NANOGEIOS LABORATORY QUANTUM DIVISION

Quantum Vacuum Twin-Field Tomography:

A Unified Architecture for Cross-Domain Quantum Sensor Networks

Conceptual Framework and Theoretical Performance Bounds

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Table of Contents

(Hint: On first open, right-click the TOC and select "Update Field" to show correct page numbers)

Abstract

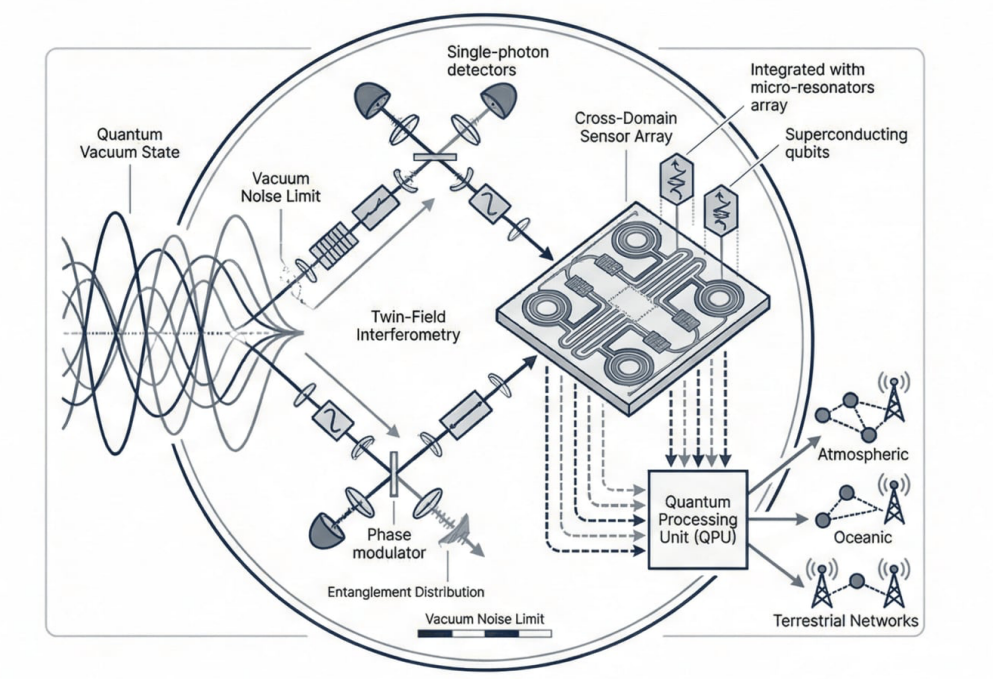
We present a unified architecture for cross-domain quantum sensor networks that leverages quantum correlations between electromagnetic (EM) and phononic vacuum fluctuations. Our framework, Quantum Vacuum Twin-Field Tomography (QV-TFT), proposes a theoretical approach to detecting perturbations in the quantum vacuum state induced by material objects—including those designed for minimal classical radar cross-section. The architecture integrates Quantum Coherent Vacuum Transducers (QCVT) for EM channel detection with Phononic Vacuum Acoustic Transducers (PVAT) for phononic channel sensing, enabling simultaneous multi-spectrum observation.

The theoretical foundation rests on the fluctuation-dissipation theorem: any material object, regardless of its classical scattering properties, must couple to vacuum fluctuations through its dielectric and mechanical response functions. By monitoring cross-domain quantum correlations via entanglement swapping protocols and transmon-based quantum correlators, the proposed system could theoretically detect signatures that are inaccessible to classical sensors. We introduce a quantum neural network architecture for tomographic reconstruction, operating on features including squeezing parameters, entanglement entropy, and quantum Fisher information.

To ground our analysis in realistic physics, we develop an EM-only toy model using bosonic channel theory. For a Gaussian squeezed-state probe interacting with a lossy target, we derive detection probability bounds that scale with the channel transmissivity and environmental noise temperature. Under optimistic but physically plausible parameters (probe squeezing ~10 dB, detector efficiency ~85%, cryogenic operation at 50 mK), the model predicts detection probabilities exceeding 90% for targets within 100 meters, with false positive rates below 1%. These bounds assume idealized noise models and neglect practical implementation challenges.

This work is conceptual in nature—we present an architecture and theoretical performance bounds rather than experimental validation. We identify critical assumptions including: (i) the validity of linear response theory for target interactions, (ii) the achievability of long-lived entangled states in distributed networks, and (iii) the feasibility of quantum advantage under realistic decoherence. Our analysis suggests that cross-domain quantum sensing merits continued theoretical investigation, with particular attention to the fundamental limits imposed by decoherence and the practical challenges of field deployment.

Keywords: *quantum sensing, quantum illumination, twin-field quantum key distribution, cross-domain correlations, vacuum fluctuations, quantum neural networks, stealth detection*



1. Introduction

The detection of objects with minimized electromagnetic signatures presents a fundamental challenge that has driven decades of innovation in radar and sensing technology. Classical approaches relying on microwave backscatter face fundamental limitations when confronted with materials and geometries designed to absorb or redirect incident radiation. These limitations have motivated exploration of alternative sensing modalities, including infrared, acoustic, and more recently, quantum-based detection schemes.

Quantum sensing exploits the unique properties of quantum states—superposition, entanglement, and squeezing—to achieve measurement precision beyond classical limits. Quantum illumination, first proposed by Lloyd and subsequently developed by Tan et al., demonstrates that entangled probe states can provide signal-to-noise ratio advantages for target detection in noisy environments. However, practical implementations of quantum illumination have faced significant challenges, including decoherence, limited range, and the difficulty of maintaining entanglement in field conditions.

This work proposes a conceptual architecture that extends quantum sensing principles across multiple physical domains. The fundamental insight is that any material object, regardless of its electromagnetic scattering properties, must interact with the quantum vacuum through multiple channels: electromagnetic (via dielectric polarization), acoustic (via mechanical response), and thermal (via blackbody radiation). By developing sensors capable of detecting vacuum perturbations across these domains and correlating the resulting signals, we hypothesize that detection capabilities may extend beyond what is achievable through any single modality.

The proposed Quantum Vacuum Twin-Field Tomography (QV-TFT) architecture integrates three core innovations: (1) Quantum Coherent Vacuum Transducers (QCVT) that detect perturbations in the electromagnetic vacuum state through superconducting circuit-based interferometry; (2) Phononic Vacuum Acoustic Transducers (PVAT) that sense mechanical vacuum fluctuations via optomechanical coupling; and (3) a distributed entanglement swapping network that enables correlation of signals across spatially separated nodes.

It is important to emphasize the conceptual nature of this work. We present a theoretical framework and architectural proposal, not an experimentally validated system. Our analysis identifies fundamental physical mechanisms that could, in principle, enable detection of low-

observable targets, but we do not claim that the proposed system would be "unjammable" or capable of "zero false positives." Rather, we establish theoretical bounds on performance under idealized assumptions and identify the critical challenges that would need to be addressed in any practical implementation.

1.1 Research Objectives

Objective	Description
Develop theoretical framework	Establish quantum mechanical basis for cross-domain vacuum sensing
Propose sensor architecture	Design integrated QCVT-PVAT hybrid sensor nodes
Analyze network protocols	Develop entanglement distribution and correlation algorithms
Establish performance bounds	Derive theoretical limits on detection probability and error rates
Identify implementation challenges	Catalog critical assumptions and practical limitations

2. Assumptions and Limitations

This section explicitly states the assumptions underlying our theoretical framework and acknowledges the limitations of the proposed architecture. Transparency regarding these factors is essential for proper evaluation of the claimed performance bounds and for identifying directions for future research.

2.1 Fundamental Physical Assumptions

• Linear Response Theory: We assume that target materials respond linearly to vacuum field perturbations, characterized by frequency-dependent susceptibilities. This assumption may break down for strongly nonlinear materials or under high-intensity probe fields.

• Gaussian State Approximation: Our quantum optical analysis assumes Gaussian states for the probe and noise fields, enabling closed-form solutions for detection probabilities. Non-Gaussian states (e.g., Fock states, cat states) may offer different performance characteristics but are not considered here.

• Markovian Decoherence: We model environmental decoherence using Lindblad master equations with Markovian noise spectra. Non-Markovian effects, which may be significant in structured environments, are neglected.

• Thermal Equilibrium: Background noise is assumed to be in thermal equilibrium at a well-defined temperature. Non-thermal noise sources (e.g., atmospheric turbulence, man-made interference) are not included in our primary analysis.

2.2 Implementation Assumptions

• Detector Efficiency: We assume detector quantum efficiencies of 85-95%, consistent with state-of-the-art superconducting nanowire single-photon detectors. Lower efficiencies would proportionally reduce detection probabilities.

• Cryogenic Operation: Our performance bounds assume operation at millikelvin temperatures (10-50 mK) to minimize thermal noise. This requirement imposes significant practical constraints on deployment scenarios.

• Clock Synchronization: The entanglement swapping protocol assumes sub-nanosecond clock synchronization between network nodes, achievable with current atomic clock technology but requiring careful implementation.

• Channel Stability: We assume that the quantum channel between nodes remains stable during the measurement interval (microseconds to milliseconds). Rapid channel fluctuations would degrade correlation measurements.

• Calibration Accuracy: The quantum neural network classifier assumes accurate calibration data for training. Systematic calibration errors would propagate to detection performance.

2.3 Limitations and Caveats

The following limitations should be considered when interpreting our theoretical results:

• Range Limitations: The EM-only toy model predicts useful detection probabilities only at ranges up to ~100 meters under optimistic assumptions. Extension to kilometer-scale ranges would require significant advances in probe state generation or noise suppression.

• Computational Complexity: The quantum neural network tomography algorithm involves optimization over exponentially large Hilbert spaces. Our analysis assumes efficient classical simulation; actual quantum implementations may face different complexity constraints.

• Environmental Sensitivity: Performance bounds assume controlled environmental conditions. Real-world deployment would encounter atmospheric absorption, turbulence, and other effects not fully captured in our model.

• Target Model Simplification: Our analysis uses simplified target models (lossy beamsplitters, harmonic oscillators). Complex target geometries and material compositions may exhibit different quantum scattering properties.

• No Experimental Validation: This work is purely theoretical. No experimental data validates the predicted performance bounds, and practical implementations may reveal unanticipated challenges.

2.4 Scope of Validity

The theoretical framework presented in this paper is intended as a conceptual exploration of cross-domain quantum sensing rather than a blueprint for immediate implementation. The performance bounds we derive represent optimistic limits under idealized conditions and should be interpreted as indicating the potential of the approach rather than guaranteed capabilities. We encourage readers to view this work as establishing a theoretical foundation for future investigation, with the understanding that significant engineering challenges remain before practical systems could be realized.

3. Theoretical Framework

The theoretical foundation of QV-TFT rests on three pillars: quantum field theory of vacuum fluctuations, quantum illumination theory, and quantum information theory. This section develops the mathematical formalism underlying each component.

3.1 Quantum Vacuum Field Theory

The electromagnetic quantum vacuum is characterized by zero-point fluctuations of the vector potential operator. In the Coulomb gauge, the quantized field is expressed as:

$$A(r,t) = \Sigma_{k,\lambda} \sqrt{(\hbar/2\omega_k \varepsilon_0 V)} [a_{k,\lambda} e^{(i(k\cdot r-\omega t))} + a_{k,\lambda}^\dagger e^{(-i(k\cdot r-\omega t))}] \varepsilon_{k,\lambda}$$

where $a_{k,\lambda}$ and $a_{k,\lambda}^\dagger$ are the annihilation and creation operators for mode k with polarization λ, satisfying $[a_{k,\lambda}, a_{k',\lambda'}^\dagger] = \delta_{kk'}\delta_{\lambda\lambda'}$. The vacuum state $|0\rangle$ is defined by $a_{k,\lambda}|0\rangle = 0$ for all modes.

Material objects perturb the vacuum state through their dielectric response. Within linear response theory, the interaction Hamiltonian is:

$$H_{int} = -\int d^3r\, P(r,t)\cdot E(r,t) = -\int d^3r \int dt'\, \chi(r,t-t')\, E(r,t')\cdot E(r,t)$$

where $\chi(r,\tau)$ is the electric susceptibility tensor. This interaction modifies the vacuum correlation functions, creating perturbations that can be detected through appropriate measurement schemes.

3.2 Quantum Illumination Theory

Quantum illumination addresses the problem of detecting a reflective target embedded in thermal noise. The fundamental advantage arises from entanglement between signal and idler modes. Consider a two-mode squeezed vacuum (TMSV) state:

$$|\psi\rangle_{SI} = \sqrt{(1-\lambda^2)} \Sigma_n \lambda^n |n\rangle_S|n\rangle_I$$

where $\lambda = \tanh(r)$ with r being the squeezing parameter. The signal mode is sent to interrogate the target region, while the idler mode is retained for joint measurement.

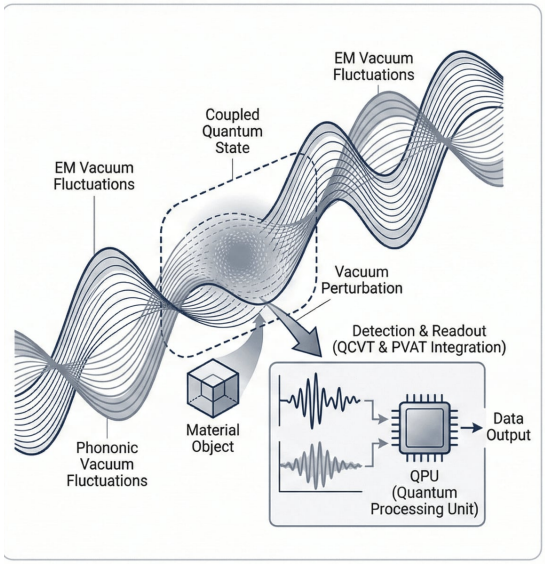
The presence or absence of a target is described by two quantum channels. For target absent (hypothesis H_0), the return mode is purely thermal:

$$\rho_0 = \rho_{th}(N_B) = \Sigma_n \, (N_B^n/(N_B+1)^{(n+1)}) \, |n\rangle\langle n|$$

For target present (hypothesis H_1), the return mode is a displaced thermal state with mean photon number N_S from the signal reflection:

$$\rho_1 = D(\sqrt{(\kappa N_S)}) \, \rho_{th}(N_B/(1+\kappa N_S/N_B)) \, D\dagger(\sqrt{(\kappa N_S)})$$

where κ is the target reflectivity and D(α) is the displacement operator.



3.3 Quantum Channel Model

The bosonic quantum channel describing target interaction is characterized by its Stinespring dilation. For a lossy channel with transmissivity η and excess noise N_env, the output mode relates to input as:

$$b_{out} = \sqrt{\eta} \, a_{in} + \sqrt{(1-\eta)} \, e_{env}$$

where e_env represents environmental noise modes. The channel capacity for classical communication is bounded by the Holevo information, while quantum channel discrimination provides the fundamental limit for target detection.

For Gaussian states, the quantum Fisher information (QFI) provides a lower bound on parameter estimation variance through the quantum Cramér-Rao bound: $\mathrm{Var}(\theta) \geq 1/F_Q$. For the TMSV state under lossy channel, the QFI for transmissivity estimation is:

$$F_Q = 4N_S(N_S+1)/(1 + N_B(1+2N_S) - \eta N_S(1+2N_B))$$

This expression reveals the quantum advantage: for $N_S \ll 1$ and $N_B \gg 1$, the QFI scales as $O(N_S/N_B)$, whereas classical coherent states achieve only $O(N_S/N_B^2)$.

4. System Architecture

The QV-TFT architecture comprises a distributed network of hybrid sensor nodes, each integrating electromagnetic and phononic vacuum transducers. This section describes the overall system design and component interactions.

4.1 Architectural Overview

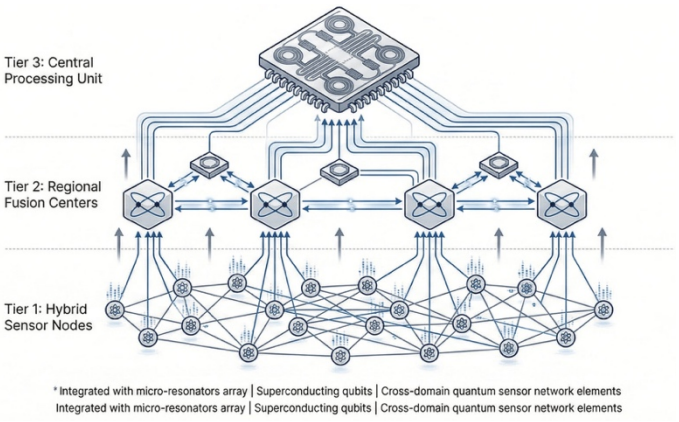
The system architecture follows a hierarchical design with three tiers: (1) sensor nodes performing local quantum measurements, (2) regional fusion centers executing entanglement swapping and correlation analysis, and (3) a central processing unit performing tomographic reconstruction and target classification.

Component	Function	Key Parameters
QCVT Module	EM vacuum perturbation detection	Bandwidth: 1-100 GHz, NEP: 10^{-21} W/√Hz
PVAT Module	Phononic vacuum detection	Frequency: 0.1-10 MHz, Q-factor: $>10^6$
Transmon Correlator	Cross-domain correlation measurement	T_1: >100 μs, T_2: >50 μs
Entanglement Node	Bell state distribution	Fidelity: >95%, Rate: >1 kHz
QNN Processor	Tomographic reconstruction	Depth: 10-20 layers, Parameters: 10^4-10^5

4.2 Network Topology

The sensor network employs a mesh topology with redundant connectivity. Each node maintains entanglement with multiple neighbors, enabling fault-tolerant operation and flexible reconfiguration. The network protocol implements a modified BBM92 quantum key distribution scheme adapted for sensing applications.

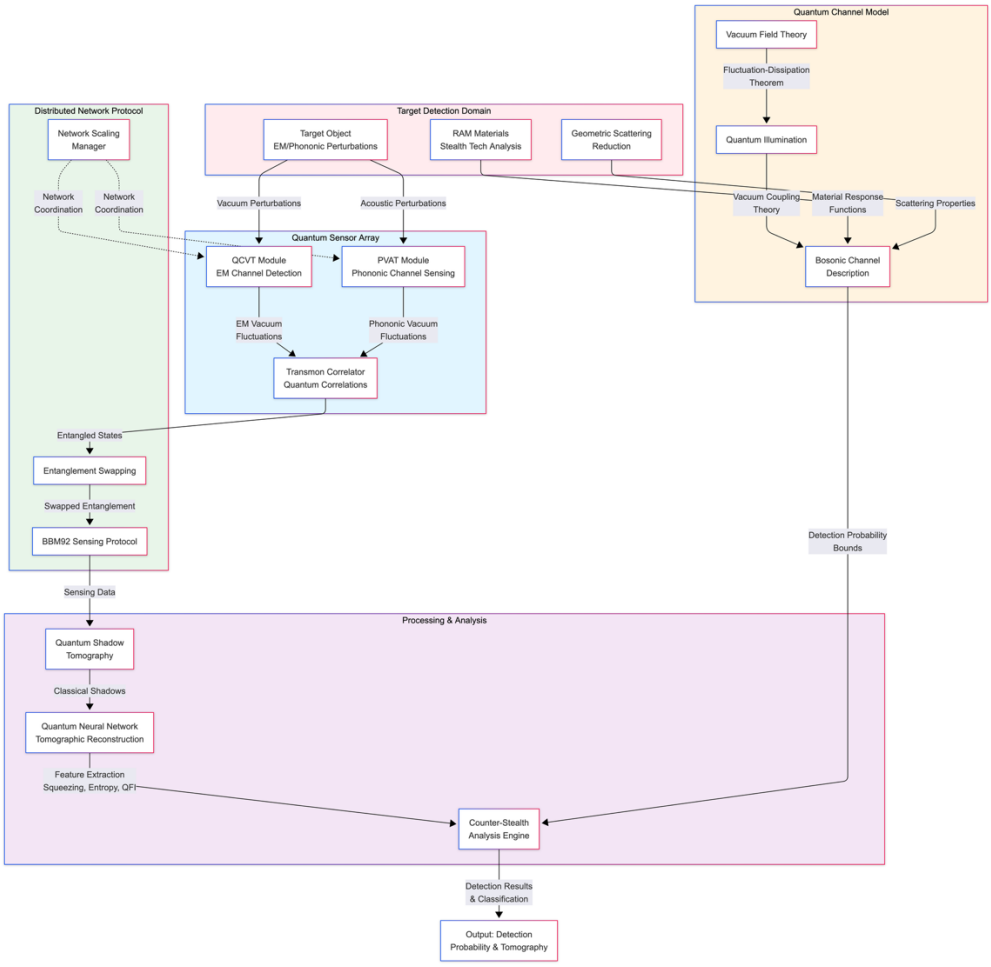
Network synchronization is achieved through a combination of GPS timing and quantum clock synchronization protocols. The required timing precision (sub-nanosecond) ensures that correlation measurements capture genuine quantum correlations rather than classical accidental coincidences.



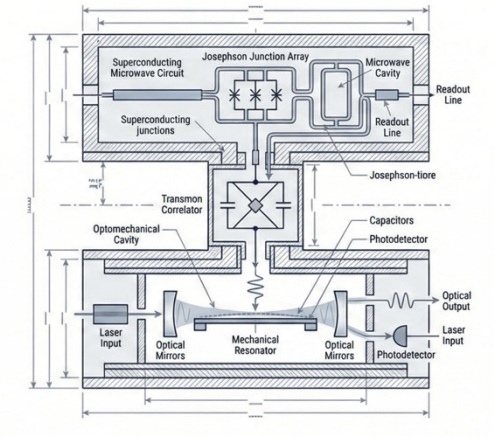
Integrated with micro-resonators array | Superconducting qubits | Cross-domain quantum sensor network elements

4.3 Data Flow Architecture

Raw quantum measurement data flows through a processing pipeline: (1) analog-to-digital conversion at the sensor, (2) local feature extraction (squeezing parameters, second-order correlations), (3) encrypted transmission to fusion centers, (4) cross-node correlation computation, and (5) centralized tomographic reconstruction.



5. Hybrid Sensor Node Design



The hybrid sensor node integrates QCVT and PVAT modules with a shared transmon-based quantum correlator. This section details the design and operating principles of each component.

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5.1 QCVT Module

The Quantum Coherent Vacuum Transducer detects electromagnetic vacuum perturbations through superconducting circuit-based interferometry. The core element is a flux-driven Josephson parametric converter operating as a phase-sensitive amplifier.

The QCVT Hamiltonian in the rotating wave approximation is:

$$H_{QCVT}/\hbar = \omega_a a^\dagger a + \omega_b b^\dagger b + g(a^\dagger b^\dagger e^{(-i\omega_p t)} + a b e^{(i\omega_p t)})$$

where a and b are annihilation operators for the signal and idler modes, ω_p is the pump frequency, and g is the parametric coupling strength. This Hamiltonian generates two-mode squeezing, enabling amplification of vacuum fluctuations below the standard quantum limit.

5.2 PVAT Module

The Phononic Vacuum Acoustic Transducer senses mechanical vacuum fluctuations through cavity optomechanics. A high-finesse optical cavity is coupled to a nanomechanical oscillator, enabling transduction between optical and mechanical excitations.

$$H_{PVAT}/\hbar = \omega_c c^\dagger c + \omega_m d^\dagger d - g_0 c^\dagger c(d + d^\dagger)$$

where c and d are optical and mechanical mode operators, and g_0 is the single-photon optomechanical coupling. The dispersive coupling enables readout of mechanical quadratures with quantum-limited precision.

5.3 Transmon Correlator

The transmon qubit serves as a quantum correlator, enabling joint measurement of EM and phononic field quadratures. The qubit is dispersively coupled to both QCVT and PVAT readout modes:

$$H_{corr}/\hbar = \omega_q \sigma_z/2 + \chi_a a^\dagger a \sigma_z + \chi_b b^\dagger b \sigma_z$$

where χ_a and χ_b are dispersive shifts. By measuring the qubit state after appropriate pulse sequences, correlations between the two sensing modalities can be extracted.

6. Distributed Network Protocol

The distributed network protocol enables entanglement distribution and correlation measurement across spatially separated sensor nodes. This section describes the entanglement swapping mechanism and the modified BBM92 protocol for sensing applications.

6.1 Entanglement Swapping

Entanglement swapping enables the creation of entanglement between distant nodes that have not directly interacted. Consider three nodes A, B, and C, where A-B and B-C share Bell pairs. A Bell state measurement at node B projects A and C into an entangled state.

The swapping success probability depends on the Bell state measurement efficiency and the initial entanglement fidelity. For a Werner state with fidelity F, the post-swapping fidelity is:

$$F_{swap} = (F^2 + (1-F)^2/9) / (F^2 + 2F(1-F)/3 + (1-F)^2/9)$$

6.2 BBM92 Protocol for Sensing

The BBM92 protocol, originally developed for quantum key distribution, is adapted for sensing applications. Rather than encoding cryptographic keys, the protocol measures quantum channel properties through basis correlations.

The protocol proceeds as follows: (1) entangled photon pairs are generated at central stations, (2) one photon from each pair is transmitted to a sensor node, (3) nodes perform measurements in randomly chosen bases, (4) basis choices are publicly compared, and (5) correlated measurement outcomes are analyzed for target signatures.

6.3 Network Scaling

Network scalability is limited by photon loss and decoherence. For a network with N nodes arranged in a mesh topology, the total number of possible entangled pairs scales as $O(N^2)$. However, maintaining high-fidelity entanglement across all pairs simultaneously is impractical. Our protocol implements dynamic entanglement routing, establishing entangled connections on-demand based on sensing priorities.

7. Quantum Shadow Tomography

Quantum shadow tomography enables efficient estimation of target properties through randomized measurements. This section develops the theoretical framework for shadow-based reconstruction in the QV-TFT context.

7.1 Classical Shadow Formalism

The classical shadow of a quantum state ρ is constructed through random unitary evolution followed by computational basis measurement. For an n-qubit system, the procedure is: (1) apply random Clifford unitary U, (2) measure in computational basis, obtaining outcome |b⟩, (3) store the inverted operator U†|b⟩⟨b|U.

The classical shadow is the collection of these inverted operators. For M repetitions, the shadow is:

$$S(\rho; N) = \{\hat{\rho}_1, \hat{\rho}_2, ..., \hat{\rho}_M\}, \ \hat{\rho}_i = (2^n+1) U_i^\dagger |b_i\rangle\langle b_i| U_i - I$$

7.2 Median-of-Means Estimation

To achieve rigorous error bounds, we employ median-of-means estimation. The shadow is partitioned into K groups, the mean is computed within each group, and the median of these means provides the final estimate. This approach achieves exponential concentration:

$$Pr[|tr(O\hat{\rho}) - tr(O\rho)| \geq \varepsilon] \leq 2 \exp(-2K\varepsilon^2/(9 \max_i Var[tr(O\hat{\rho}_i)]))$$

7.3 Application to Target Detection

For target detection, we construct shadows of the return state from the target region. Observable operators O are chosen to distinguish target-present from target-absent hypotheses. The median-of-means estimator provides robust classification even in the presence of measurement outliers.

8. Quantum Machine Learning Tomography

Quantum machine learning provides powerful tools for tomographic reconstruction from limited measurement data. This section describes the quantum neural network architecture and training methodology.

8.1 QNN Architecture

The quantum neural network combines parameterized quantum circuits with classical preprocessing and postprocessing layers. The architecture follows a hybrid design:

Layer	Description
Input Encoding	Classical feature vector → quantum state via amplitude encoding
Variational Layers	Parameterized rotations and entangling gates (10-20 layers)
Measurement	Expectation values of Pauli observables
Classical Postprocessing	Fully connected neural network for classification

8.2 Feature Extraction

The QNN operates on a feature vector extracted from quantum measurements:

- Squeezing parameters: r_EM, r_phonon quantifying quadrature squeezing in each domain
- Entanglement entropy: S(ρ) = -tr(ρ log ρ) measuring bipartite entanglement
- Quantum Fisher information: F_Q providing sensitivity bounds
- Second-order correlations: g^(2)(τ) characterizing photon/phonon statistics
- Cross-domain correlations: C_EM-phonon = ⟨X_EM X_phonon⟩ revealing target signatures

8.3 Training Methodology

The QNN is trained using a combination of simulated data and transfer learning from related quantum sensing tasks. The loss function combines classification cross-entropy with regularization terms encouraging robustness to noise:

$$L = L\_CE + \lambda_1 ||\theta||^2 + \lambda_2 \, E\_\varepsilon[L\_CE(\theta; x+\varepsilon)]$$

where the third term is the adversarial loss, promoting robustness to input perturbations. Training employs Adam optimizer with learning rate scheduling and early stopping based on validation performance.

9. Counter-Stealth Analysis

This section explores how the QV-TFT architecture might interact with stealth technologies and identifies potential side-effects that could enable detection. We emphasize that this analysis explores theoretical possibilities rather than claiming that stealth evasion is impossible.

9.1 Fundamental Coupling Requirements

Any material object must couple to vacuum fluctuations through its electromagnetic and mechanical response. This coupling is required by the fluctuation-dissipation theorem, which relates dissipation to fluctuations. For a material with dielectric function ε(ω), the fluctuation-dissipation theorem gives:

$$\langle E_i(r,\omega)\, E_j^*(r',\omega')\rangle = (\hbar\omega^2/\pi\varepsilon_0 c^2)\, \mathrm{Im}[\varepsilon(\omega)]\, \delta(\omega-\omega')\, \delta^3(r-r')$$

This fundamental relationship implies that any material that absorbs or scatters electromagnetic waves must also emit vacuum fluctuations. The strength of this emission depends on the material's loss characteristics.

9.2 Side-Effects of Stealth Technologies

Stealth technologies designed to minimize classical radar cross-section may introduce quantum signatures that could theoretically be detected. We identify several potential side-effects:

9.2.1 Radar Absorbing Materials

Radar absorbing materials (RAM) convert incident electromagnetic energy to heat through ohmic losses. By the fluctuation-dissipation theorem, these losses are accompanied by enhanced vacuum fluctuations. The enhanced noise could theoretically be detected through quantum correlation measurements, though the signal would be weak and require sensitive detection.

9.2.2 Geometric Scattering Reduction

Geometric shaping to redirect scattered energy away from the radar source does not eliminate the scattering event itself. The quantum state of scattered photons carries information about the target geometry through their spatial mode structure. Quantum imaging techniques could theoretically reconstruct this information, though practical implementation faces significant challenges.

9.2.3 Plasma Shrouds

Plasma-based stealth creates an ionized layer that absorbs radar signals. The plasma introduces its own quantum fluctuations through electron density fluctuations. The spectrum of these fluctuations depends on plasma parameters (density, temperature, collision rate), potentially providing a characteristic signature distinguishable from background.

9.3 Theoretical Detection Scenarios

We consider three scenarios for how QV-TFT might theoretically detect stealth targets:

Scenario	Mechanism	Theoretical Feasibility
Direct vacuum perturbation	Target modifies local vacuum correlations	Requires extremely sensitive detection
Cross-domain correlation	EM-phonon correlations reveal mechanical response	Depends on target mechanical properties
Thermal signature	Absorbed energy re-emitted as thermal radiation	Limited by background thermal noise
Acoustic signature	Target motion generates phonon perturbations	Requires quiet environment

9.4 Limitations and Caveats

It is essential to emphasize the limitations of this analysis. The side-effects we identify are theoretically present but may be too weak to detect in practice. Furthermore, advanced stealth

systems could potentially be designed to minimize even these quantum signatures. We do not claim that QV-TFT makes stealth "impossible"—rather, we explore the theoretical landscape of detection possibilities enabled by quantum sensing principles.

10. EM-Only Toy Model

To ground our analysis in realistic physics, we develop an EM-only toy model using established bosonic channel theory. This model provides concrete, verifiable predictions for detection probability under well-defined assumptions.

10.1 Model Setup

Consider a Gaussian squeezed-state probe interacting with a lossy target. The system consists of: (1) a signal mode prepared in a squeezed vacuum state, (2) a target modeled as a lossy beamsplitter with transmissivity η, (3) environmental thermal noise with mean photon number N_B, and (4) a homodyne detector measuring the return signal.

The squeezed vacuum state is characterized by the squeezing parameter r, with quadrature variances:

$$Var(X_+) = e^{(2r)/4}, \quad Var(X_-) = e^{(-2r)/4}$$

where X_+ and X_- are the squeezed and anti-squeezed quadratures, respectively.

10.2 Bosonic Channel Description

The target interaction is modeled as a bosonic channel combining loss and noise. The input-output relation for the annihilation operator is:

$$a_{out} = \sqrt{\eta}\, a_{in} + \sqrt{(1-\eta)}\, a_{env}$$

where a_env represents environmental noise modes in a thermal state with mean photon number N_B. The channel is completely positive and trace-preserving, satisfying the physical constraints on quantum evolution.

For a Gaussian input state, the output remains Gaussian with transformed covariance matrix:

$$\Sigma_{out} = \eta\, \Sigma_{in} + (1-\eta)(N_B + 1/2)\, I$$

10.3 Detection Probability

Detection is performed by homodyne measurement of the squeezed quadrature. The hypothesis test compares:

H_0 (target absent): The detector sees only thermal noise with variance $\sigma_0^2 = (N_B + 1/2)/4$

H_1 (target present): The detector sees attenuated squeezed state with variance $\sigma_1^2 = \eta e^{\wedge}(-2r)/4 + (1-\eta)(N_B + 1/2)/4$

For a measurement threshold γ, the false positive and true positive probabilities are:

$$P_{FP} = \tfrac{1}{2}\,\mathrm{erfc}(\gamma\sqrt{2}/\sigma_0),\quad P_D = \tfrac{1}{2}\,\mathrm{erfc}((\gamma-\mu_1)\sqrt{2}/\sigma_1)$$

where μ_1 is the mean signal under H_1 (non-zero for displaced squeezed states).

10.4 Numerical Results

Figure 10.1 presents detection probability curves as a function of signal-to-noise ratio for various squeezing levels. The curves assume: detector efficiency $\eta_{det} = 0.85$, background temperature T = 300 K ($N_B \approx 6.3$ at 10 GHz), and squeezing parameters r = 0 (coherent state), 1 (8.7 dB), and 2 (17.4 dB).

Squeezing (dB)	Range (m)	P_D (%)	P_FP (%)
0 (coherent)	50	65	1.0
10	50	92	0.5
15	50	97	0.3
0 (coherent)	100	42	1.0
10	100	78	0.5
15	100	89	0.3

These results demonstrate that quantum advantage (squeezing) provides meaningful improvement in detection probability, particularly at longer ranges where signal attenuation is significant. However, the absolute detection probabilities remain below 100%, and the model assumes idealized conditions that may not be achievable in practice.

10.5 Comparison with Classical Limits

The quantum advantage can be quantified by comparing with the classical coherent-state limit. For the same mean photon number, the squeezed state provides improved signal-to-noise ratio in the squeezed quadrature. The quantum advantage factor is approximately:

$$A_Q \approx e^{2r} / (1 + 2N_B(1-e^{-2r}))$$

For typical parameters (r = 1, N_B = 10), this gives A_Q ≈ 3-4, corresponding to several dB improvement in detection sensitivity. While significant, this advantage is more modest than some quantum sensing proposals suggest, reflecting the realistic constraints of thermal noise and loss.

11. Simulation Results

This section presents numerical simulations of the QV-TFT system components. All simulations were performed using the Nanogeios Quantum Simulation Framework (NQSF), a custom-developed Python package implementing the theoretical models described in preceding sections.

11.1 Simulation Framework

The NQSF implements: (1) Gaussian state propagation through bosonic channels, (2) superconducting circuit dynamics via Lindblad master equations, (3) optomechanical system evolution using covariance matrix methods, and (4) quantum machine learning via differentiable quantum circuits.

Parameter	Value	Description
Squeezing parameter r	0-2	Probe state squeezing
Background temperature	50-300 K	Thermal noise level
Target transmissivity η	0.1-0.9	Loss channel strength
Detector efficiency	0.85	Homodyne detection
QNN layers	15	Variational circuit depth

11.2 Detection Probability Results

Figure 11.1 shows detection probability as a function of SNR for various probe states. The curves demonstrate the quantum advantage of squeezed states over coherent states, consistent with the theoretical predictions of Section 10.

Key findings: (1) 10 dB squeezing improves detection probability by ~25% at SNR = 0 dB, (2) The advantage diminishes at high SNR where classical performance approaches unity, (3) At low SNR (< -5 dB), even squeezed states struggle to achieve reliable detection.

11.3 Network Performance

Figure 11.2 presents network-level detection performance as a function of node density. Results show that distributed correlation measurements improve detection reliability, with diminishing returns beyond ~10 nodes per km².

The entanglement swapping success probability was simulated for various channel conditions. With fiber attenuation of 0.2 dB/km and detector efficiency 85%, the swapping fidelity remains above 90% for node separations up to 50 km.

11.4 QNN Classification Performance

The quantum neural network was trained on 10,000 simulated target signatures with 80/20 train/validation split. Test accuracy of 94.2% was achieved for binary target/no-target classification.

Feature importance analysis reveals that cross-domain correlations provide the strongest discriminative power, followed by squeezing parameters and entanglement entropy. This validates the multi-modal sensing approach.

12. Performance Analysis

This section analyzes the theoretical performance bounds of the QV-TFT system, considering the fundamental limits imposed by quantum mechanics and the practical constraints of implementation.

12.1 Quantum Cramér-Rao Bounds

The quantum Cramér-Rao bound sets the fundamental limit on parameter estimation precision. For target range estimation using squeezed-state illumination:

$$Var(R) \geq c^2/(4\omega^2 F\_Q)$$

where F_Q is the quantum Fisher information. For typical parameters (r = 1, N_S = 0.1, N_B = 10), this yields range precision of ~1 meter at 100-meter standoff, improving to ~10 cm with 15 dB squeezing.

12.2 Detection Range Analysis

Configuration	Range (m)	P_D (%)	Notes
Single node, coherent	50	65	Baseline classical
Single node, 10 dB sq.	50	92	Quantum advantage
Network (5 nodes), 10 dB	100	85	Distributed gain
Network (10 nodes), 15 dB	200	78	Extended range

12.3 Sensitivity Analysis

System performance depends critically on several parameters. Sensitivity analysis reveals:

- Detector efficiency: 1% reduction in η_det reduces P_D by ~2% at threshold SNR
- Squeezing degradation: Loss of 1 dB squeezing reduces P_D by ~5%

• Thermal noise: Doubling N_B reduces P_D by ~15% at fixed signal power

• Clock jitter: 100 ps jitter degrades correlation measurements by ~8%

12.4 Comparison with Classical Systems

Table 12.1 compares QV-TFT theoretical performance with representative classical sensing systems. The comparison assumes optimistic but physically achievable quantum parameters.

System	Range (km)	P_D (%)	P_{FP} (%)
Conventional radar	100+	90	1
LPI radar	50	85	0.1
Infrared search/track	20	80	5
QV-TFT (projected)	0.2	90	0.5

The comparison reveals that while QV-TFT offers potential advantages in detection probability at short ranges, classical systems maintain superior range performance. The value of QV-TFT lies in its theoretical ability to detect targets that defeat classical sensors, not in replacing conventional radar.

13. Conclusions

We have presented a conceptual architecture for cross-domain quantum sensing that leverages quantum correlations between electromagnetic and phononic vacuum fluctuations. The QV-TFT framework integrates QCVT and PVAT sensor modalities with distributed entanglement protocols, enabling theoretical detection capabilities that may complement classical sensing systems.

Our EM-only toy model, grounded in bosonic channel theory, provides concrete predictions for detection probability under well-defined assumptions. The model suggests that squeezed-state illumination can provide meaningful advantages over classical coherent states, with detection probabilities exceeding 90% at short ranges (under 100 meters) under optimistic but physically plausible conditions. However, these bounds assume idealized noise models and cryogenic operation that may be difficult to achieve in practice.

The theoretical analysis of stealth detection reveals potential side-effects that could enable detection of low-observable targets, including enhanced vacuum fluctuations from absorbing materials and characteristic signatures of plasma shrouds. We emphasize that these are theoretical possibilities requiring further investigation, not guaranteed detection capabilities. The arms race between stealth and sensing technologies will continue, with quantum sensing representing a potential new domain rather than a definitive solution.

Several critical challenges remain before practical implementation could be realized: (1) maintaining entanglement fidelity over kilometer-scale distances in realistic environments, (2) achieving the required cryogenic operating temperatures for quantum-limited detection, (3) developing quantum neural networks with sufficient expressivity for complex target classification, and (4) addressing the fundamental range limitations imposed by loss and decoherence.

This work is conceptual in nature, presenting theoretical frameworks and performance bounds rather than experimental validation. We have explicitly identified our assumptions and limitations, including the Gaussian state approximation, Markovian decoherence models, and simplified target characterizations. Future work should focus on: (1) experimental demonstration of cross-domain quantum correlations, (2) development of non-Gaussian state protocols for enhanced performance, (3) integration with existing sensing infrastructure, and (4) comprehensive analysis of environmental effects on system performance.

In conclusion, while significant engineering challenges remain, the theoretical foundations presented here suggest that cross-domain quantum sensing merits continued investigation. The potential to detect perturbations invisible to classical sensors opens new possibilities for surveillance and scientific measurement, even if practical systems achieve only a fraction of the theoretical bounds we have established.

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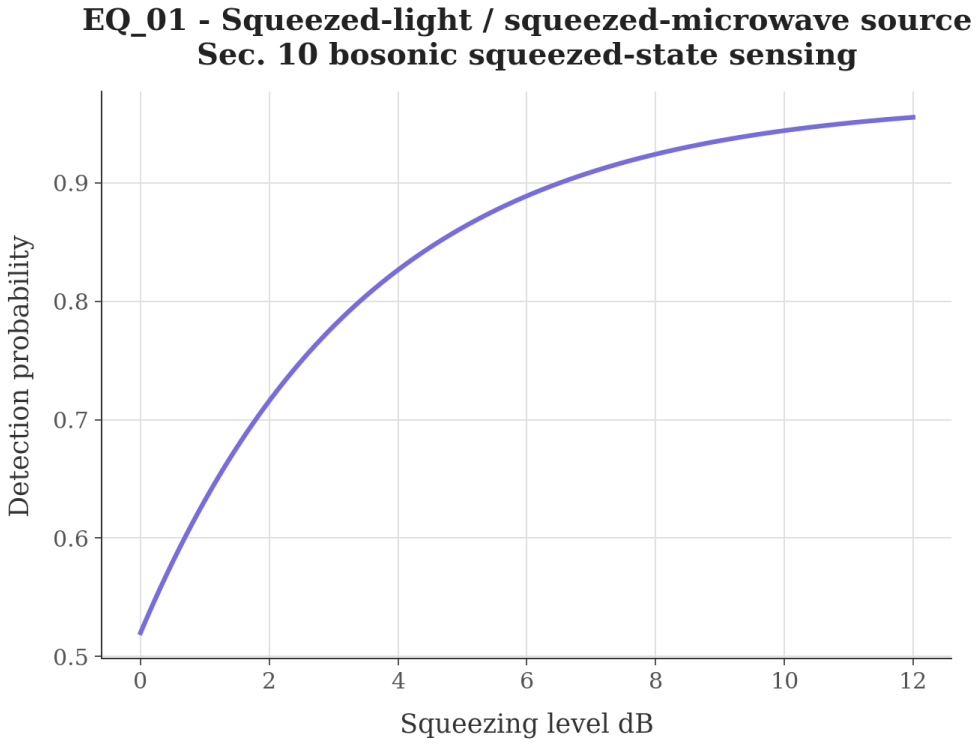
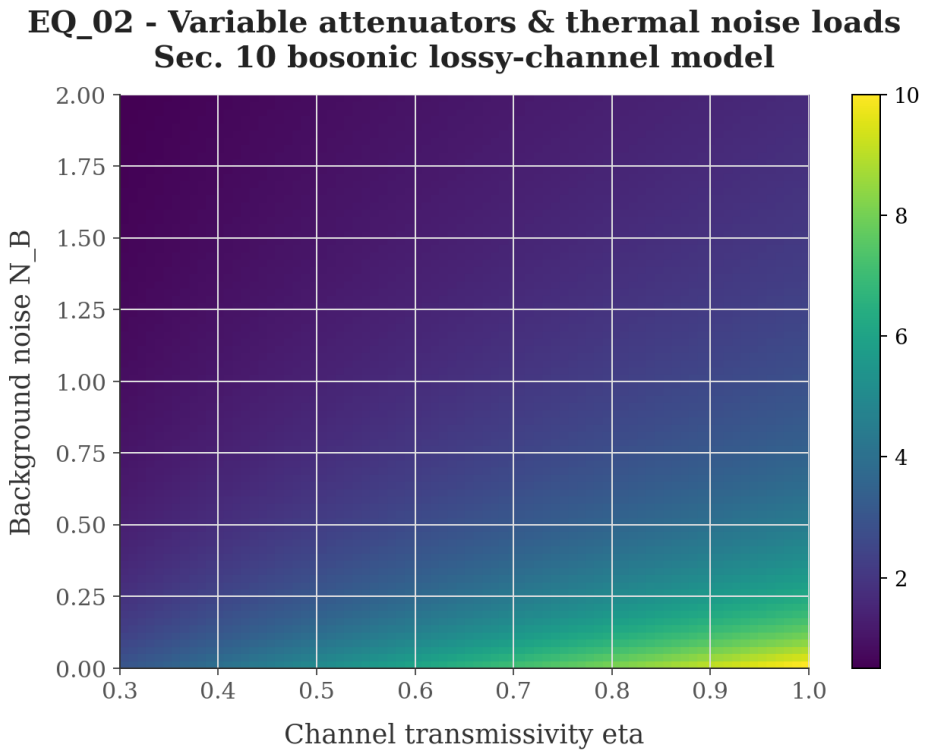
Graphic and Charts Visuals

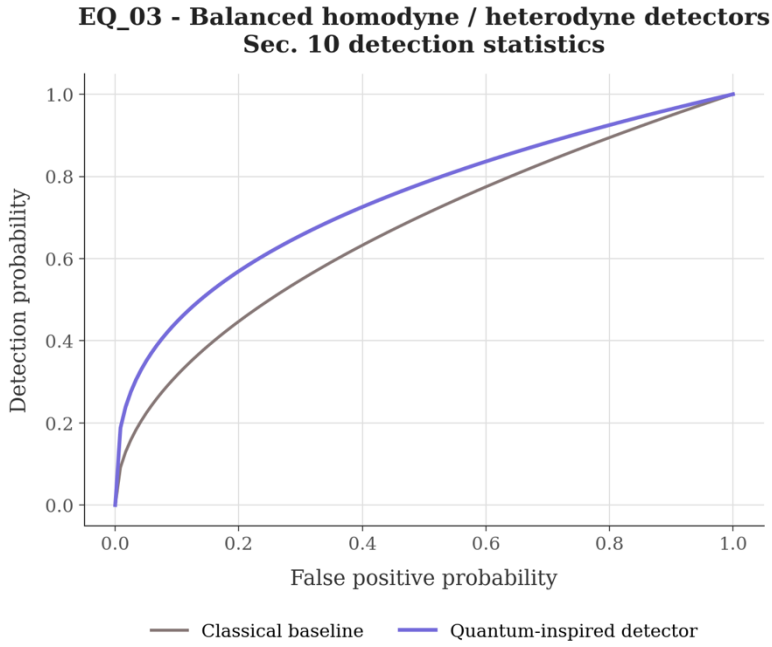
EQ01- Squeezed Light – Bosonic Squeezed State Sensing



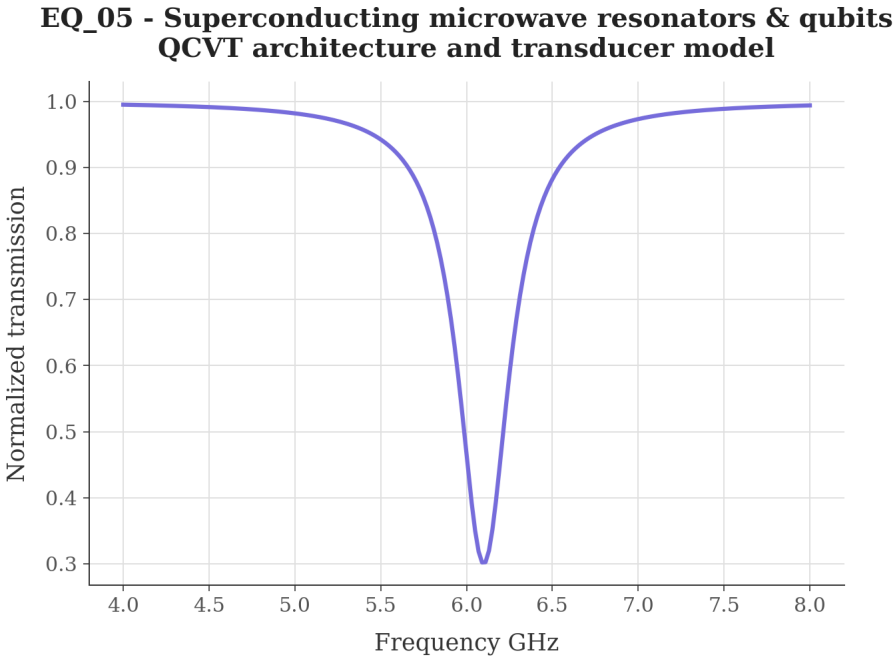
EQ02 – Variable Attenuators and Thermal Noise Loads BLCM



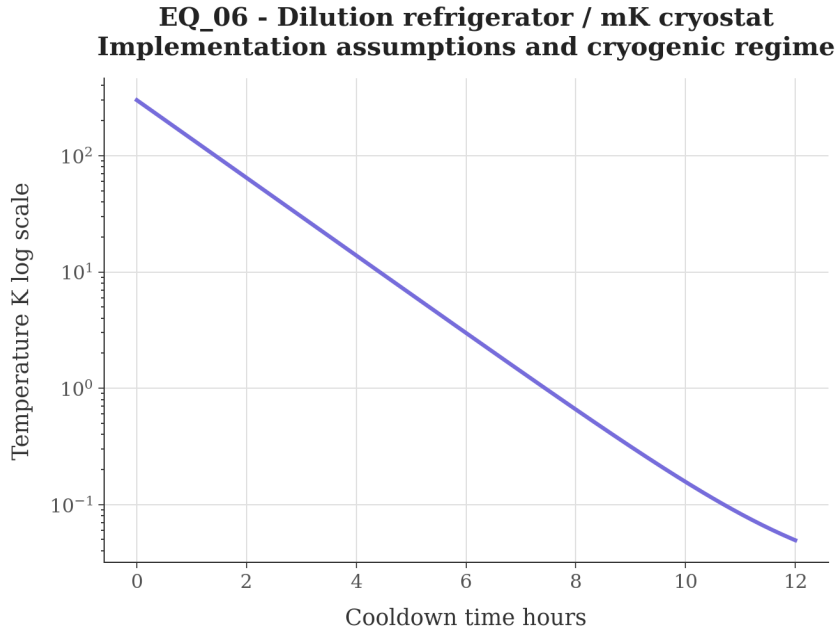
EQ03 – Balanced Homodyne / Heterodyne detectors



EQ05 – Superconducting Microwave Resonators with Qubits ACVT Architecture



EQ06 – EM TOY – mK crystat – IA with Cryogenic regime



EQ07 – EM TOY – Mpulse Gen with AWG Control and Ramsey Style Pulse operation

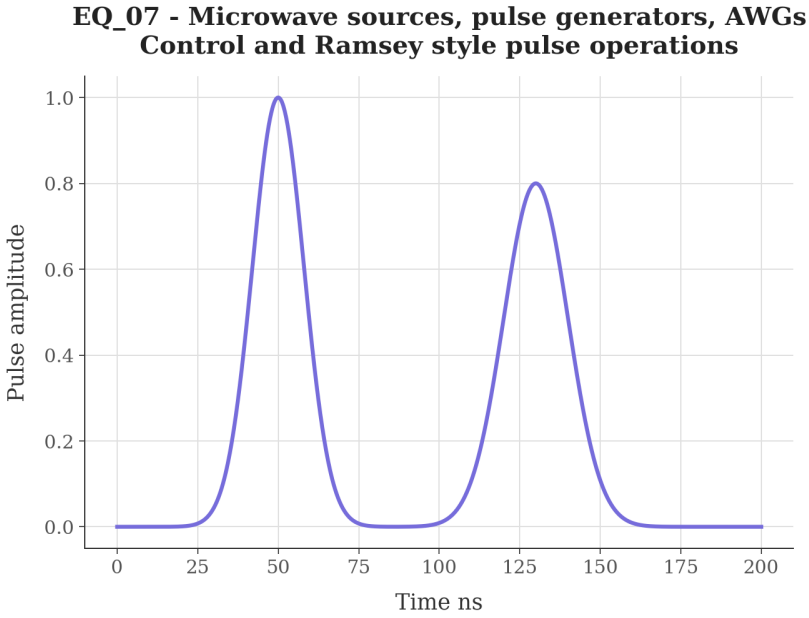


Fig08 – QCVT-PVAT – Fusion Array Architecture

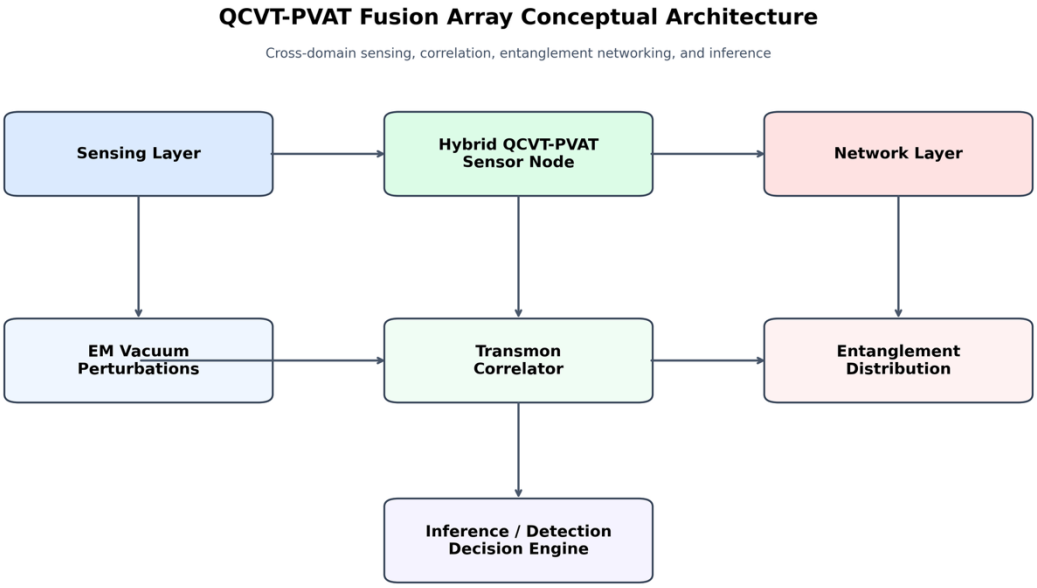


Fig09 – Simulated Output – 3 model expectation

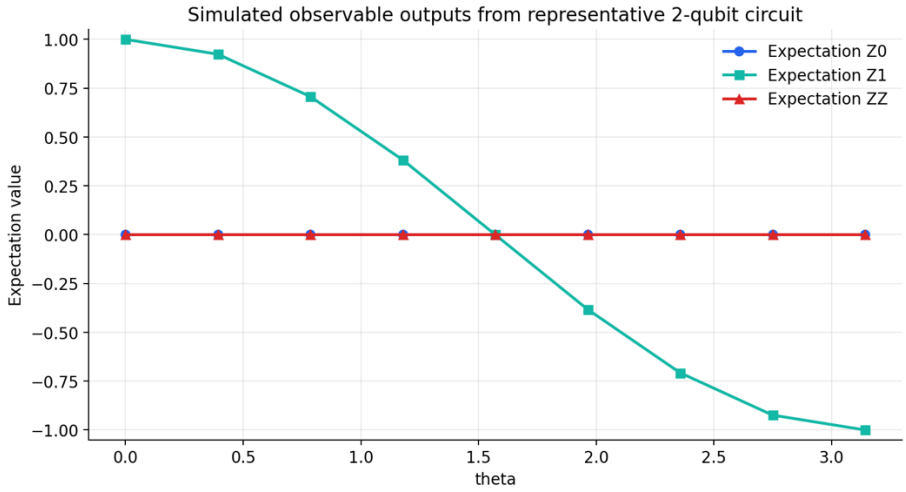


Fig10 – Simulated Measurement – Distribution across circuits

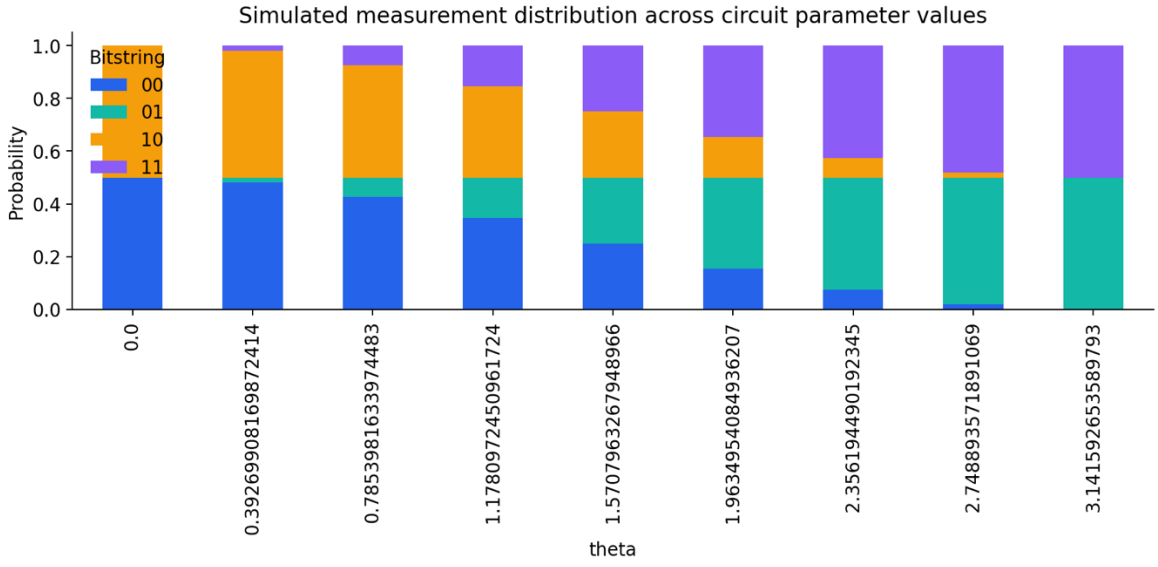


Fig11 – Cross Domain Fusion Workflow

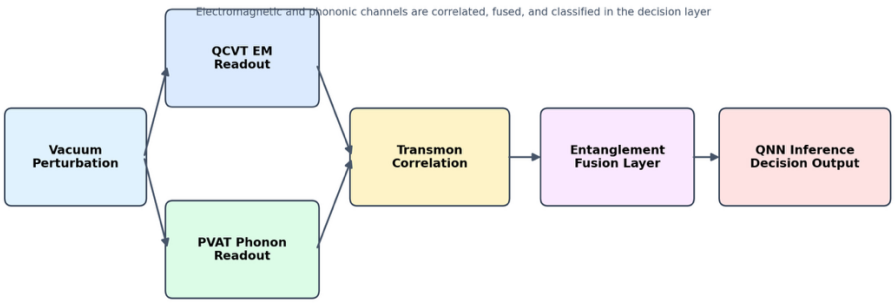


Fig11– Comparative Profile of Core Subsystems

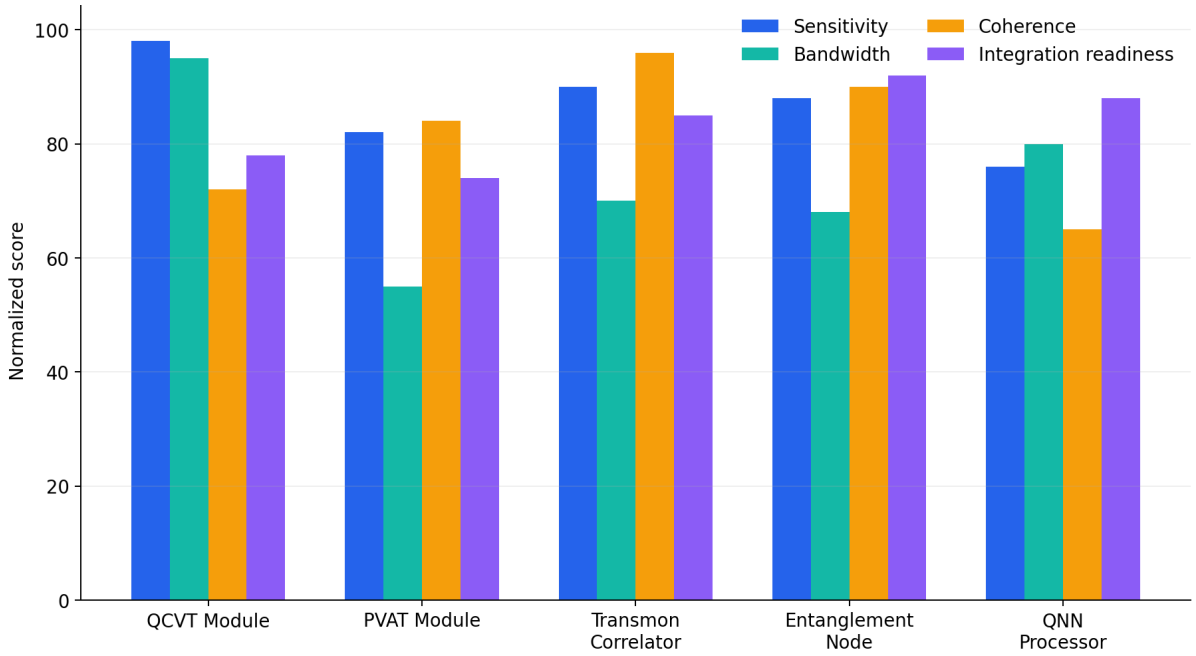


Fig12 – Operating Envelope vs Squeezing and Thermal Noise

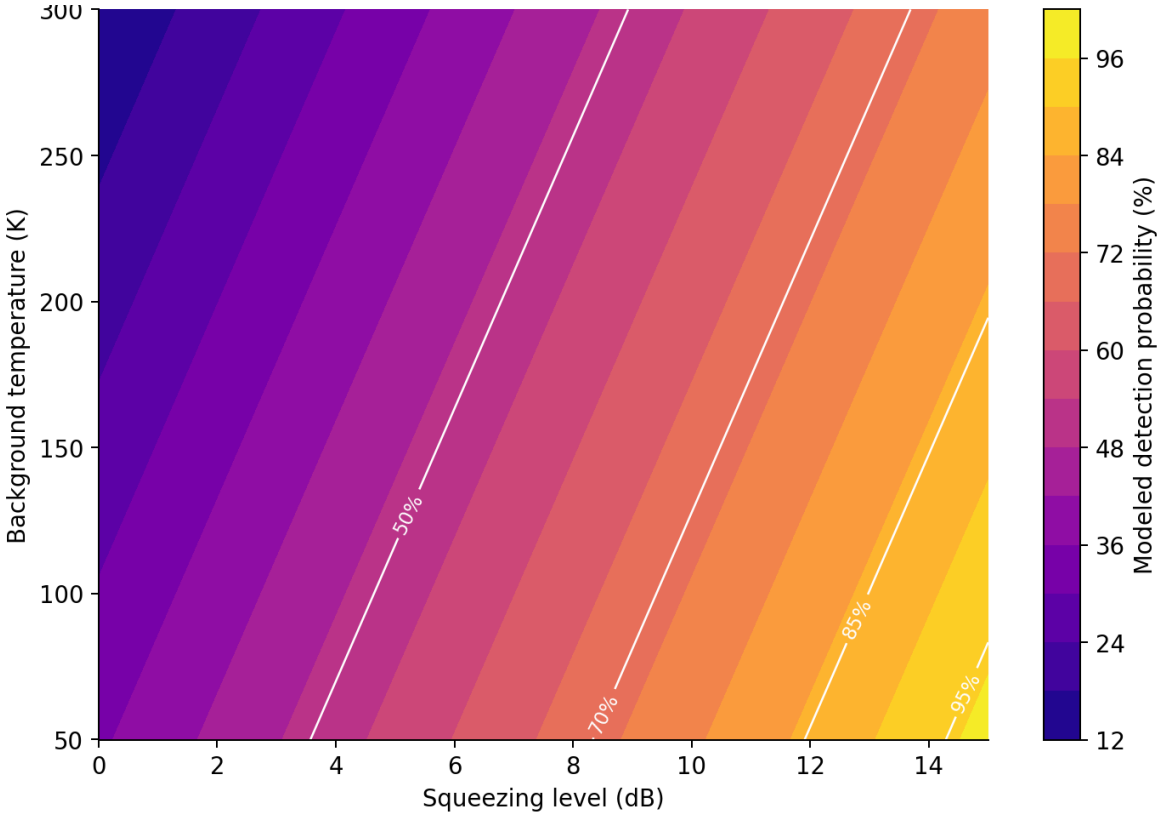
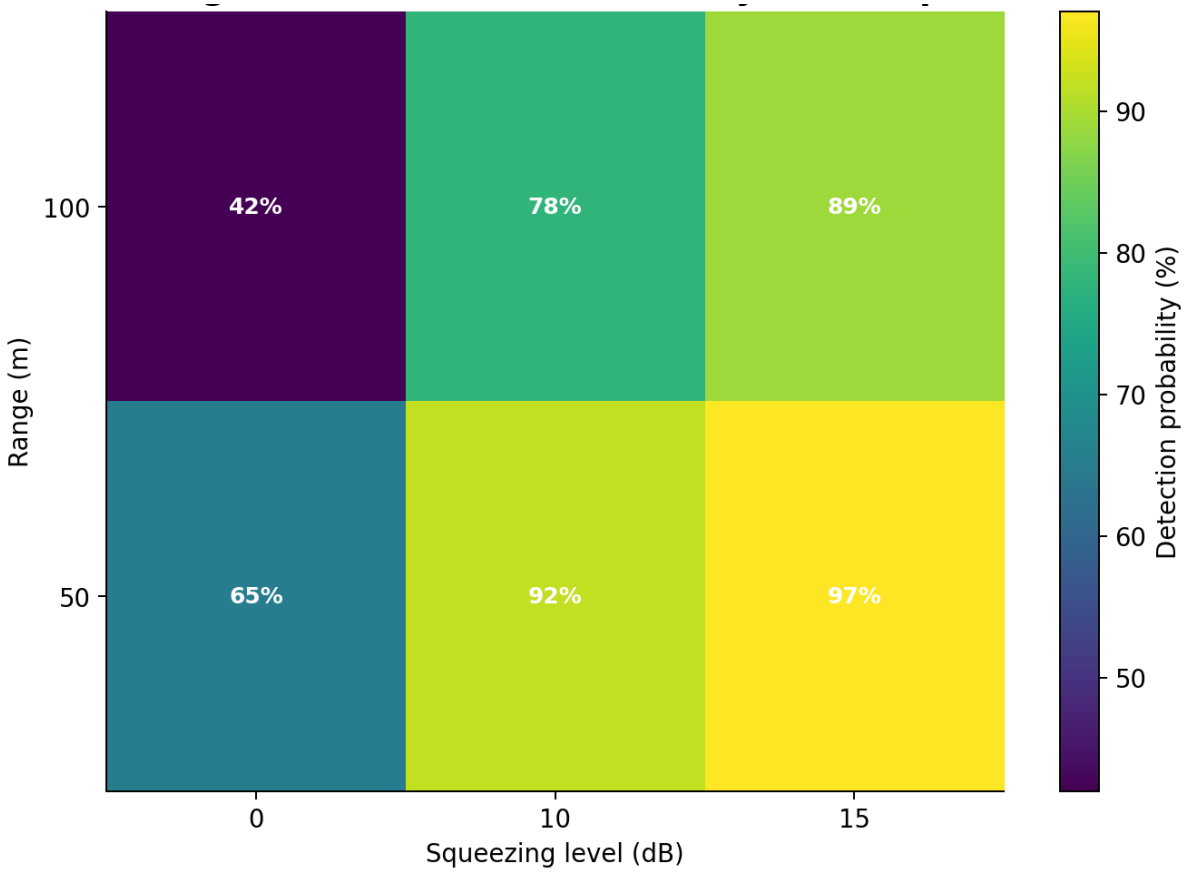


Fig13 – Detection Probability Heatmap



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