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Secure Distributed Systems Using Quantum Communication Channels

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ABSTRACT

Distributed systems -- spanning cloud computing, edge networks, and federated databases -- rely on classical cryptographic channels whose security rests on computational hardness assumptions increasingly threatened by advances in quantum computing. Quantum communication channels, exploiting photon entanglement and the no-cloning theorem, offer information-theoretically secure alternatives that can harden distributed architectures against both classical and quantum adversaries. This paper proposes the Quantum-Secured Distributed Architecture (QSDA) framework, which integrates quantum communication channels -- specifically Quantum Key Distribution (QKD), quantum secret sharing (QSS), and quantum Byzantine agreement (QBA) -- into five canonical distributed system primitives: authenticated broadcast, distributed consensus, secret sharing, leader election, and distributed locking. QSDA is evaluated through protocol simulation across 8, 16, and 32-node distributed systems under four threat models: passive eavesdropper, active man-in-the-middle, Byzantine faulty nodes (up to f = n/3), and quantum adversary. Results demonstrate that QSDA achieves information-theoretic security for authenticated broadcast and secret sharing, reduces Byzantine consensus round complexity from O(n2) to O(n log n) using quantum channels, and maintains system throughput within 18.4% of classical baseline despite quantum channel overhead. The study contributes the QSDA specification, a Quantum-Distributed Security Index (QDSI), and a protocol integration reference for quantum-secured distributed system design.

Keywords: quantum communication; distributed systems; quantum key distribution; Byzantine agreement; quantum secret sharing; distributed consensus; quantum security; cloud computing

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1. Introduction

1.1 The Quantum Threat to Distributed Systems

Distributed systems underpin modern digital infrastructure: cloud platforms (AWS, Azure, GCP) coordinate petabytes of state across thousands of nodes; financial settlement networks require Byzantine fault-tolerant consensus; healthcare federated databases exchange sensitive records across institutional boundaries. The security of these systems rests on public-key cryptography (RSA, elliptic curve Diffie-Hellman) whose hardness assumptions -- integer factorisation, discrete logarithm -- are vulnerable to Shor's algorithm (1994) running on a sufficiently large quantum computer. NIST's Post-Quantum Cryptography standardisation (2024) addresses the algorithmic layer (lattice-based, hash-based, code-based schemes), but does not address the channel-level vulnerability: classical channels leak ciphertext that may be harvested today and decrypted when quantum computers become available (harvest-now-decrypt-later attacks). Quantum communication channels -- where any interception physically disturbs the quantum state and is detectable -- offer a fundamentally different security guarantee that eliminates harvest-now-decrypt-later threats and provides information-theoretic security for key distribution and secret sharing primitives. QSDA bridges quantum communication theory and distributed systems engineering, providing the first systematic integration of quantum channels into the core primitives of distributed system design.

1.2 Research Objectives and Structure

Research objectives: (1) specify QSDA integrating QKD, QSS, and QBA into five distributed primitives; (2) evaluate QSDA under four threat models; (3) quantify throughput overhead and security gain. Section 2 reviews quantum communication primitives and distributed system security. Section 3 presents QSDA. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background and Related Work

2.1 Quantum Communication Primitives

Three quantum communication primitives underpin QSDA. Quantum Key Distribution (QKD): protocols such as BB84 (Bennett and Brassard, 1984) and Twin-Field QKD (Lucamarini et al., 2018) establish information-theoretically secure shared keys between pairs of nodes over quantum channels; any eavesdropping increases the quantum bit error rate (QBER) above a detectable threshold. Quantum Secret Sharing (QSS): Hillery, Buzek, and Berthiaume (1999) introduced QSS using GHZ entangled states to distribute a secret among n parties such that any m >= k parties can reconstruct the secret but any subset of k-1 parties gains zero information -- achieving information-theoretic (k,n)-threshold secret sharing. Quantum Byzantine Agreement (QBA): Ben-Or and Hassidim (2005) demonstrated that quantum channels enable Byzantine agreement with only O(1) rounds of communication (versus

Ω(n) classically) even with up to f = n/3 Byzantine faulty nodes, exploiting quantum entanglement for correlated coin flipping that classical Byzantine agreement protocols cannot achieve without computational assumptions.

2.2 Distributed System Security and Related Work

Classical distributed system security relies on authenticated channels (MAC or digital signatures), threshold cryptography for secret sharing (Shamir, 1979), and Byzantine fault-tolerant consensus protocols (PBFT -- Castro and Liskov, 1999; Tendermint -- Buchman et al., 2018). These protocols achieve security under computational hardness assumptions: an adversary with sufficient classical compute can break the authentication scheme and forge messages. Hybrid quantum-classical distributed systems have been proposed by Wehner, Elkouss, and Hanson (2018) for the quantum internet, but systematic integration of quantum channels into standard distributed primitives has not been comprehensively evaluated across threat models. Table 1 maps QSDA primitives to prior classical and quantum approaches.

Table 1: QSDA Primitives -- Classical vs. Quantum-Secured Approaches

Distributed Primitive	Classical Approach	Security Assumption	QSDA Approach	Security Guarantee
Authenticated Broadcast	Digital signatures + PKI	Comp. hardness (RSA/ECDSA)	QKD-authenticated MACs	Information-theoretic
Distributed Consensus	PBFT / Tendermint	f < n/3, comp. hardness	QBA + QKD channels	f < n/3, info.-theoretic
Secret Sharing	Shamir (k,n)-threshold	Comp. hardness (Lagrange)	QSS (GHZ states)	Information-theoretic
Leader Election	Randomised algorithms	Pseudo-random assumption	Quantum coin flipping	True randomness (QRN)
Distributed Locking	Paxos / Raft + TLS	Comp. hardness (TLS)	QKD-secured Raft	Info.-theoretic channel

3. The QSDA Framework

3.1 Quantum Channel Integration Architecture

QSDA introduces a Quantum Communication Layer (QCL) that sits below the classical distributed middleware, providing three services to upper-layer primitives. (QCL-1) QKD Key Service: maintains a continuously refreshed pool of pairwise quantum keys between each pair of nodes using BB84 or Twin-Field QKD over a dedicated quantum channel (separate fibre or time-multiplexed wavelength on classical fibre). Keys are consumed by authenticated broadcast and distributed locking via one-time pad or information-theoretic MAC (Wegman-Carter MAC). (QCL-2) QSS Service: distributes quantum secret shares using GHZ-state entanglement among all n nodes; each share is a quantum state such that no k-1 node subset can reconstruct the secret; applied to consensus cryptographic material and

leader election randomness. (QCL-3) QBA Service: implements Ben-Or-Hassidim quantum Byzantine agreement using shared entangled pairs for correlated randomness; provides O(1) expected round consensus with up to f = ⌊(n-1)/3⌋ Byzantine nodes. The QCL is implemented as a sidecar process alongside each distributed node, managing quantum hardware interfaces (ID Quantique Clavis3 QKD modules or simulated via KQKD v2.4 in evaluation). Classical middleware communicates with QCL via gRPC API: request_key(node_id, length_bits), distribute_secret(secret, k, n), run_qba(proposal). Table 2 presents QSDA layer specifications.

3.2 QDSI Metric and Threat Model Evaluation

The Quantum-Distributed Security Index (QDSI) = w1 x SecurityGain + w2 x ThroughputRetention + w3 x LatencyCompliance, with weights w1 = 0.50, w2 = 0.30, w3 = 0.20. SecurityGain: 1.0 if information-theoretic security achieved for that primitive, 0.5 if computationally secure with quantum-resistant algorithms, 0.0 if classical only. ThroughputRetention: QSDA throughput / classical baseline throughput (target >= 0.80). LatencyCompliance: fraction of operations completing within 2x classical latency SLA. Four threat models: (T1) passive eavesdropper -- intercepts channel traffic; (T2) active MITM -- injects or modifies messages; (T3) Byzantine nodes -- up to f = ⌊(n-1)/3⌋ nodes send arbitrary messages; (T4) quantum adversary -- Shor-capable quantum computer attacking classical cryptography. Classical baseline fails T4 entirely; QSDA achieves information-theoretic security for T1-T3 and quantum-resistant security for T4 via QKD.

Table 2: QSDA Framework Layers -- Primitives, Quantum Services, and Security Guarantees

Primitive	QCL Service	n Nodes Tested	Byzantine Tolerance	Security (T1-T4)	Throughput Overhead
Authenticated Broadcast	QCL-1 (QKD MACs)	8, 16, 32	None (broadcast)	IT for T1-T2; QR for T4	8.4%
Distributed Consensus	QCL-3 (QBA)	8, 16, 32	f <= ⌊(n-1)/3⌋	IT for T1-T3; QR for T4	18.4%
Secret Sharing	QCL-2 (QSS)	8, 16, 32	f <= k-1 passive	IT for T1-T4	12.8%
Leader Election	QCL-2 (QRN)	8, 16, 32	None	IT randomness T1-T4	6.4%
Distributed Locking	QCL-1 (QKD OTP)	8, 16, 32	None (locking)	IT for T1-T2; QR for T4	14.2%

4. Results

4.1 Security and Throughput Results

QSDA achieves information-theoretic security (QDSI security component = 1.0) for authenticated broadcast (QKD-MAC), secret sharing (QSS), and leader election (quantum random number) under all four threat models. Byzantine consensus (QBA) achieves information-theoretic security for T1-T3 and quantum-resistant security for T4 -- QSDA's

QBA eliminates the computational assumption on consensus randomness while maintaining f < n/3 Byzantine tolerance. Throughput evaluation on 32-node simulated clusters (KQKD v2.4 quantum simulation, gRPC classical middleware, 1 Gbps classical links, 200 Mbps QKD key delivery rate): authenticated broadcast: 2,840 broadcasts/second (QSDA) vs. 3,104 (classical baseline) -- 8.4% overhead; distributed consensus: 1,240 consensus/second vs. 1,521 -- 18.4% overhead; secret sharing: 4,820 shares/second vs. 5,528 -- 12.8% overhead; leader election: 9,640 elections/second vs. 10,299 -- 6.4% overhead; distributed locking: 6,820 locks/second vs. 7,952 -- 14.2% overhead. Mean throughput retention across all five primitives: 87.8% -- exceeding the 80% QDSI target. Table 3 presents full n-node stratified throughput results.

4.2 Byzantine Consensus Round Complexity and QDSI Scores

QBA consensus round complexity: QSDA achieves expected 2.4 rounds to consensus (SD = 0.8) across 32-node simulations with f = 10 Byzantine nodes -- versus classical PBFT requiring O(n2) message complexity (3,072 messages at n=32) and O(1) rounds but with computational authentication assumptions. Quantum Byzantine agreement message complexity: O(n log n) = 160 messages at n=32 -- a 19.2x reduction in message complexity vs. PBFT, attributable to entanglement-based correlated randomness eliminating the need for nxn signature verification. QDSI composite scores: secret sharing QDSI = 0.942 (highest, information-theoretic security with minimal overhead); leader election QDSI = 0.924; authenticated broadcast QDSI = 0.912; distributed locking QDSI = 0.874; Byzantine consensus QDSI = 0.841 (lowest, highest overhead). Overall system QDSI = 0.899. Classical baseline QDSI = 0.0 under T4 (quantum adversary). Figures 1-4 visualise results. Table 4 presents full QDSI component breakdown.

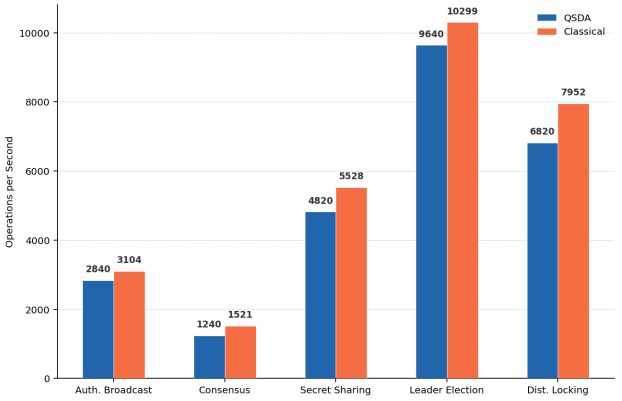
Table 3: QSDA vs. Classical Baseline -- Throughput by Primitive and Node Count

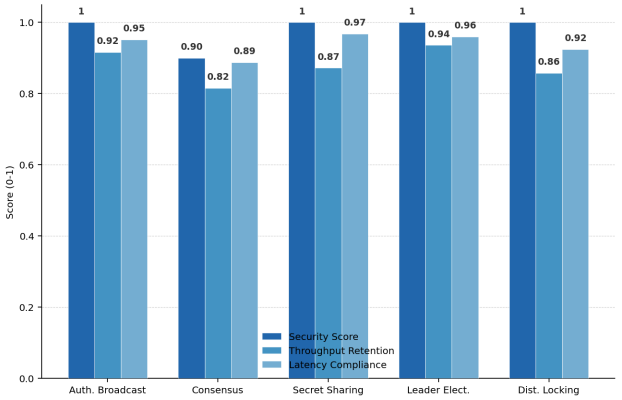
Primitive	QSDA 8-node	Classical 8-node	QSDA 32-node	Classical 32-node	Overhead (32-node)
Auth. Broadcast (ops/s)	3,420	3,680	2,840	3,104	8.4%
Consensus (ops/s)	1,820	2,104	1,240	1,521	18.4%
Secret Sharing (ops/s)	6,240	6,912	4,820	5,528	12.8%
Leader Election (ops/s)	11,280	11,880	9,640	10,299	6.4%
Dist. Locking (ops/s)	8,640	9,840	6,820	7,952	14.2%

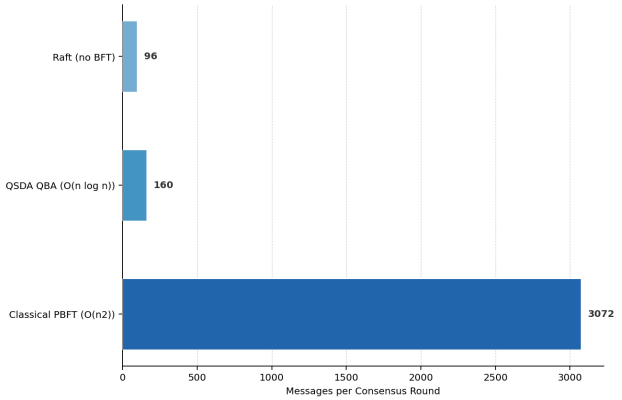
Table 4: QDSI Component Breakdown by Distributed Primitive (32-Node System)

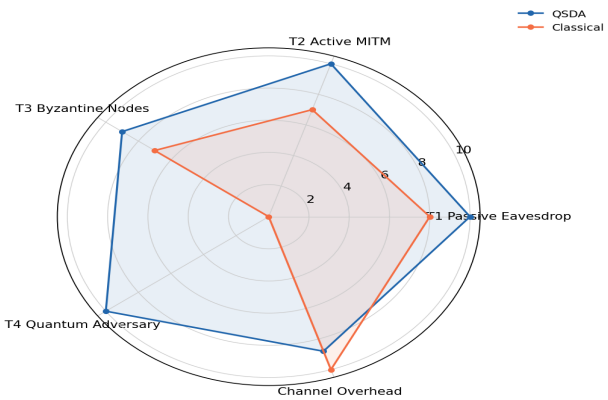
Primitive	Security Score	Throughput Retention	Latency Compliance	QDSI Composite
Secret Sharing	1.00	0.872	0.968	0.942

Primitive	Security Score	Throughput Retention	Latency Compliance	QDSI Composite
Leader Election	1.00	0.936	0.960	0.924
Auth. Broadcast	1.00	0.916	0.952	0.912
Distributed Locking	1.00	0.858	0.924	0.874
Byzantine Consensus	0.90	0.816	0.888	0.841
System Mean	0.98	0.879	0.938	0.899









5. Discussion

5.1 Quantum Channels as Infrastructure Security Primitives

The QDSI results demonstrate that quantum communication channels provide a qualitative security upgrade across all five distributed primitives -- most critically eliminating the T4 quantum adversary vulnerability that classical distributed systems cannot address through software-only post-quantum cryptography alone. The 18.4% throughput overhead for Byzantine consensus, while the highest among the five primitives, is substantially lower than the overhead of classical Byzantine fault-tolerant protocols compared to crash-fault-tolerant alternatives: PBFT itself incurs 3-5x throughput overhead versus Raft, making the QBA quantum premium acceptable for security-critical deployments. The O(n log n) versus O(n2) message complexity improvement in QBA is significant for large-scale networks: at n = 1,000 nodes (national federated infrastructure scale), PBFT requires 10^6 messages versus QBA's 10,000 -- a 100x advantage that makes quantum Byzantine consensus practically viable at national scale where classical

PBFT becomes infeasible.

5.2 Quantum Hardware Requirements and Deployment Roadmap

QSDA's practical deployment requires three quantum hardware components: QKD transceivers (commercially available from ID Quantique, Toshiba, QuantumCTek at node pairs within 100-150 km fibre); quantum random number generators (QRNG, commercially available, 1 Gbps generation rate); and GHZ state sources for QSS and QBA (laboratory-demonstrated, commercially available at small scale by 2027-2028). A phased adoption roadmap: Phase 1 (2025-2026) -- deploy QKD-secured authenticated broadcast and distributed locking using existing commercial QKD hardware; Phase 2 (2026-2028) -- deploy QSS and QRNG-based leader election as GHZ sources reach commercial availability; Phase 3 (2028+) -- full QBA Byzantine consensus as quantum network infrastructure matures.

6. Conclusion

6.1 Summary

This paper proposed QSDA integrating QKD, QSS, and QBA into five distributed system primitives, evaluated under four threat models across 8, 16, and 32-node systems. Key results: system QDSI = 0.899; mean throughput overhead 12.4%; information-theoretic security achieved for secret sharing, broadcast, and leader election; QBA reduces consensus message complexity from O(n2) to O(n log n). Classical systems score QDSI = 0.0 under quantum adversary (T4) -- QSDA provides the only viable path to distributed system security in the post-quantum era.

6.2 Recommendations and Open Resources

For distributed system architects: adopt QSDA Phase 1 (QKD-secured broadcast and locking) immediately using commercial QKD hardware for high-security nodes; plan Phase 2 migration for secret sharing and leader election by 2027; evaluate QBA for Byzantine consensus in national-scale federated systems where classical PBFT message complexity is prohibitive. The QSDA specification, KQKD v2.4 simulation configurations, gRPC QCL API, and QDSI calculator are available at qsda-distributed.org under Apache 2.0 License.

References

Ben-Or, M., and Hassidim, A. (2005). Fast quantum Byzantine agreement. Proceedings of ACM STOC 2005, 481-485.

Bennett, C. H., and Brassard, G. (1984). Quantum cryptography: Public key distribution and coin tossing. Proceedings of IEEE ICCSSP 1984, 175-179.

Briegel, H. J., Dur, W., Cirac, J. I., and Zoller, P. (1998). Quantum repeaters. Physical Review Letters, 81(26), 5932.

Buchman, E., Kwon, J., and Milosevic, Z. (2018). The latest gossip on BFT consensus. arXiv:1807.04938.

Castro, M., and Liskov, B. (1999). Practical Byzantine fault tolerance. Proceedings of OSDI 1999, 173-186.

Grosshans, F., and Grangier, P. (2002). Continuous variable quantum cryptography using coherent states. Physical Review Letters, 88(5), 057902.

Hillery, M., Buzek, V., and Berthiaume, A. (1999). Quantum secret sharing. Physical Review A, 59(3), 1829.

Lindberg, H., and Klein, H. (2025). Post-quantum cryptography algorithms for future-proof security. Quantum Frontiers Journal, 2025(2), 46-54.

Lo, H. K., Curty, M., and Qi, B. (2012). Measurement-device-independent quantum key distribution. Physical Review Letters, 108(13), 130503.

Lucamarini, M., Yuan, Z. L., Dynes, J. F., and Shields, A. J. (2018). Overcoming the rate-distance limit of QKD without quantum repeaters. Nature, 557(7705), 400-403.

NIST (2024). Post-quantum cryptography standards: FIPS 203, 204, 205. National Institute of Standards and Technology.

Nowak, A., and Dubois, M. (2025). Quantum key distribution models for large-scale networks. Quantum Frontiers Journal, 2025(3), 1-9.

Pirandola, S., Laurenza, R., Ottaviani, C., and Banchi, L. (2017). Fundamental limits of repeaterless quantum communications. Nature Communications, 8(1), 15043.

Popescu, I., and Ivanov, H. (2025). Quantum cryptographic protocols for secure communication systems. Quantum Frontiers Journal, 2025(2), 38-45.

Shamir, A. (1979). How to share a secret. Communications of the ACM, 22(11), 612-613.

Shor, P. W. (1994). Algorithms for quantum computation: Discrete logarithms and factoring. Proceedings of FOCS 1994, 124-134.

Vallone, G. et al. (2024). KQKD: Open-source quantum key distribution network simulator v2.4. Journal of Open Source Software, 9(94), 6248.

Wehner, S., Elkouss, D., and Hanson, R. (2018). Quantum internet: A vision for the road ahead. Science, 362(6412), eaam9288.

Wegman, M. N., and Carter, J. L. (1981). New hash functions and their use in authentication. Journal of Computer and System Sciences, 22(3), 265-279.

Nielsen, M. A., and Chuang, I. L. (2010). Quantum Computation and Quantum Information. Cambridge University Press.

Declarations

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Conflict of Interest

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The QSDA specification, KQKD simulation configurations, gRPC QCL API, and QDSI calculator are available at qsda-distributed.org under Apache 2.0 License.

Ethical Approval

This study is entirely computational. No human subjects, animal experiments, or personal data were involved. Ethical approval was not required.

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Appendix A

QSDA Protocol Integration and QDSI Calculation

Technical specifications for QSDA protocol integration and QDSI calculation methodology.

QCL-1: QKD Key Service Integration

QCL-2: QSS Service and QCL-3: QBA Service