QALICE

Quantum-Mirror Network Architecture

Whitepaper | Quantum Communication, Control, and Network Architecture

Document status	Conceptual research and engineering framework; pre-experimental
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Public project resources	qalice.com | Qalice documentation

Technical status

Qalice is a conceptual, pre-experimental research and engineering framework. The project has not yet demonstrated a fabricated physical quantum mirror, quantum teleportation, or a deployed quantum network. Results drawn from published literature and preprints are identified as external results. Qalice-specific architecture, simulation methods, integration choices, and validation plans are presented as proposed work.

Abstract

Qalice defines a modular architecture for modeling, controlling, and evaluating quantum-mirror nodes in quantum networks. The framework is grounded in recent work on quantum-controlled optical scattering, in which a control qubit determines whether incident optical modes are transmitted or reflected. Qalice extends that scientific basis into an implementation-neutral systems model that combines node abstractions, optical and classical interfaces, channel and detector models, calibration workflows, and a staged validation program.

Because the underlying hardware remains experimental, this whitepaper distinguishes cited scientific results from Qalice-specific proposals and defines the evidence required before claims concerning performance, security, distance, or deployment can be supported.

Scope and evidence status | This document presents a research architecture and validation framework. It does not report a completed quantum-mirror network, original experimental data, or independently replicated performance results.

Contents

1. Executive Summary

Qalice proposes a modular control, simulation, and systems integration architecture for networks that use physical quantum mirrors as nodes. In the 2026 preprint by Uria et al. [1], a quantum mirror is a quantum-controlled optical scatterer rather than a conventional reflective cavity: its transmission and reflection depend on the state of a control qubit. Two propagating coherent-state modes mediate interactions between remote control qubits, supporting theoretical protocols for quantum teleportation, quantum state transfer, and entanglement swapping.

Qalice contributes an engineering framework around this physical model. It defines implementation-neutral node roles, optical and classical interfaces, synchronization and calibration workflows, nonideal channel models, simulation tools, and a staged route from numerical reproduction to laboratory validation.

Throughout this whitepaper, “quantum mirror” refers to the conditional-scattering device defined in Section 2. Deformable mirrors are treated only as classical adaptive-optics components. Generic QED or Dirac equations are not used as evidence for system performance, and claims concerning teleportation, error correction, security, distance, or efficiency are limited to results supported by a defined model or cited source.

1.1 Technical maturity and evidence status

Evidence category	Current evidence basis	Next validation step
Established in cited literature	Quantum-controlled transmission and reflection in quantum-metasurface models; experimental switching of a subwavelength atomic array by a single Rydberg atom; theoretical QM protocols using coherent optical states.	Use cited definitions, assumptions, and equations as the scientific baseline.
Defined by Qalice	Logical qTr, qRe, and qReTr roles; a control, simulation, and telemetry layer; candidate PIC routing; phase, mode, and wavefront stabilization; reproducible modeling and validation workflows.	Demonstrate through model reproduction, sensitivity analysis, interface definition, and hardware feasibility assessment.
Not yet demonstrated by Qalice	A fabricated physical quantum mirror; experimental teleportation; a validated long-distance link; measured fidelity, rate, or security performance; commercial readiness.	Require independent measurement, documented methods, and uncertainty analysis.

1.2 Core development objectives

- Define the physical quantum-mirror model and notation consistently with the cited scientific literature.
- Formalize the qTr, qRe, and qReTr logical roles as implementation-neutral node abstractions with explicit optical, quantum, and classical interfaces.
- Model the dominant non-idealities, including loss, phase mismatch, finite reflectivity, detector behavior, qubit decoherence, mode mismatch, and free-space turbulence.
- Identify a credible experimental platform and a staged path from numerical reproduction to laboratory validation.
- Maintain clear prior-art attribution, terminology boundaries, and traceability between technical statements and supporting evidence.

2. Scientific Foundations and Prior Art

2.1 Physical meaning of a quantum mirror

A physical quantum mirror (QM) is an optical scatterer whose response is conditioned on a quantum degree of freedom. Under the ideal transformation in Uria et al. [1], the control state $|0\rangle$ transmits two incident modes unchanged, whereas $|1\rangle$ reflects the fields, exchanges the spatial modes, and contributes a π phase to each coherent-state amplitude. A superposition of control states can therefore entangle the control qubit with the optical fields.

$$\mathcal{M}|0\rangle_c|\alpha\rangle_1|\beta\rangle_2 = |0\rangle_c|\alpha\rangle_1|\beta\rangle_2$$
$$\mathcal{M}|1\rangle_c|\alpha\rangle_1|\beta\rangle_2 = |1\rangle_c|-\beta\rangle_1|-\alpha\rangle_2$$

Equation 1. Ideal conditional quantum-mirror transformation, adapted from Ref. [1].

Here, c labels the control qubit; subscripts 1 and 2 label distinguishable optical modes; and $|\alpha\rangle$ and $|\beta\rangle$ are coherent states. This conditional transformation is the physical basis of the Qalice architecture. Classical mirror equations, deformable-mirror surface models, and generic relativistic field equations describe different phenomena and do not define the QM node.

2.2 Relationship to quantum metasurfaces

Quantum mirrors arise from work on quantum metasurfaces and collective light–matter interactions in ordered atomic arrays. Bekenstein et al. introduced quantum operator-valued reflectivity in atom-array metasurfaces [2]. Srakaew et al. subsequently demonstrated a subwavelength atomic array whose collective optical response could be switched using a single Rydberg control atom [3]. Uria et al. proposed using conditional scatterers of this type as quantum-network nodes [1]. Qalice adopts this scientific lineage and reserves its original contribution for system architecture, modeling, control, and validation.

2.3 Qalice terminology

Naming convention

“Physical quantum mirror (QM)” denotes the quantum-controlled optical device. “Qalice qMirror Control Layer” denotes the software and control infrastructure used to model, calibrate, monitor, and visualize QM-enabled systems. The distinction prevents a digital control product from being confused with the physical quantum device.

2.4 Role of adjacent technologies

Technology	Role in the architecture	Technical boundary
Photonic integrated circuits (PICs)	Candidate platform for routing, modulation, filtering, interfacing, and detection around a node.	PIC integration with an atomic-array QM is a proposed engineering path, not an established feature of the protocol.
Deformable mirrors / adaptive optics	Potential correction of wavefront distortion, pointing error, and mode coupling for free-space optical links.	They do not directly preserve an internal qubit’s coherence and are not required for a fiber-only implementation.
Quantum electrodynamics	Underlying theory of light–matter interaction. Effective Hamiltonians, scattering matrices, input–output theory, and open-system master equations provide the useful system-level description.	A generic Dirac equation does not specify or validate the proposed network architecture.
Quantum error correction	Potential future layer for fault-tolerant processors, memories, and repeaters.	The quantum-mirror teleportation protocol is not itself a complete QEC scheme.
Quantum key distribution	A possible application after a specific networking protocol and security model are defined.	A QM node does not automatically provide QKD, endpoint security, authentication, or “unbreakable” communications.

3. Proposed Qalice Architecture

Qalice is organized as a systems architecture for modeling and coordinating QM-enabled nodes. The qTr, qRe, and qReTr names denote logical functions rather than distinct fabricated devices. A practical node may implement several roles depending on its source, measurement, routing, and control capabilities.

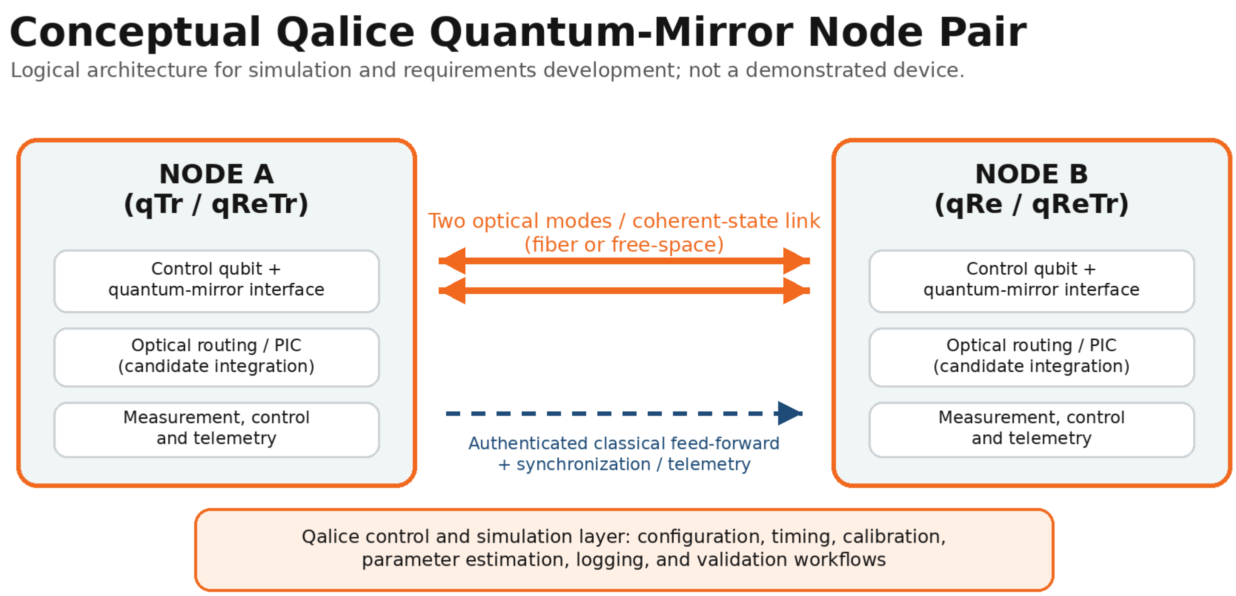

Figure 1. Conceptual Qalice node pair. Quantum optical modes propagate through the optical channel; a separate authenticated classical channel carries measurement outcomes, feed-forward instructions, timing, calibration, and telemetry.

3.1 Logical node roles

Role	Proposed responsibility	Minimum modeled interfaces
qTr — optical launch role	Prepare mediator optical modes, initialize the local control qubit, apply the QM interaction, and launch the modes into the channel.	State preparation; optical source; QM transformation; timing trigger; channel launch; health telemetry.
qRe — optical receive and measurement role	Receive and mode-match optical fields, apply or complete the QM interaction, perform control-qubit and optical measurements, and publish classical outcomes.	Link receive; mode matching; QM transformation; detector model; qubit measurement; authenticated classical output.
qReTr — hybrid node role	Combine launch, receive, measurement, and routing functions for bidirectional protocols, state-transfer experiments, or repeater-like workflows.	All qTr and qRe interfaces plus scheduling, isolation/circulation, and direction control.

Role	Proposed responsibility	Minimum modeled interfaces
qMirror Control Layer	Configure simulations or hardware, manage calibration, synchronize events, estimate parameters, and preserve experimental provenance.	Device API; clocking; calibration data; parameter registry; audit log; experiment manifest; results store.

3.2 Node functional blocks

- Control qubit and physical QM interface: the quantum-controlled scattering element and its preparation, control, and readout mechanisms.
- Optical source and preparation: coherent-state generation, amplitude and phase control, polarization/spatial-mode preparation, filtering, and isolation.
- Optical routing: free-space or integrated routing, mode multiplexing, coupling, switching, and optional PIC interfaces.
- Channel stabilization: path-length and phase stabilization; for free space, pointing, tracking, wavefront correction, and atmospheric monitoring.
- Measurement: optical detection and control-qubit measurement, with modeled efficiency, dead time, dark counts, timing jitter, and discrimination errors.
- Classical control plane: authenticated communication for measurement outcomes, Pauli feed-forward, timing, calibration, logging, and safety interlocks.

3.3 Teleportation-oriented evaluation sequence

1. Initialize Bob’s control qubit in an equal superposition and prepare the two mediator optical modes.
2. Apply Bob’s QM transformation to entangle the control qubit with the optical modes.
3. Propagate the optical modes through the characterized channel to Alice.
4. Prepare Alice’s control qubit in the unknown input state and apply Alice’s QM transformation.
5. Measure Alice’s control qubit and optical output modes in the protocol-defined bases using the specified detector model.
6. Transmit the measurement outcome through an authenticated classical channel.
7. Apply the corresponding local correction at Bob and estimate protocol success probability, teleportation fidelity, and uncertainty.

Causality note: *Quantum teleportation requires classical communication of the measurement outcome and cannot transmit usable information faster than light.*

Protocol-direction note: *In the protocol of Ref. [1], Bob launches the mediator optical modes but receives the teleported qubit. The qTr and qRe labels therefore describe node functions, not ownership or direction of the unknown quantum state.*

4. Protocol and Performance Model

4.1 Ideal benchmark from the cited protocol

For the idealized case analyzed in Ref. [1], with one optical input in vacuum, ideal state discrimination, and mean photon number $\bar{n} = |\alpha|^2$, the no-detection failure probability decreases exponentially. The reported success probability and unconditional average teleportation fidelity are shown below. Supporting state, channel, measurement, detector, and control equations are collected in Appendix B.

$$P_s = 1 - e^{-\bar{n}}, \qquad \overline{F} = 1 - \tfrac{1}{2} e^{-\bar{n}}, \qquad \bar{n} = |\alpha|^2$$

Equation 2. Ideal benchmark quantities reported in Ref. [1]. These are literature results, not Qalice measurements.

At $\bar{n} = 4$, the ideal equations give P□ ≈ 0.9817 and $\bar{F} \approx 0.9908$. These values provide a numerical reproduction benchmark rather than a hardware forecast. Practical performance requires the full channel, detector, control-qubit, and mode-overlap model.

4.2 Link budget and state propagation

An engineering link budget should separate channel transmission from detector efficiency so that losses are not counted twice. For a fiber link, the optical transmission to the detector input can be estimated from distributed attenuation and lumped coupling or component losses:

$$\eta_{\mathrm{ch}} = 10^{-[\alpha_{\mathrm{f}} L + L_{\mathrm{c}}]/10}, \qquad \bar{n}_{\mathrm{rx}} = \eta_{\mathrm{ch}} \bar{n}_{\mathrm{tx}}, \qquad \eta_{\mathrm{sys}} = \eta_{\mathrm{ch}} \eta_{\mathrm{d}}$$

Equation 3. Basic optical link relation. Protocol fidelity under loss must be calculated with the corresponding quantum channel and measurement model rather than inferred from the link budget alone.

For free-space links, η_{ch} should be decomposed into geometric coupling, atmospheric transmission, pointing and tracking, mode overlap, and optical throughput, while detector efficiency η_d remains a separate measurement parameter. Turbulence and phase noise require time-dependent or statistical models. Deformable mirrors may improve mode overlap and pointing stability, but the improvement must be evaluated against added optical loss, control bandwidth, calibration complexity, and latency.

4.3 Required nonideal model parameters

Parameter	Meaning	Modeling requirement
$\bar{n} = |\alpha|^2$	Mean photon number in the coherent state.	Controls non-orthogonality and ideal no-click failure; sweep with Fock-space convergence checks.
η_{ch}	Optical transmission to the detector input, excluding detector quantum efficiency.	Apply a pure-loss channel and separate propagation, coupling, device, and filtering losses.

Parameter	Meaning	Modeling requirement
δ	Relative phase mismatch between optical modes.	Model path-length noise, phase lock performance, and time variation.
r_j, t_j, φ_j	Complex QM reflection and transmission amplitudes and associated phase errors.	Replace the ideal conditional swap with a nonunitary, lossy, or otherwise imperfect scattering model.
η_d, p_{dark}, τ_j	Detector efficiency, dark-count probability, and timing jitter.	Modify discrimination outcomes and false-positive or false-negative event rates.
T_1, T_2, ε_{prep}, ε_{meas}	Control-qubit relaxation, dephasing, preparation, and measurement errors.	Use open-system evolution or calibrated channels during the full protocol duration.
M	Spatial, spectral, polarization, and temporal mode overlap.	Imperfect overlap reduces interference and discrimination; model as visibility or multimode coupling.
t_{ff}, p_{msg}	Classical feed-forward latency and message-error probability.	Affects memory-time requirements, scheduling, and operational success without altering causality.

4.4 Metrics to report

- Protocol success probability with an explicit event definition and uncertainty or confidence intervals appropriate to the data source.
- Conditional fidelity for accepted events and unconditional average fidelity that includes failure outcomes.
- Entanglement fidelity or process fidelity when characterizing the effective channel.
- Successful protocol events per second, including source repetition rate, detector dead time, classical latency, and calibration duty cycle.
- Parameter sensitivity and uncertainty propagation, not just best-case curves.
- Resource assumptions, including photon number, qubit coherence time, detector performance, channel loss, stabilization bandwidth, and required hardware.

5. Assumptions, Risks, and Limitations

5.1 Core technical risks

Risk	Current uncertainty	Evidence required for advancement
Physical QM availability	High-performance, controllable QM platforms remain specialized research systems.	Identify a partner platform, realistic reflectivity/phase specifications, control-qubit lifetime, coupling geometry, and measurement access.
Ideal-to-physical protocol gap	The ideal equations omit several detector, control, and multimode effects.	Independent numerical reproduction followed by calibrated nonideal simulations and uncertainty analysis.
Long-distance loss and phase stability	Coherent-state links tolerate some loss in theory, but distance claims depend strongly on all channel and node parameters.	End-to-end link budget, phase-noise spectrum, stabilization design, detector model, and rate analysis.
PIC / atom-array integration	Potentially valuable but not established in this architecture.	Interface study covering wavelength, mode size, packaging, cryogenic/vacuum constraints, loss, and control access.
Free-space turbulence	Beam wander and wavefront distortion may dominate.	Atmospheric channel model, adaptive-optics simulation, pointing budget, weather envelope, and field-test plan.
Security interpretation	Quantum networking does not automatically make every layer secure.	Protocol-specific threat model, authentication design, implementation-security review, and composable security proof where applicable.
Prior-art and contribution boundary	Qalice terminology could obscure the distinction between cited QM physics and Qalice-specific systems engineering.	Maintain a clear prior-art map and an explicit statement of Qalice-specific engineering contributions.

5.2 Explicit limitations of this document

- No original simulation data, laboratory measurements, device specifications, or independent replication results are included yet.
- The architecture does not select a final physical platform; atomic arrays, waveguide QED, and superconducting/microwave conditional-scattering systems have different constraints.
- The qTr / qRe / qReTr terminology is provisional and may evolve as the physical platform, protocol interfaces, and implementation evidence mature.
- Applications beyond state transfer, teleportation, entanglement swapping, and state characterization remain speculative until protocol-level models are supplied.

- Business, energy, and cybersecurity claims are intentionally excluded from the technical core because they are not established by the current physics model.

5.3 Scientific interpretation boundaries

Topic	Whitepaper interpretation
Quantum coherence	A QM conditionally transmits or reflects optical modes according to a control-qubit state. Coherence performance must be quantified for the selected implementation.
Security	QM-enabled networks may support protocol-specific security functions, subject to authentication, implementation assumptions, and a defined security analysis.
Causality	Quantum-state protocols require classical communication for usable feed-forward information and obey relativistic causality.
Distance and deployment	Distance and rate depend on the complete channel, node, detector, and stabilization model and remain to be validated experimentally.
Model validity	Implementation-specific Hamiltonians and scattering models must be tied to measurable parameters and validated against selected hardware.

6. Research and Validation Roadmap

The development program is staged so that each technical claim is tied to a reproducible model, dataset, or experiment before deployment conclusions are drawn.

6.1 Phase 0 — literature and requirements baseline

- Create a structured prior-art map for physical QMs, quantum metasurfaces, conditional scattering, coherent-state teleportation, repeaters, and tomography.
- Define the target protocol, physical platform, link type, wavelength, and measurement assumptions.
- Freeze notation, units, metrics, and a claim-evidence matrix.

Milestone: the physical model, notation, contribution boundary, and prior-art map are internally consistent, traceable, and complete enough to support reproducible simulation.

6.2 Phase 1 — reproduce the published ideal model

- Implement the control qubit plus two bosonic modes with an explicit Fock-basis truncation and convergence test.
- Reproduce the ideal success probability and average fidelity curves from Ref. [1].
- Document numerical precision, truncation error, random-state sampling, and code provenance.

Milestone: analytic and numerical results agree within a predefined tolerance, such as 10^{-3} for benchmark quantities over the selected parameter range.

6.3 Phase 2 — non-ideal digital twin

- Add optical loss, phase mismatch, imperfect reflectivity/transmissivity, detector efficiency, dark counts, mode mismatch, and control-qubit errors one at a time and in combination.
- Perform sensitivity analysis and uncertainty propagation, including worst-case and realistic parameter sets.
- Report success, conditional fidelity, unconditional fidelity, rate, and parameter confidence intervals.

Milestone: the parameter model passes consistency and sensitivity checks, and the viable operating region remains credible under combined nonidealities and uncertainty bounds.

6.4 Phase 3 — optical control and measurement testbed

- Build a classical or semiclassical optical surrogate to validate timing, mode routing, phase stabilization, detector logic, telemetry, and free-space pointing or adaptive-optics controls.
- Treat this as control-system validation only; do not label it a physical QM demonstration.

Milestone: repeatable calibration and measurement workflows with quantified drift, loss, timing, and mode-overlap performance.

6.5 Phase 4 — physical-QM laboratory validation

- Agree on a minimal experiment that tests one conditional-scattering transformation and its characterization before attempting a network protocol.
- Develop shared data formats, calibration procedures, authorship/attribution terms, and independent analysis.
- Progress to two-node state transfer or teleportation only after the single-node transformation and measurement model are validated.

Milestone: independently reproducible experimental evidence with documented methods, uncertainty analysis, data-access terms, and a clearly bounded result.

6.6 Development deliverables

Deliverable	Minimum contents	Completion criterion
D1. Scientific model specification	Hilbert spaces, transformations, channel models, measurement operators, assumptions, notation, and references.	Every equation maps to a defined physical operation, parameter, and measurable output.

Deliverable	Minimum contents	Completion criterion
D2. Reproducible simulation repository	Versioned code, environment, tests, benchmark data, parameter files, and figure-generation scripts.	An independent environment can reproduce the ideal benchmark curves and numerical tolerances.
D3. Non-ideal sensitivity report	Loss, phase, reflectivity, detector, qubit, and mode-overlap sweeps with uncertainty.	Dominant parameters, uncertainty bounds, and experimentally credible operating regions are identified.
D4. Node and interface specification	Logical roles, timing, optical and classical interfaces, calibration, telemetry, and safety.	The architecture supports implementation without overstating the underlying physics or maturity.
D5. Experimental collaboration plan	Minimal test, required equipment, partner responsibilities, data plan, and publication/attribution boundaries.	The proposed experiment is technically feasible, scientifically meaningful, and governed by clear data, authorship, and attribution terms.

7. Research Applications and Development Boundaries

7.1 Near-term research uses

- Reproducible numerical studies of QM-based teleportation, state transfer, and entanglement swapping.
- Control-plane and telemetry design for experiments that evaluate quantum-controlled optical scatterers.
- Comparison of fiber, free-space, waveguide, and integrated-photonic interfaces using common channel and detector metrics.
- Quantum-state characterization workflows, informed by emerging work on QM-enabled continuous-variable tomography [7].

7.2 Longer-term conditional applications

With successful experimental validation, QM-enabled nodes could contribute to distributed quantum processing, remote quantum-state transfer, repeater-like operations, networked sensing, or quantum-state tomography. Each application requires a dedicated protocol, hardware assumptions, rate and fidelity analysis, and, where relevant, a security model. These capabilities do not follow automatically from the existence of a QM node.

7.3 Out-of-scope claims at the current stage

- Commercial deployment timelines, cost savings, energy reductions, global coverage, and enterprise service-level guarantees.
- Post-quantum cryptography claims unrelated to the physical quantum-network protocol.
- General quantum computing acceleration without a defined processor architecture and workload.
- Any claim of endorsement, affiliation, or institutional support without written authorization.

8. Conclusion

Qalice defines a disciplined research and engineering framework for translating quantum-mirror theory into testable network components. Its near-term value lies in reproducing the cited protocol, extending it to realistic nonidealities, specifying node and control interfaces, and producing the evidence required for laboratory implementation.

By maintaining explicit assumptions, traceable equations, measurable interfaces, and staged validation criteria, Qalice can mature from a conceptual architecture into a reproducible experimental program. Performance, security, distance, and deployment claims remain contingent on the corresponding model and measurement evidence.

Appendix A — Symbols, Metrics, and Reporting Checklist

A.1 Core symbols

Symbol	Definition / unit	Implementation note
c	Control qubit associated with the physical QM.	Specify basis, preparation, measurement, T_1/T_2, and control errors for a selected platform.
$\|\alpha\rangle$, $\|\beta\rangle$	Coherent states in optical modes 1 and 2.	Specify amplitude, phase, wavelength, bandwidth, polarization, and spatial mode.
$\bar{n} = \|\alpha\|^2$	Mean photon number.	Report transmitter and receiver values and all loss assumptions.
ηch	Optical channel transmission to the detector input, dimensionless.	Break out propagation, coupling, device, and filtering components; report ηd separately.
δ	Relative optical phase mismatch, radians.	Connect to path-length stability and phase-lock bandwidth.
P□	Protocol success probability.	Define accepted outcomes, detector model, and postselection.
$\bar{F}$	Average state fidelity.	State whether conditional or unconditional and how input states are sampled.
M	Mode-overlap or visibility parameter.	Define spatial, spectral, temporal, and polarization contributions.

A.2 Technical reporting checklist

- ☐ Qalice-specific statements are identified as proposed, simulated, measured, or externally reported.
- ☐ Every equation maps to a cited source, documented derivation, or explicitly labeled engineering model.
- ☐ Parameters include units, physical meaning, assumed ranges, and uncertainty.
- ☐ Conditional and unconditional fidelities are defined separately.
- ☐ Classical communication, feed-forward, authentication, and timing requirements are explicit.
- ☐ PICs and adaptive optics are treated as candidate engineering components rather than proven coherence mechanisms.
- ☐ Security, distance, and rate statements include the complete protocol, channel, detector, and timing assumptions.
- ☐ Prior art, cited results, Qalice contributions, and institutional relationships are clearly distinguished.

Appendix B — Mathematical Reference Model

This appendix collects the equations used throughout the whitepaper and distinguishes established identities from Qalice engineering models. Equation 1 remains the defining ideal quantum-mirror transformation. Each additional equation is included only where it maps to a named component, parameter, or measurement.

Mathematical scope

The mathematical reference set includes qubit normalization, Bell states, the standard teleportation identity, unitary evolution, a local light–matter interaction reference, photonic-mode coupling, phase accumulation, bosonic loss, generalized measurement, detector response, a simple qubit-noise channel, and a classical adaptive-optics surface model. Generic Dirac or QED expressions and unsupported logical-codeword expressions are not included because they do not map to a defined Qalice component, protocol, or validation measurement.

B.1 State preparation and normalization

A single qubit may be represented as a normalized superposition. In a simulation, the amplitudes and basis convention must be explicit, and mixed states should be represented with a density operator rather than a state vector.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \qquad |\alpha|^2 + |\beta|^2 = 1$$

Equation B1. Pure-state qubit representation and normalization [10].

B.2 Bell-basis entangled resource states

The four Bell states provide the standard two-qubit maximally entangled basis. They are included as a reference for the control-qubit resource and measurement language used in teleportation-oriented protocols.

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

Equation B2. The four Bell states used as the standard maximally entangled two-qubit basis [6, 10].

B.3 Standard teleportation identity

The identity below is the conventional qubit-teleportation decomposition. It shows how a Bell-basis result and two classical bits identify the local Pauli correction at the receiving qubit. It is included as a reference identity; the quantum-mirror protocol in Ref. [1] uses its own optical interaction and measurement sequence.

$$|\psi\rangle_A|\Phi^+\rangle_{BC} = \tfrac{1}{2}[|\Phi^+\rangle_{AB}|\psi\rangle_C + |\Phi^-\rangle_{AB}Z|\psi\rangle_C$$
$$+ |\Psi^+\rangle_{AB}X|\psi\rangle_C + |\Psi^-\rangle_{AB}XZ|\psi\rangle_C]$$

Equation B3. Standard teleportation decomposition. The XZ term is equivalent to a Pauli Y operation up to a global phase [6, 10].

Model requirement: document the exact resource-state, basis-ordering, feed-forward, and phase conventions used when mapping the Qalice simulation to Ref. [1].

B.4 Dynamics and candidate light–matter interaction

Closed-system evolution can be represented by a unitary operator. A realistic node model then adds the relevant open-system channel, master equation, or completely positive trace-preserving map for loss and decoherence.

$$\rho(t) = U(t)\rho(0)U^\dagger(t), \qquad U(t) = \exp\left(-\frac{iHt}{\hbar}\right)$$

Equation B4. Unitary density-operator evolution [10].

A Jaynes–Cummings-type Hamiltonian is shown only as a candidate local coupling model for a two-level emitter interacting with one quantized mode. It is not a universal quantum-mirror Hamiltonian. A physical implementation based on an atomic array, waveguide QED, a cavity, or another platform must substitute its derived many-body scattering Hamiltonian and measured parameters.

$$H = \hbar\omega_c a^\dagger a + \frac{\hbar\omega_q}{2}\sigma_z + H_{\text{int}}$$
$$H_{\text{int}} = \hbar g\left(a^\dagger\sigma_- + a\sigma_+\right)$$

Equation B5. Jaynes–Cummings interaction used as a local reference model; a platform-specific replacement is required [11].

B.5 Photonic routing and phase control

A beam-splitter Hamiltonian provides a compact model for coherent coupling between two optical modes in a PIC, directional coupler, or equivalent routing element. The coupling angle, insertion loss, dispersion, and fabrication errors are parameterized separately.

$$H_{\text{BS}} = \hbar\kappa(a^\dagger b + ab^\dagger), \qquad U_{\text{BS}}(\theta) = \exp[-i\theta(a^\dagger b + ab^\dagger)]$$

Equation B6. Ideal coherent coupling between two bosonic modes [12].

Optical phase depends on propagation constant, path length, vacuum wavelength, and any applied control phase. The Qalice model reports its phase convention, residual mismatch, drift spectrum, stabilization bandwidth, and calibration cadence.

$$\phi = \beta L + \phi_{\mathrm{ctrl}} = \frac{2\pi n_{\mathrm{eff}} L}{\lambda_0} + \phi_{\mathrm{ctrl}}, \qquad \Delta\phi = \phi_1 - \phi_2$$

Equation B7. Phase accumulation and relative phase mismatch.

B.6 Loss channel and received photon number

A pure-loss bosonic channel can be represented by mixing the signal with an environmental vacuum mode. The engineering dB relation is useful for budgeting, while protocol performance is computed by applying the channel to the optical state and measurement model.

$$a_{\mathrm{out}} = \sqrt{\eta_{\mathrm{ch}}}\, a_{\mathrm{in}} + \sqrt{1-\eta_{\mathrm{ch}}}\, \nu$$

$$\eta_{\mathrm{ch}} = 10^{-[\alpha_f L + L_c]/10}, \qquad \bar{n}_{\mathrm{rx}} = \eta_{\mathrm{ch}} \bar{n}_{\mathrm{tx}}$$

Equation B8. Pure-loss bosonic transformation and corresponding engineering link relation [12].

B.7 Measurement, detector response, and simple noise channels

Generalized measurement probabilities should be computed from a positive-operator-valued measure. This avoids treating a detector click, a no-click event, a Bell-state outcome, or a thresholded analog signal as interchangeable measurements.

$$p(m) = \mathrm{Tr}(M_m \rho), \qquad M_m \succcurlyeq 0, \qquad \sum_m M_m = I$$

Equation B9. Born rule in POVM form [10].

For a coherent state measured by an idealized threshold detector, the no-click probability can include detector efficiency and a dark-count probability per detection window. A complete detector model may also require afterpulsing, dead time, saturation, background counts, and timing-window dependence.

$$P_0 = (1 - p_{\mathrm{dark}}) \exp(-\eta_d \bar{n}_{\mathrm{rx}}), \qquad P_{\mathrm{click}} = 1 - P_0$$

Equation B10. Simplified threshold-detector response for a coherent-state input [12].

The depolarizing channel below is a simple benchmark for control-qubit noise. It should not be used as a substitute for measured amplitude damping, dephasing, preparation, gate, and readout errors when platform data are available.

$$\mathcal{E}_p(\rho) = (1-p)\rho + \frac{p}{3}(X\rho X + Y\rho Y + Z\rho Z)$$

Equation B11. Simple single-qubit depolarizing channel [10].

B.8 Classical adaptive-optics surface model

A deformable mirror is a classical optical control element that may improve beam pointing, wavefront quality, or mode overlap. Its surface can be expanded in actuator influence functions or Zernike modes. This model is distinct from the physical quantum-mirror transformation.

$$z(x,y) = z_0(x,y) + \sum_{j=1}^{N} a_j Z_j(x,y)$$

Equation B12. Generic classical deformable-mirror surface expansion [13].

Model requirement: define the minimum turbulence and adaptive-optics model for any proposed free-space experiment, including sensing wavelength, correction bandwidth, residual phase variance, and added optical loss.

B.9 Equation-to-model traceability requirements

Equation set	Model status	Required parameters	Validation requirement
Eq. 1; B1–B3	Established ideal definitions / protocol reference	Basis ordering, coherent-state amplitude, control-qubit resource, measurement convention	The Qalice notation reproduces Ref. [1] without altering the protocol, basis ordering, or feed-forward convention.
B4–B5	Reference and candidate dynamics	Hamiltonian, coupling strengths, detunings, decoherence, collective interactions	Replace the local reference model with a platform-specific Hamiltonian and open-system model tied to measurable parameters.
B6–B8	Engineering and channel model	Coupling angle, insertion loss, phase drift, attenuation, mode overlap, environment state	Represent all dominant optical non-idealities with independently measurable parameters and uncertainty bounds.

Equation set	Model status	Required parameters	Validation requirement
B9–B11	Measurement and noise model	POVM elements, detector efficiency, dark counts, dead time, T1/T2, SPAM errors	Report conditional and unconditional performance without post-selection bias and with a complete detector/noise model.
B12	Classical supporting optics only	Wavefront basis, actuator response, residual phase, latency, bandwidth, optical loss	Justify adaptive optics through a quantified link improvement that exceeds its added loss, latency, and control complexity.

References

Equation-source note: Equation 1 and the ideal protocol benchmark follow Ref. [1]. Equations B1–B4, B9, and B11 use standard notation consistent with Ref. [10]; Equation B3 follows Refs. [6, 10]; Equation B5 uses the Jaynes–Cummings reference model [11]; Equations B6, B8, and B10 follow standard quantum-optics models [12]; and Equation B12 uses a standard adaptive-optics surface expansion [13]. Every engineering model still requires platform-specific parameters and validation.

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