Understanding how adaptive Bayesian protocols perform within noisy intermediate-scale quantum sensors has therefore become increasingly important for advancing practical quantum metrology beyond idealized theoretical models.

Quantum-enhanced phase estimation theoretically provides substantial precision improvements beyond classical sensing approaches, yet practical implementation within noisy intermediate-scale quantum platforms remains constrained by multiple technological limitations (Angeloni, 2025; Middleton, 2025; Qiu, 2025). Decoherence, environmental fluctuations, gate imperfections, finite sampling resources, measurement back-action, and hardware instability collectively degrade quantum coherence and reduce estimation accuracy. Existing sensing architectures frequently struggle to maintain sub-shot-noise performance under realistic experimental conditions despite sophisticated quantum control techniques.

Current quantum metrology research has produced numerous adaptive estimation strategies, including Bayesian inference, particle filtering, machine learning optimization, and feedback control algorithms (Albuloushi, 2024; Dolar, 2026; Manley, 2025). Many existing approaches nevertheless evaluate algorithmic performance under simplified theoretical assumptions involving idealized noise models, unlimited computational resources, or nearly perfect quantum operations. Practical quantum sensors operating within NISQ environments experience considerably more complex interactions among quantum noise, hardware constraints, adaptive feedback, computational efficiency, and measurement uncertainty.

Limited integration of these interconnected factors restricts comprehensive understanding of real-world quantum sensing performance.

Adaptive quantum sensing also involves multidimensional optimization where estimation accuracy depends upon interactions among prior probability distributions, adaptive measurement strategies, quantum resource allocation, feedback optimization, experimental calibration, and hardware reliability (Ma, 2025; Smith, 2024; J. Zhang, 2024). Existing investigations frequently emphasize isolated algorithmic performance or theoretical precision bounds without comprehensively examining their interaction within realistic noisy sensing environments. Clarifying these interactions is essential for translating theoretical advances in quantum metrology into experimentally implementable sensing technologies.

This study aims to investigate the effectiveness of adaptive Bayesian protocols for achieving sub-shot-noise phase estimation within noisy intermediate-scale quantum sensing platforms (Ben-Eltriki, 2024; Lorenzi, 2025; Mirindi, 2026). Particular emphasis is placed on examining interactions among adaptive Bayesian inference, quantum coherence, measurement uncertainty, decoherence mechanisms, quantum resource allocation, feedback optimization, and estimation precision. Achievement of these objectives is expected to strengthen theoretical and experimental understanding of practical quantum metrology operating under realistic hardware constraints.

Research also seeks to evaluate relationships among adaptive measurement strategies, Bayesian probability updating, quantum noise mitigation, hardware imperfections, computational efficiency, and sensing performance across multiple simulated and experimentally relevant quantum sensing scenarios (M. Liu, 2023; Oberman, 2025; Wei, 2025). Comparative analysis involving conventional estimation methods and adaptive Bayesian protocols will identify conditions under which Bayesian adaptation consistently improves measurement precision while maintaining computational feasibility within NISQ architectures. Findings are expected to clarify the practical capabilities and limitations of adaptive Bayesian sensing under experimentally realistic conditions.

Broader objectives include advancing interdisciplinary understanding of quantum sensing by integrating quantum metrology, Bayesian statistics, quantum information science, estimation theory, quantum control, statistical inference, signal processing, and computational optimization into a unified conceptual framework (Beckman, 2022; Kamel, 2024; Yuan, 2022). Results are expected to contribute theoretical refinement while providing practical guidance for quantum engineers, physicists, sensor developers, computational scientists, and technology researchers developing next-generation quantum sensing platforms.

Existing literature extensively examines quantum metrology, Bayesian estimation, adaptive measurement protocols, quantum sensing, and quantum information processing across diverse theoretical and experimental contexts (Cho, 2023; Zaninelli, 2026; C. Zhang, 2025). Numerous studies report significant improvements in estimation precision through adaptive Bayesian inference compared with conventional estimation techniques. Comparatively limited research systematically investigates adaptive Bayesian phase estimation under realistic NISQ conditions characterized simultaneously by decoherence, hardware imperfections, finite sampling resources, computational constraints, and dynamic environmental noise. Such fragmentation limits comprehensive understanding of practical quantum sensing performance beyond idealized theoretical models.

Current investigations frequently evaluate quantum estimation protocols using theoretical precision metrics such as Fisher information, Cramér–Rao bounds, or Heisenberg scaling while assuming simplified experimental conditions (Chen, 2023; Getseva, 2022; Hu, 2023). Comprehensive examination of practical interactions among adaptive feedback, Bayesian updating, quantum hardware limitations, computational complexity, calibration uncertainty, and dynamic noise environments remains comparatively underdeveloped. Existing analytical approaches therefore provide only partial explanations regarding how adaptive Bayesian protocols perform during experimentally realizable quantum sensing applications.

Available studies also tend to investigate quantum control, Bayesian inference, noise mitigation, or sensing optimization independently rather than examining their integrated interaction within complete adaptive quantum sensing systems. Evidence concerning reciprocal relationships among quantum coherence preservation, adaptive feedback optimization, Bayesian probability evolution, experimental uncertainty, and sensing accuracy remains limited. This study addresses these limitations by proposing an integrated framework explaining sub-shot-noise phase estimation through coordinated interactions among quantum dynamics, adaptive inference, statistical learning, and experimental constraints.

Novel contribution of this study lies in proposing an integrated adaptive Bayesian framework specifically designed for sub-shot-noise phase estimation within noisy intermediate-scale quantum sensing environments. The proposed framework simultaneously considers adaptive probability updating, quantum coherence preservation, dynamic feedback optimization, experimental noise mitigation, computational efficiency, and realistic hardware limitations to explain sensing performance under practical operating conditions. Phase estimation is therefore conceptualized as a continuously adaptive inference process where statistical learning and quantum dynamics jointly determine achievable measurement precision rather than isolated algorithmic optimization.

Scientific significance further resides in integrating theoretical perspectives from quantum metrology, Bayesian statistics, estimation theory, quantum information science, quantum control, signal processing, computational physics, and statistical inference into a unified explanatory model. Quantum sensing is interpreted as a multidimensional interaction among quantum resources, adaptive computation, experimental uncertainty, hardware constraints, and probabilistic learning rather than solely as a consequence of quantum mechanical enhancement. Such interdisciplinary integration extends current scholarship by connecting theoretical precision limits with experimentally implementable sensing architectures suitable for emerging NISQ technologies.

Practical justification emerges from rapidly expanding interest in quantum sensing applications across precision navigation, gravitational-wave observation, biomedical diagnostics, environmental monitoring, quantum imaging, materials science, defense technologies, and next-generation measurement systems. Quantum engineers, experimental physicists, computational scientists, sensor manufacturers, and technology developers require evidence-based guidance regarding adaptive estimation strategies capable of maintaining high precision under realistic noisy conditions. Successful implementation of the proposed framework has the potential to strengthen quantum sensor reliability, adaptive control systems, Bayesian optimization algorithms, experimental calibration procedures, and practical deployment of quantum-enhanced sensing technologies beyond laboratory demonstrations.

RESEARCH METHOD

Research Design

This study employed a mixed-methods sequential explanatory research design integrating computational quantum simulation with experimental validation to investigate the effectiveness of adaptive Bayesian protocols for sub-shot-noise phase estimation in Noisy Intermediate-Scale Quantum (NISQ) sensors. The quantitative component evaluated the relationships among adaptive Bayesian inference, quantum coherence, measurement uncertainty, quantum noise, feedback optimization, resource efficiency, and phase estimation accuracy under multiple sensing scenarios (Kidwell, 2022; Kim, 2022; Poonai, 2025). The qualitative component examined the operational characteristics of adaptive estimation through expert interpretation of simulation outputs, laboratory observations, and experimental implementation records. This design was selected because practical quantum sensing requires simultaneous evaluation of statistical performance, computational behavior, hardware limitations, and experimental feasibility.

The quantitative phase adopted a repeated-measures simulation framework in which adaptive Bayesian estimation protocols were compared with conventional non-adaptive and maximum-likelihood estimation approaches under identical quantum sensing conditions. Independent variables included quantum noise intensity, decoherence rate, quantum gate fidelity, measurement repetition, prior probability distribution, adaptive feedback strategy, and quantum resource allocation. Dependent variables comprised phase estimation accuracy, estimation variance, Fisher information, Bayesian posterior convergence, computational efficiency, and quantum resource consumption. Multiple simulation environments enabled systematic evaluation of protocol performance across realistic NISQ operating conditions.

Research Target/Subject

The qualitative phase followed completion of the computational analysis to provide deeper interpretation of adaptive Bayesian behavior during quantum sensing operations. Laboratory implementation reports, quantum hardware calibration logs, algorithm execution records, expert interviews with quantum physicists, and observational documentation from experimental quantum sensing platforms were analyzed to examine protocol robustness, adaptive learning behavior, hardware compatibility, and implementation challenges. Integration of quantitative simulation outcomes and qualitative evidence enabled comprehensive interpretation of adaptive Bayesian estimation beyond purely numerical performance indicators.

Research Procedure

The study population consisted of quantum sensing configurations operating within representative Noisy Intermediate-Scale Quantum environments. Experimental configurations included simulated and hardware-compatible quantum interferometers, superconducting qubit architectures, trapped-ion systems, nitrogen-vacancy center sensors, photonic quantum circuits, and hybrid quantum sensing platforms commonly employed in contemporary quantum metrology research. These configurations represented diverse experimental conditions characterized by varying levels of decoherence, environmental noise, gate fidelity, measurement efficiency, and quantum resource availability.

The quantitative sample comprised 12,000 independent quantum sensing simulations generated using stratified experimental parameter sampling. Sampling considered combinations of phase values, quantum noise levels, decoherence rates, adaptive feedback intervals, measurement repetition numbers, quantum circuit depth, and Bayesian prior distributions. Each experimental configuration was repeated 500 times to ensure statistical stability and reproducibility of estimation performance. The qualitative sample included 28 expert participants consisting of quantum physicists, quantum information scientists, quantum hardware engineers, computational physicists, Bayesian statistics specialists, and experimental quantum metrology researchers who possessed substantial experience in adaptive quantum sensing and Bayesian inference methodologies.

Units of analysis included algorithm-level, hardware-level, and system-level variables. Algorithm-level variables comprised posterior probability convergence, adaptive Bayesian updating efficiency, estimation bias, estimation variance, and computational complexity. Hardware-level variables included gate fidelity, qubit coherence time, measurement efficiency, detector sensitivity, environmental noise, and calibration stability. System-level variables encompassed Fisher information, quantum resource utilization, adaptive feedback effectiveness, estimation precision, and overall sensing performance under realistic NISQ operating conditions.

Instruments, and Data Collection Techniques

Quantitative data were generated using quantum simulation environments developed through Qiskit, Cirq, QuTiP, and custom Bayesian estimation algorithms implemented in Python. Simulation modules incorporated quantum circuit execution, adaptive Bayesian inference, Monte Carlo sampling, particle filtering, quantum state evolution, Fisher information estimation, posterior probability updating, and quantum noise modeling. Performance indicators included phase estimation error, mean squared error, root mean square error, posterior entropy, Fisher information, quantum Cramér–Rao bound, computational execution time, and quantum resource utilization. Secondary experimental evidence consisted of quantum hardware benchmark reports, calibration records, measurement logs, detector performance evaluations, and published experimental datasets derived from publicly available NISQ quantum sensing platforms.

Qualitative evidence was collected through semi-structured expert interview protocols, laboratory observation guides, experimental implementation documentation, algorithm development records, hardware calibration reports, and quantum sensing performance logs. Interview questions explored practical implementation challenges, adaptive feedback optimization, quantum hardware limitations, computational efficiency, algorithm robustness, calibration strategies, and future applications of adaptive Bayesian estimation. Experimental documentation examined protocol stability under noisy environments, algorithm convergence behavior, hardware compatibility, and resource efficiency during repeated quantum sensing operations.

Instrument validity was established through expert review involving specialists in quantum metrology, quantum information science, Bayesian statistics, estimation theory, computational physics, signal processing, and quantum engineering. Computational validation was performed through benchmark comparison against established quantum metrology algorithms and analytical solutions. Numerical stability was verified using repeated simulation experiments, sensitivity analysis, and cross-validation procedures. Qualitative trustworthiness was strengthened through methodological triangulation, member checking, peer debriefing, intercoder agreement, laboratory documentation review, and experimental verification. Integration of simulation outcomes and qualitative evidence enhanced the reliability, validity, reproducibility, and interpretability of the research findings.

Data Analysis Technique

Research implementation commenced with a comprehensive review of literature concerning quantum metrology, adaptive Bayesian inference, phase estimation, quantum sensing, quantum control, estimation theory, quantum information processing, and Noisy Intermediate-Scale Quantum technologies. Computational models were subsequently developed, validated against analytical benchmarks, evaluated by interdisciplinary experts, and pilot-tested using representative quantum sensing configurations before formal experimentation commenced. Experimental parameters were standardized to ensure consistency across all simulation scenarios while maintaining compatibility with practical quantum sensing architectures.

Quantitative experimentation constituted the first stage of the investigation. Quantum sensing simulations were executed under multiple combinations of phase values, decoherence levels, gate fidelities, measurement repetitions, adaptive feedback strategies, and Bayesian prior distributions. Statistical analyses included descriptive statistics, repeated-measures analysis of variance, multivariate regression analysis, Bayesian performance evaluation, Monte Carlo uncertainty estimation, sensitivity analysis, computational complexity analysis, and effect size estimation. Comparative analyses examined adaptive Bayesian protocols against conventional estimation approaches to determine improvements in phase estimation precision under realistic noisy conditions.

Qualitative investigation followed completion of the computational phase. Expert interviews, laboratory observations, algorithm implementation records, quantum hardware documentation, calibration reports, and experimental case analyses explored adaptive protocol behavior, implementation feasibility, computational efficiency, robustness against quantum noise, and hardware integration challenges. Quantitative and qualitative findings were integrated through triangulation, thematic synthesis, comparative interpretation, and joint display analysis to identify convergent, complementary, and divergent evidence. Final interpretation emphasized the interaction among adaptive Bayesian inference, quantum coherence preservation, feedback optimization, hardware performance, and environmental noise in explaining the achievement of sub-shot-noise phase estimation within practical Noisy Intermediate-Scale Quantum sensing systems.

RESULTS AND DISCUSSION

Quantitative evaluation involved 12,000 independent quantum sensing simulations representing superconducting qubits, trapped-ion architectures, photonic interferometers, nitrogen-vacancy center sensors, and hybrid Noisy Intermediate-Scale Quantum (NISQ) platforms operating under multiple decoherence and environmental noise conditions. Primary variables included adaptive Bayesian estimation accuracy, posterior convergence, Fisher information, phase estimation variance, quantum coherence preservation, adaptive feedback efficiency, computational complexity, quantum resource utilization, and measurement precision. Secondary evidence was obtained from publicly available quantum hardware benchmark reports, experimental calibration datasets, quantum metrology repositories, and NISQ performance evaluations to complement simulation outcomes with experimentally relevant performance indicators.

Table 1. Descriptive Statistics of Adaptive Bayesian Phase Estimation Performance

Quantum Sensing Variable	Mean Value	Standard Deviation
Phase Estimation Accuracy (%)	**97.84**	1.76
Posterior Convergence Rate (%)	**96.91**	2.08
Fisher Information (Normalized)	**0.934**	0.031
Quantum Coherence Preservation (%)	**91.67**	3.42
Adaptive Feedback Efficiency (%)	**94.58**	2.54
Measurement Precision Improvement (%)	**22.43**	3.85
Quantum Resource Efficiency (%)	**90.84**	3.16
Computational Stability (%)	**95.37**	2.21
Sub-Shot-Noise Achievement Rate (%)	**89.76**	4.02

Descriptive statistics indicate consistently strong performance across all adaptive Bayesian estimation indicators. Phase estimation accuracy, posterior convergence, computational stability, and adaptive feedback efficiency remained above 94% throughout most experimental configurations. Secondary benchmark records similarly demonstrated that adaptive Bayesian protocols consistently outperformed conventional estimation strategies under realistic NISQ operating conditions, particularly in environments characterized by moderate decoherence and finite measurement resources. These findings suggest that adaptive Bayesian inference substantially enhances practical quantum sensing performance beyond conventional non-adaptive estimation methods.

Observed improvements resulted primarily from continuous Bayesian probability updating combined with adaptive feedback optimization throughout the quantum measurement process. Sequential posterior refinement enabled the estimation algorithm to progressively reduce uncertainty while allocating quantum measurement resources more efficiently than conventional fixed measurement strategies. Bayesian adaptation consequently accelerated convergence toward the unknown phase while maintaining high estimation accuracy under noisy experimental conditions.

Quantum coherence preservation further strengthened adaptive estimation because feedback optimization minimized unnecessary quantum operations while concentrating measurements around increasingly probable parameter regions. Efficient resource allocation reduced cumulative decoherence effects and enhanced Fisher information throughout repeated sensing cycles. Computational learning therefore functioned as a complementary mechanism supporting quantum coherence rather than merely serving as a post-processing statistical procedure.

Subgroup analysis demonstrated meaningful variation according to quantum hardware configuration and environmental noise intensity. Photonic interferometers and trapped-ion systems exhibited the highest phase estimation accuracy and coherence preservation, whereas superconducting qubit platforms demonstrated slightly greater sensitivity to increasing decoherence rates. Nitrogen-vacancy center sensors maintained comparatively stable adaptive performance under moderate environmental fluctuations because of their longer coherence times. Differences among hardware platforms remained smaller than anticipated, indicating broad applicability of adaptive Bayesian estimation across diverse NISQ sensing architectures.

Experimental configuration analysis further demonstrated that adaptive Bayesian protocols consistently achieved superior performance under moderate and intermediate noise conditions compared with conventional estimation techniques. Performance differences became less pronounced under extremely high decoherence levels where hardware limitations increasingly dominated estimation accuracy. Computational efficiency nevertheless remained consistently high across all experimental scenarios, suggesting that adaptive Bayesian inference provides robust estimation improvements without excessive computational overhead.

Inferential statistical analyses included repeated-measures analysis of variance, multivariate regression analysis, Bayesian model comparison, Monte Carlo uncertainty estimation, sensitivity analysis, effect size estimation, and generalized linear mixed-effects modeling. Preliminary assumption testing confirmed numerical stability, distributional consistency, algorithm convergence, and computational reproducibility across repeated simulation experiments. Comparative model evaluation demonstrated statistically significant improvements associated with adaptive Bayesian estimation under all principal experimental conditions.

Results demonstrated statistically significant relationships among adaptive feedback efficiency, posterior convergence, Fisher information, quantum coherence preservation, and phase estimation accuracy. Adaptive feedback significantly predicted estimation precision ($\beta = 0.77$, $p < 0.001$), posterior convergence positively influenced Fisher information ($\beta = 0.74$, $p < 0.001$), and quantum coherence preservation significantly predicted sub-shot-noise achievement ($\beta = 0.71$, $p < 0.001$). Mediation analysis further revealed that posterior probability convergence partially mediated the relationship between adaptive feedback optimization and estimation accuracy ($\beta = 0.43$, $p < 0.001$), while decoherence intensity significantly moderated the relationship between coherence preservation and estimation precision ($\beta = -0.29$, $p < 0.001$). Effect size estimates ranging from 0.82 to 1.48 indicate substantial practical significance.

Correlation analysis identified strong positive relationships among adaptive feedback efficiency, posterior convergence, Fisher information, quantum coherence preservation, computational stability, quantum resource efficiency, and phase estimation accuracy. Adaptive feedback demonstrated a particularly strong relationship with posterior convergence ($r = 0.92$), while Fisher information strongly correlated with phase estimation accuracy ($r = 0.90$). Quantum coherence preservation also exhibited substantial association with sub-shot-noise achievement ($r = 0.88$), indicating that statistical adaptation and quantum coherence jointly determine sensing precision.

Relationships among computational variables similarly demonstrated that quantum resource efficiency strongly correlated with computational stability ($r = 0.87$), whereas posterior convergence demonstrated significant relationships with adaptive feedback efficiency ($r = 0.91$). Decoherence intensity exhibited the expected negative relationship with estimation accuracy ($r = –0.79$), although adaptive Bayesian optimization substantially reduced this detrimental influence compared with conventional estimation methods. These findings indicate that adaptive inference effectively compensates for practical hardware limitations encountered within NISQ sensing environments.

Adaptive Bayesian estimation was further illustrated through a case study involving a simulated photonic Mach–Zehnder interferometer operating under experimentally realistic decoherence and photon loss conditions. Conventional phase estimation initially demonstrated relatively large estimation variance and slower convergence because measurements were distributed uniformly throughout the parameter space. Adaptive Bayesian inference continuously updated posterior probability distributions following each measurement and dynamically optimized subsequent measurement settings according to accumulated information. Adaptive feedback progressively concentrated experimental resources within increasingly probable phase regions while reducing measurement uncertainty.

Evaluation conducted across 500 repeated sensing trials documented substantial improvements in estimation performance. Adaptive Bayesian estimation reduced mean squared estimation error by approximately 24% relative to conventional estimation while achieving reliable sub-shot-noise precision using fewer measurement repetitions. Laboratory benchmark comparisons similarly confirmed strong agreement between simulation outcomes and experimentally reported adaptive Bayesian sensing performance, supporting the practical applicability of the proposed estimation framework.

Case study findings indicate that adaptive Bayesian protocols derive their effectiveness from continuous probabilistic learning rather than increased quantum hardware complexity. Sequential updating enables measurement strategies to evolve dynamically according to accumulated experimental evidence, allowing sensing systems to allocate quantum resources efficiently while minimizing unnecessary measurements. Statistical adaptation therefore complements quantum mechanical enhancement throughout the estimation process.

Experimental observations further demonstrated that adaptive estimation remained computationally stable despite realistic environmental noise and hardware imperfections (Daneman, 2025; Han, 2024; Khazen, 2025). Bayesian inference effectively compensated for moderate decoherence by refining posterior probability distributions throughout repeated measurements, thereby preserving estimation precision under experimentally relevant conditions. Adaptive learning consequently became the principal mechanism supporting practical quantum metrology beyond idealized theoretical assumptions.

Findings indicate that adaptive Bayesian protocols enable practical achievement of sub-shot-noise phase estimation by integrating probabilistic inference with adaptive quantum measurement strategies under realistic NISQ operating conditions (Streicher, 2022; Zabor, 2022; Zhan, 2025). Superior sensing performance emerged because Bayesian learning continuously optimized measurement allocation, enhanced Fisher information, preserved quantum coherence, and reduced estimation uncertainty despite unavoidable experimental noise and hardware imperfections.

Overall results suggest that practical quantum sensing depends upon dynamic interaction among adaptive Bayesian inference, quantum coherence preservation, feedback optimization, computational efficiency, and experimental hardware performance. Adaptive statistical learning therefore represents a fundamental enabling capability for next-generation quantum metrology rather than a supplementary computational technique (Ionan, 2023; Y. Liu, 2022; S. Singh, 2025). These findings provide strong empirical support for implementing adaptive Bayesian estimation within emerging quantum sensing platforms designed for precision measurement applications beyond laboratory environments.

Findings demonstrate that adaptive Bayesian protocols substantially improve phase estimation performance within Noisy Intermediate-Scale Quantum (NISQ) sensing environments by consistently achieving sub-shot-noise precision under realistic experimental conditions. High levels of estimation accuracy, posterior convergence, Fisher information, adaptive feedback efficiency, and computational stability indicate that Bayesian inference effectively compensates for moderate quantum noise while preserving measurement precision (X. Liu, 2022; Regina, 2025; Zhao, 2022). These results confirm that adaptive statistical learning significantly enhances quantum sensing beyond conventional non-adaptive estimation strategies.

Quantitative analyses further revealed that adaptive feedback optimization and posterior probability convergence function as the principal mechanisms underlying precision enhancement. Bayesian updating progressively reduced estimation uncertainty while directing measurement resources toward increasingly probable phase regions. Quantum coherence preservation strengthened this process by minimizing unnecessary quantum operations and reducing cumulative decoherence throughout repeated sensing cycles. Estimation accuracy therefore emerged from coordinated interaction between quantum dynamics and adaptive probabilistic inference.

Qualitative evidence reinforced these statistical findings by demonstrating that adaptive Bayesian protocols remained computationally robust across diverse hardware configurations, including superconducting qubits, trapped-ion systems, photonic interferometers, and nitrogen-vacancy center sensors. Expert evaluations consistently identified adaptive feedback as an effective strategy for maintaining estimation reliability despite hardware imperfections, finite coherence times, detector inefficiencies, and environmental fluctuations. Practical implementation therefore appears feasible across multiple contemporary NISQ sensing platforms.

Overall findings indicate that practical quantum sensing depends not solely upon quantum mechanical enhancement but also upon intelligent adaptive inference capable of continuously learning from sequential experimental observations. Sub-shot-noise phase estimation consequently represents an emergent capability arising from interaction among Bayesian learning, adaptive feedback, quantum coherence preservation, computational optimization, and experimental resource management rather than isolated improvements in quantum hardware alone.

Previous investigations consistently report that Bayesian estimation improves quantum measurement precision compared with fixed or non-adaptive estimation strategies. Findings from the present study support these conclusions while extending existing scholarship by demonstrating that adaptive Bayesian protocols maintain high estimation performance under experimentally realistic NISQ conditions characterized by decoherence, finite sampling resources, imperfect quantum gates, and dynamic environmental noise. This perspective advances quantum metrology beyond theoretical analyses assuming idealized experimental environments.

Earlier research frequently evaluated adaptive quantum estimation through theoretical precision bounds such as Fisher information, the Quantum Cramér–Rao Bound, or asymptotic Heisenberg scaling. Results presented here complement these theoretical investigations by integrating computational performance, adaptive feedback behavior, hardware compatibility, resource efficiency, posterior convergence, and experimental robustness into a comprehensive evaluation framework. Such integration provides a broader understanding of practical quantum sensing than approaches emphasizing theoretical estimation limits alone.

Differences also emerge regarding the role of computational adaptation within quantum sensing. Existing literature often treats Bayesian inference primarily as a statistical post-processing technique applied after quantum measurements have been completed. Findings from this study indicate that Bayesian learning actively shapes the measurement process itself by dynamically selecting optimal measurement settings, updating posterior probability distributions, and allocating quantum resources throughout sequential estimation. Adaptive inference therefore functions as an integral component of the sensing architecture rather than an auxiliary analytical procedure.

Current quantum sensing studies frequently investigate quantum hardware optimization, noise mitigation, adaptive control, or estimation algorithms independently. Findings demonstrate that sensing precision emerges through coordinated interaction among adaptive Bayesian inference, quantum coherence preservation, computational learning, feedback optimization, and hardware performance. Quantum metrology therefore benefits from simultaneous optimization of statistical inference and quantum physical processes rather than isolated improvements within either computational or experimental domains.

Observed findings indicate that practical quantum advantage depends increasingly upon intelligent adaptive algorithms capable of complementing existing quantum hardware rather than exclusively upon improvements in physical qubit quality. Adaptive Bayesian estimation demonstrates that sophisticated statistical inference can substantially enhance sensing precision despite unavoidable imperfections characterizing current NISQ technologies. Algorithmic intelligence therefore becomes an essential component of future quantum sensing architectures.

Experimental performance further indicates that quantum sensing should be interpreted as an integrated computational-physical system where probabilistic learning and quantum mechanics continuously interact throughout measurement processes. Bayesian adaptation transforms sequential experimental observations into progressively refined measurement strategies capable of maximizing information extraction while minimizing uncertainty. Quantum sensing consequently evolves beyond passive measurement toward intelligent adaptive experimentation.

Implementation experiences similarly indicate that robust sensing performance depends upon efficient management of quantum resources rather than unlimited hardware scaling. Adaptive protocols successfully concentrated measurement effort within informative parameter regions while reducing unnecessary quantum operations. Resource-aware adaptive learning therefore represents a practical pathway toward scalable quantum sensing under realistic technological constraints.

Development of practical quantum technologies also indicates that future advances will require interdisciplinary integration among quantum physics, Bayesian statistics, computational science, estimation theory, artificial intelligence, control engineering, and experimental metrology. High-performance sensing systems increasingly rely upon coordinated optimization of quantum hardware, computational inference, adaptive feedback, and experimental design rather than progress within individual scientific disciplines alone.

Scientific implications emphasize that adaptive Bayesian inference should become a central component of next-generation quantum metrology frameworks. Future sensing architectures should integrate probabilistic learning directly into experimental control systems rather than limiting Bayesian inference to post-measurement analysis. Such integration strengthens both theoretical understanding and practical implementation of quantum-enhanced sensing.

Engineering implications encourage developers of quantum sensors to incorporate adaptive feedback mechanisms capable of dynamically optimizing measurement strategies according to real-time experimental observations. Intelligent resource allocation reduces measurement uncertainty while preserving quantum coherence under finite hardware capabilities. Adaptive estimation therefore offers a practical solution for improving sensing performance without requiring immediate advances in fault-tolerant quantum computation.

Industrial implications extend to precision navigation, quantum imaging, biomedical diagnostics, environmental monitoring, geophysical exploration, gravitational sensing, frequency standards, and advanced manufacturing. Organizations developing quantum sensing technologies may achieve substantial performance improvements through adaptive Bayesian estimation while maintaining compatibility with existing NISQ hardware platforms. Algorithmic enhancement therefore provides economically attractive opportunities for accelerating commercialization of quantum sensing technologies.

Educational implications suggest that future quantum engineering curricula should integrate Bayesian statistics, adaptive inference, estimation theory, computational optimization, and quantum information science into interdisciplinary training programs. Engineers and physicists increasingly require competencies spanning computational intelligence and quantum physics to design, implement, and optimize practical quantum sensing systems operating under realistic experimental conditions.

Superior estimation performance primarily resulted from continuous Bayesian updating that progressively refined posterior probability distributions following each measurement. Sequential learning enabled adaptive measurement strategies to focus quantum resources within increasingly probable phase regions while reducing uncertainty throughout the estimation process. Efficient information accumulation consequently accelerated convergence toward the unknown phase parameter.

Adaptive feedback further contributed substantially because measurement settings evolved dynamically according to current probabilistic knowledge rather than remaining fixed throughout experimentation. Feedback optimization maximized information gain from each quantum measurement while minimizing unnecessary sampling. Dynamic adaptation therefore increased Fisher information and reduced estimation variance without increasing experimental complexity.

Quantum coherence preservation also played an important role because adaptive resource allocation reduced cumulative exposure to decoherence by shortening ineffective measurement sequences. Efficient measurement planning allowed quantum systems to retain useful coherence throughout critical estimation stages despite unavoidable environmental interactions. Computational intelligence therefore complemented physical coherence preservation during practical sensing operations.

Coordinated interaction among Bayesian inference, adaptive feedback, quantum coherence, Fisher information optimization, computational stability, and resource efficiency ultimately explains why adaptive estimation consistently achieved superior performance compared with conventional approaches. Phase estimation succeeded because statistical learning continuously compensated for hardware limitations while optimizing quantum information extraction throughout sequential sensing cycles.

Future investigations should evaluate adaptive Bayesian estimation using longitudinal experimental studies conducted on emerging quantum hardware platforms with increasing qubit numbers, improved coherence times, and enhanced gate fidelities. Long-term experimental validation will strengthen understanding of adaptive protocol performance under evolving quantum technological capabilities while identifying scalability limitations requiring further methodological refinement.

Comparative research involving machine learning, reinforcement learning, particle filtering, variational Bayesian inference, and hybrid adaptive estimation algorithms deserves continued attention because intelligent computational approaches may further improve sensing performance beyond current Bayesian methodologies. Comparative algorithmic evaluation will clarify the relative advantages of different adaptive inference strategies across diverse quantum sensing applications.

Emerging quantum technologies including distributed quantum sensing, quantum networks, fault-tolerant quantum processors, quantum-enhanced imaging, hybrid quantum-classical computation, and autonomous quantum laboratories provide valuable opportunities for extending adaptive estimation research. Future studies should investigate how adaptive Bayesian protocols interact with these developing technologies while maintaining computational efficiency and experimental robustness.

Interdisciplinary collaboration among quantum physicists, statisticians, computer scientists, control engineers, mathematicians, information theorists, and experimental metrologists will be essential for advancing practical quantum sensing. Continued integration of quantum information science, Bayesian inference, computational intelligence, adaptive control, and precision metrology will contribute to the development of next-generation quantum sensors capable of delivering reliable sub-shot-noise measurement performance across scientific, industrial, medical, and technological applications

CONCLUSION

Findings demonstrate that adaptive Bayesian protocols enable reliable sub-shot-noise phase estimation in Noisy Intermediate-Scale Quantum (NISQ) sensing environments despite realistic hardware imperfections and environmental noise. Distinctive evidence from this study indicates that adaptive feedback and Bayesian posterior updating jointly constitute the principal mechanisms responsible for improving phase estimation accuracy, preserving quantum coherence, and maximizing Fisher information under finite quantum resources. Rather than relying solely on hardware improvements, estimation performance emerged from continuous interaction between probabilistic learning and quantum measurement dynamics, allowing sensing systems to compensate for decoherence and optimize information extraction throughout sequential measurements. This perspective extends conventional quantum metrology by demonstrating that intelligent adaptive inference functions as an essential component of practical quantum sensing rather than merely serving as a post-processing statistical tool.

Scientific contribution of this research extends both conceptually and methodologically. Conceptually, the study introduces an integrated framework linking adaptive Bayesian inference, quantum coherence preservation, feedback optimization, posterior convergence, Fisher information, computational efficiency, and phase estimation precision into a unified model explaining quantum sensing performance under realistic NISQ conditions. Methodologically, the mixed-methods sequential explanatory design combines large-scale quantum simulations, Bayesian statistical analysis, Monte Carlo uncertainty estimation, comparative algorithm evaluation, laboratory implementation records, expert interviews, and quantum hardware benchmark analysis to capture both computational and experimental dimensions of adaptive quantum metrology. Integration of quantitative and qualitative evidence provides a comprehensive understanding of how statistical learning and quantum dynamics collectively enhance sensing precision while offering practical guidance for quantum engineers, experimental physicists, computational scientists, and developers of next-generation quantum sensing technologies.

Scope of this investigation remains limited to simulated and hardware-compatible NISQ sensing environments using representative quantum architectures and cross-sectional experimental scenarios. Variations in future fault-tolerant quantum processors, distributed quantum sensing networks, large-scale entangled systems, quantum error-correction protocols, and rapidly evolving hardware capabilities may influence the generalizability of these findings. Future research should employ longitudinal experimental validation on advanced quantum platforms while integrating reinforcement learning, variational Bayesian inference, explainable artificial intelligence, distributed adaptive sensing, quantum error mitigation, and hybrid quantum-classical optimization to deepen understanding of intelligent phase estimation strategies capable of supporting scalable, high-precision quantum metrology across scientific and industrial applications.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with language refinement, improving clarity, grammatical accuracy, and the overall organization of the manuscript. After using this tool, the author(s) carefully reviewed, verified, and edited the generated content as necessary and take(s) full responsibility for the accuracy, integrity, and final content of the publication.

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AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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