

SkyBridge Compass: A Crypto-Agile Peer-to-Peer Remote Desktop and File Transfer System with Post-Quantum Readiness on Apple Platforms

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Abstract—Peer-to-peer remote desktop and file transfer systems increasingly operate across heterogeneous devices, untrusted networks, and long lifecycles in which cryptographic assumptions may expire faster than products. Yet “post-quantum readiness” is often treated as a one-off algorithm swap rather than a migration problem with downgrade resistance, auditability, and reproducibility requirements. This paper presents SkyBridge Compass, a crypto-agile P2P system that explicitly separates (i) negotiated cryptographic suites, (ii) platform-specific provider backends, and (iii) a policy layer that governs when (and whether) classic fallback is permissible. We introduce an actor-isolated handshake state machine with deterministic failure semantics and structured security-event emission, enabling end-to-end audit trails for downgrade, identity mismatch, and signature verification failures. We evaluate three configurations on macOS 26.x: classic (X25519 + Ed25519), PQC via liboqs (ML-KEM-768 + ML-DSA-65), and PQC via native CryptoKit (ML-KEM-768 + ML-DSA-65). End-to-end handshake completion latency (including event emission overhead) is 1.81 ms (p95 2.09 ms) for classic, 6.32 ms (p95 8.15 ms) for liboqs PQC, and 11.02 ms (p95 16.15 ms) for CryptoKit PQC over N=1000 iterations. The wire-format size grows from 819 B (classic) to 12,155 B (PQC), and we provide a conservative projection for a hybrid X-Wing-style exchange of approximately 12.4 KB. Beyond performance, we validate security-centric properties under fault injection and downgrade workloads, and we provide scripts and tests that reproduce all primary figures and tables from released artifacts.

Index Terms—post-quantum cryptography, crypto agility, downgrade resistance, secure handshake, peer-to-peer systems, remote desktop, Apple platforms, auditability, reproducibility.

1 INTRODUCTION

Peer-to-peer (P2P) remote desktop and file transfer systems must establish secure sessions under adversarial network conditions, device churn, and multi-year lifecycles. These systems face a practical tension: users demand “it just works” pairing across heterogeneous stacks, while defenders require that cryptographic negotiation remains robust against downgrade and implementation-level failure modes. Post-quantum cryptography (PQC) increases this tension. Larger messages, higher computational cost, and uneven platform support make fallback tempting—yet fallback is exactly where silent downgrade and unverifiable behavior tend to hide.

Existing secure-channel designs and frameworks provide mature cryptographic building blocks, but they do not, by default, solve the migration problem an implementer actually faces: (i) selecting among classic/PQC/hybrid suites across platform strata, (ii) guaranteeing that policy (e.g., “require PQC”) is enforced at the entry points where callers cannot accidentally violate it, (iii) ensuring deterministic failure semantics under timeouts, reorder/duplication, and malformed inputs, and (iv) emitting security-relevant telemetry that can be audited without turning the system into a logging minefield. In practice, many systems either hard-code a single suite, or allow “compatibility” to creep into negotiation in ways that are hard to reason about and harder to verify.

This paper addresses these gaps with SkyBridge Compass, a crypto-agile P2P system designed for explicit PQC migration and auditability on Apple platforms. The core idea is to

treat crypto agility as a layered contract: negotiated suites define the protocol surface; provider backends implement suites using platform-native or portable cryptography; and a policy layer governs fallback and produces structured evidence when (and only when) downgrade occurs. We complement this design with an actor-isolated handshake driver that enforces one-shot completion, timeouts, and sensitive-material zeroization, yielding deterministic outcomes even under adverse transport behaviors.

1.1 Contributions

Contributions (reviewer-facing, evidence-backed):

- 1) We turn PQC migration from a narrative into an enforceable contract by making downgrade and legacy-compatibility decisions explicit, testable, and auditable rather than implicit “best-effort” fallback. (Fig. 5; Table 5; PolicyDowngradeBenchTests, LegacyFallbackPreconditionTests)
- 2) We design a crypto-agile P2P handshake that cleanly separates suite negotiation, transcript binding, and protocol-signature keys, preventing “suite says PQC but keys stay classical” class of integration bugs. (Fig. 1; Table 5; ProtocolSignatureRegressionTests, TranscriptIntegrityPropertyTests)
- 3) We provide migration safety with measurable coverage by enumerating legacy/PQC strata and validating acceptance/rejection boundaries under fault injection instead of relying on informal compatibility

- claims. (Table 10; Table 7; HandshakeFaultInjectionBenchTests)
- 4) We harden correctness under concurrency by an actor-isolated state machine with idempotent transitions and bounded retries, eliminating double-resume and state desynchronization failure modes. (Fig. 3; Table 5; HandshakeDriverTests)
 - 5) We make evaluation reproducible by shipping a benchmark harness that reports distributional statistics ($p_{50}/p_{95}/p_{99}$) over large-N runs and links each metric back to a concrete failure taxonomy. (Fig. 4; Tables 17–19; HandshakeBenchmarkTests, MessageSizeSnapshotTests)

1.2 Paper Organization

Section 2 reviews related work on P2P pairing, negotiation, and PQC migration. Section 3 details system architecture and protocol design. Section 4 presents the handshake state machine. Section 5 presents the security model and guarantees. Section 6 describes implementation details and platform instantiation. Section 7 outlines evaluation methodology and metrics. Section 8 discusses limitations and future work, and Section 9 concludes.

2 RELATED WORK

2.1 Peer-to-Peer Device Pairing

Device pairing protocols have evolved from simple PIN-based schemes to sophisticated cryptographic handshakes. Bluetooth Secure Simple Pairing (SSP) [2] introduced numeric comparison and passkey entry modes, but remains vulnerable to man-in-the-middle attacks during the initial exchange. Apple’s Continuity protocols leverage iCloud identity for cross-device authentication [3], but require cloud connectivity and Apple ID enrollment.

PAKE (Password-Authenticated Key Exchange) protocols, particularly SPAKE2+ [4], enable secure pairing using low-entropy secrets without exposing them to offline dictionary attacks. PAKE-based pairing is considered as an alternative to our current PIN-comparison approach for the initial pairing ceremony; however, the pairing phase is out of scope of this paper’s session handshake protocol. Our system uses visual PIN comparison during initial pairing while supporting hardware-backed key storage through Secure Enclave for subsequent sessions.

2.2 Cryptographic Agility and Negotiation

The concept of cryptographic agility—designing systems to accommodate algorithm changes without architectural overhaul—has gained prominence as cryptographic standards evolve [5]. TLS 1.3 and QUIC exemplify suite negotiation and downgrade defenses by binding the selected parameters into signed transcripts or transport parameters [6], [18]. However, agility introduces complexity: systems must handle negotiation failures, prevent downgrade attacks, and maintain backward compatibility across heterogeneous peers.

Barker and Roginsky [7] provide NIST guidelines for transitioning to post-quantum algorithms, emphasizing hybrid approaches that combine classical and quantum-resistant

primitives. Our CryptoProvider architecture directly implements these recommendations through its tiered selection mechanism.

2.3 Handshake Frameworks and Noise-Style Patterns

Noise provides a compact framework for describing authenticated key exchange patterns with explicit transcript binding and identity key usage [19]. While SkyBridge Compass does not implement Noise directly, our MessageA/MessageB/Finished exchange mirrors the same security goals (authenticated key agreement with transcript coverage) and explicitly encodes policy for auditability. This helps position the protocol in a language familiar to the cryptography community without constraining the implementation to a fixed pattern family.

2.4 Post-Quantum Cryptography Deployment

NIST’s PQC standardization process culminated in the selection of CRYSTALS-Kyber (now ML-KEM) for key encapsulation and CRYSTALS-Dilithium (now ML-DSA) for digital signatures [8]. Early deployment experiences from Signal [9] and Cloudflare [10] highlight challenges in key size management and performance optimization.

Apple’s announcement of PQC support in CryptoKit for macOS 26/iOS 26 represents a significant milestone for native platform integration. We treat Apple platforms as a deployable instance of a platform-agnostic design, emphasizing policy-driven migration rather than a platform-specific protocol.

2.5 Secure State Machine Design

State machine vulnerabilities have been a persistent source of security bugs in protocol implementations [11]. Actor-based concurrency models, as implemented in Swift’s actor system [12], provide compile-time guarantees against data races. We extend this model with explicit timeout handling and zeroization semantics to address the unique requirements of cryptographic handshakes.

2.6 Qualitative Comparison with Prior Systems

Table 1 summarizes qualitative differences between this work and representative, widely cited systems in the literature. This comparison focuses on whether a mechanism is explicit, auditable, and reproducible rather than on performance.

3 SYSTEM ARCHITECTURE

3.1 Overview

SkyBridge Compass implements a layered architecture separating concerns across four primary domains: discovery, cryptographic operations, handshake management, and session transport. Fig. 2 illustrates the high-level component relationships and trust boundaries.

TABLE 1

Qualitative comparison with representative systems. “N/A” indicates the dimension is not the focus of the cited work or specification.

Approach	Negotiation binding	Downgrade audit	Reproducibility artifacts	Mobile deployment constraints	Concurrency safety
TLS 1.3 / QUIC [6], [18]	Transcript-bound parameters	Downgrade prevention; auditing not explicit	N/A	N/A	N/A
Noise framework [19]	Pattern-level transcript binding	N/A	N/A	N/A	N/A
PQXDH [9]	Fixed pattern (no suite negotiation)	N/A	N/A	Mobile-focused; not audit-centric	N/A
Cloudflare PQC deployment [10]	Inherits TLS/QUIC binding	Deployment reporting; not protocol audit	N/A	N/A	N/A
SkyBridge Compass (this work)	Suite + policy bound to transcript	Explicit audit events + tests	Scripts + CSV artifacts	Provider tiers documented for iOS/macOS	Actor isolation + double-resume tests

3.2 Threat Model

We model an active network attacker in the Dolev-Yao style with the following **capability set**:

Network Capabilities (Attacker-Controlled):

- **Drop / delay / reorder / duplicate** packets on the discovery channel
- **Modify/inject** arbitrary bytes in MessageA, MessageB, or Finished frames
- **Replay** prior handshake messages across sessions
- **Spoof capability or policy claims** to induce weaker negotiation
- **Force negotiation failure** by corrupting suites, key shares, or signatures

Defense Mapping (Protocol + Policy):

- **Transcript binding:** sigB covers MessageA and the chosen suite, so modifications to supportedSuite[], keyShares[], or policy fail verification.
- **Negotiation integrity:** Responder MUST select a suite that Initiator offered and for which a key share exists; otherwise reject missingKeyShare.
- **Replay control:** handshakeId is derived from nonces and cached to reject duplicates within a window.
- **Downgrade resistance:** timeout-triggered fallback is disallowed; only whitelisted errors may fallback under default policy; strictPQC forbids all fallback.
- **Rate limiting:** per-peer fallback cooldown prevents rapid downgrade cycling.
- **Legacy gating:** legacy P-256 acceptance requires an authenticated channel or an existing trust record.

Trust Assumptions:

- 1) The initial pairing ceremony occurs over a trusted out-of-band channel (e.g., visual PIN comparison on both device screens)
- 2) The device Keychain provides integrity guarantees for stored identity keys
- 3) The Secure Enclave (when available) provides hardware-backed key isolation that resists software-level extraction
- 4) Users can visually verify device identity during pairing (no blind trust)

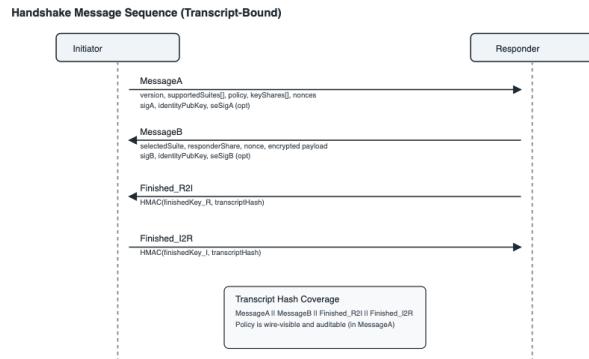


Fig. 1. Handshake sequence with transcript coverage and policy visibility.

Out of Scope:

- Side-channel attacks on cryptographic implementations
- Physical attacks on Secure Enclave hardware
- Compromise of the operating system kernel
- Social engineering attacks on users

3.3 Protocol Message Flow

Fig. 1 illustrates the handshake message sequence and transcript coverage.

Key Share Semantics: The keyShares[] .shareBytes field has suite-dependent interpretation:

- **DH suites (X25519):** shareBytes = ephemeral public key (32 bytes)
- **KEM suites (ML-KEM-768):** shareBytes = encapsulated key / ciphertext (enc, 1088 bytes)

This distinction matters: for DH, the Responder uses the Initiator’s public key to compute a shared secret; for KEM, the Initiator has already encapsulated to the Responder’s long-term KEM public key (obtained during pairing), and shareBytes carries the resulting enc. The Responder decapsulates using their private key.

Nonce Freshness: Each party contributes a 32-byte nonce (clientNonce in A, serverNonce in B). Both are bound

into the KDF info parameter, ensuring symmetric freshness and enabling a unique session identifier:

```
handshakeId = SHA256(replayTag || initiatorNonce || responderNonce || suiteWireIdLE)
```

To prevent short-window replay attacks, implementations SHOULD cache recent handshakeId values (or the (initiatorNonce, responderNonce) pair) and reject duplicates within a configurable window (default: 5 minutes).

Key Share Binding:

- The keyShares[] array contains at most two entries (one PQC, one Classic) to bound message size while enabling negotiation.
- Each entry is a (suiteId, shareBytes) tuple.
- The Responder MUST select a suite for which the Initiator provided a key share; otherwise reject with missingKeyShare.
- This binds negotiation to actual cryptographic material, preventing the "TLS key_share mismatch" class of bugs.

Explicit Key Confirmation (Finished Frames):

- The Responder sends a short Finished_R2I frame authenticated under the newly derived session keys. The Initiator verifies it and replies with Finished_I2R.
- A session is established only after both Finished frames are verified, eliminating ambiguity and reducing responder-side half-open state under failures.
- Finished frames are fixed-size authenticated messages (38 bytes each: 4-byte magic, 1-byte version, 1-byte direction, 32-byte HMAC), adding negligible wire overhead compared to PQC payloads. The Finished MAC is computed as HMAC-SHA256(finishedKey, transcriptHash), with finishedKey derived as HKDF(sessionKey, info="SkyBridge-FIN ISHED|<role>").
- Wire overhead for the full handshake including Finished frames is reported in Table 19.

Anti-Downgrade Invariant:

- The Initiator MUST verify that selectedSuite is a member of supportedSuites[] it originally sent.
- It MUST also confirm that keyShares[] contains an entry for selectedSuite.
- Since sigB commits to MessageA via transcriptA, it binds the initiator's proposal.
- Any modification to supportedSuites[] or keyShares[] by an attacker will cause sigB verification to fail.

Canonical Encoding Rules:

- supportedSuites[]: preference order, signed as-is (first = most preferred)
- keyShares[]: encoded in same order as supportedSuites[] (only suites with provided shares)
- All lists use 2-byte little-endian length prefix
- All integers use little-endian encoding

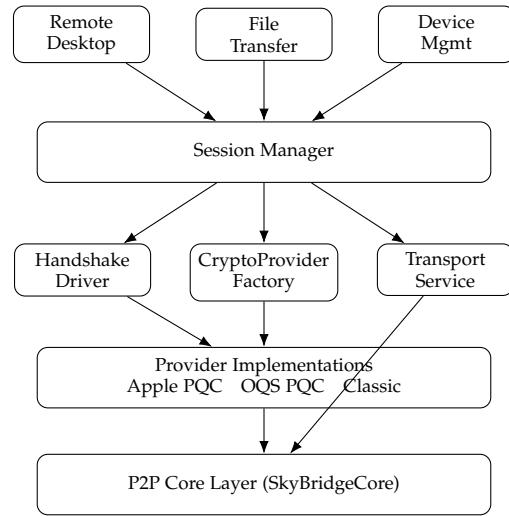


Fig. 2. SkyBridge Compass system architecture with trust boundaries and policy guard.

- Canonical encoding is byte-for-byte specified; implementations MUST NOT reserialize with language-native encoders (e.g., JSON, PropertyList) as this may introduce non-determinism

Note: The 32-byte clientNonce/serverNonce in message fields are distinct from the 12-byte aeadNonce used internally by AES-GCM for authenticated encryption.

Failure Semantics:

- All failures trigger HandshakeContext.zeroize() before error propagation
- Security events are emitted for audit logging
- No partial state is retained after failure

3.4 CryptoProvider Protocol

The CryptoProvider protocol defines a unified interface for all cryptographic operations required by the handshake and session layers. This abstraction enables transparent substitution of underlying implementations without modifying caller code.

```
public protocol CryptoProvider: Sendable {
    var providerName: String { get }
    var tier: CryptoTier { get }
    var activeSuite: CryptoSuite { get }

    func kemDemSeal(plaintext: Data,
                    recipientPublicKey: Data,
                    info: Data) async throws
    -> KemDemSealedBox
    func kemDemOpen(sealedBox:
                    KemDemSealedBox,
                    privateKey: Data,
                    info: Data) async throws
    -> Data
    func sign(data: Data, using key:
              SigningKeyHandle) async throws -> Data
    func verify(data: Data, signature: Data,
                publicKey: Data) async throws
    -> Bool
    func generateKeyPair(for usage: KeyUsage)
    -> KeyPair
}
```

TABLE 2
Suite negotiation scenarios.

Initiator supportedSuites	Responder Capability	Outcome	Notes
[PQC, Classic]	PQC available	PQC established	Best available selected
[PQC, Classic]	Classic only	Classic established	Graceful fallback
[PQC only]	Classic only	Handshake failed	Policy enforced
[Classic only]	PQC available	Classic established	Initiator policy respected

TABLE 3
Message field validation rules.

Field	Validation	Failure Action
version	Must equal protocol version (1)	
supportedSuites	Must contain at least one suite supported by local implementation; unknown IDs are ignored for negotiation but still transcript-bound	Reject with versionMismatch Reject with suiteNegotiationFailed
keyShares	Unique suiteld per entry, max 2 entries, each shareBytes must match its suiteld's expected length	Reject with invalidMessageFormat
selectedSuite	Must be in supportedSuites AND have matching keyShare	Reject with missingKeyShare
clientNonce/serverNonce	Must be 32 bytes	Reject with invalidMessageFormat
sigA/sigB	Must verify against respective identityPubKey	Reject with signatureVerificationFailed

```
// Abstraction for signing keys: software or
→ hardware-backed
public enum SigningKeyHandle: Sendable {
    case softwareKey(Data)
    → // Exportable private key bytes
    case secureEnclaveRef(SecKey)
    → // Hardware-backed, non-exportable
    case callback(any SigningCallback)
    → // Delegate to external signer
}
```

The SigningKeyHandle abstraction resolves the apparent conflict between “private key as Data” and “Secure Enclave keys never leave hardware.” Software keys are one variant; hardware-backed keys use a reference or callback, ensuring the protocol interface does not assume exportability.

The protocol mandates Sendable conformance, ensuring thread-safe usage across Swift’s structured concurrency model. Each provider exposes its tier classification (nativePQC, liboqsPQC, or classic) and active cipher suite, enabling runtime introspection for logging and policy enforcement.

3.5 CryptoSuite Wire Format

A **suite** defines the complete tuple (KEM, SIG, AEAD, KDF). Algorithm suite identifiers use a structured 16-bit wire format enabling forward compatibility:

Note: X-Wing is a hybrid KEM combining X25519 + ML-KEM-768; it does not include a signature algorithm. The suite identifier specifies the full primitive set, with ML-DSA-65 as the *preferred* signature algorithm when available; the current implementation may fall back to classic signatures (Ed25519 / Secure Enclave P-256) for broader OS/toolchain compatibility while keeping PQC confidentiality.

Unknown suite identifiers are parsed as `unknown(wireId)` rather than causing parse failures. This allows

older clients to gracefully reject unsupported suites during negotiation.

Transport/MTU considerations: handshake messages are length-prefixed and carried on reliable control channels (TCP or QUIC streams), so fragmentation is handled by the transport layer rather than by the handshake format itself. QUIC datagrams are reserved for latency-critical media frames; when datagrams are used for other payloads, senders must respect the maximum datagram size and chunk accordingly.

3.6 Provider Factory and Selection

The `CryptoProviderFactory` implements deterministic provider selection based on runtime capability detection and policy configuration:

```
public enum CryptoProviderFactory {
    public enum SelectionPolicy: Sendable {
        case preferPQC           // Default: best
        → available
        case requirePQC          // Fail if PQC
        → unavailable
        case classicOnly         // Force classic
        → algorithms
    }

    public static func make(
        policy: SelectionPolicy = .preferPQC,
        environment: any CryptoEnvironment =
        → SystemCryptoEnvironment.system
    ) -> any CryptoProvider
}
```

The selection algorithm proceeds as follows:

- 1) **Capability Detection:** Query the environment for Apple PQC availability (macOS 26+) and liboqs presence.

TABLE 4
Suite identifier ranges and components.

Range	Category	Suite Components	Examples
0x00xx	Hybrid PQC (preferred)	X-Wing KEM, ML-DSA-65, AES-256-GCM, HKDF-SHA256	0x0001
0x01xx	Pure PQC	ML-KEM-768, ML-DSA-65, AES-256-GCM, HKDF-SHA256	0x0101
0x10xx	Classic	X25519 DHKEM, Ed25519, AES-256-GCM, HKDF-SHA256	0x1001
0xF0xx	Experimental	Reserved for testing	-

- 2) **Policy Application:** Match detected capabilities against the requested policy.
- 3) **Provider Instantiation:** Create the appropriate provider instance for the detected environment and policy.
- 4) **Event Emission:** Emit a `SecurityEvent` recording the selection decision.

For `preferPQC` policy, the precedence order is `ApplePQCPprovider -> OQS_PQCPprovider -> ClassicProvider`. This order is deterministic. The `requirePQC` policy returns an `UnavailablePQCPprovider`. It throws on all operations if no PQC implementation is available.

3.7 KEM-DEM Authenticated Encryption Format

The sealed box structure encapsulates KEM-based authenticated encryption output with explicit DoS protection. Our construction follows the KEM-DEM (Key Encapsulation Mechanism + Data Encapsulation Mechanism) paradigm: `KEM.Encapsulate()` -> `HKDF-SHA256` -> `AES-256-GCM`. We call this an “HPKE-inspired KEM-DEM envelope” to distinguish it from RFC 9180 HPKE [13], which includes additional features such as multiple modes (Base, PSK, Auth, AuthPSK), context exporters, and a more complex key schedule.

We model v1 as a constrained HPKE Base-mode instance: the KEM encapsulation yields a shared secret, HKDF-Extract/Expand derives an AEAD key/nonce with domain-separated info (role, suite ID, transcript hash), and AEAD provides confidentiality and ciphertext integrity under unique nonces. This makes the security dependencies explicit and isolates deviations from RFC 9180 to the simplified header/nonce/tag framing.

On Apple 26+ platforms, CryptoKit provides native HPKE with quantum-secure cipher suites including X-Wing (ML-KEM-768 + X25519) [14]. When available, implementations SHOULD use CryptoKit’s HPKE API directly rather than this compatibility envelope.

Security Goals:

- **PQC suites:** ML-KEM provides IND-CCA2 KEM security (per FIPS 203).
- **Classic suites:** X25519 ephemeral-DH encapsulation (DHKEM-style); security relies on the X25519/Gap-DH assumption and HKDF key separation.
- **Payload encryption:** INT-CTXT and IND-CPA via AES-256-GCM in v1 (compat KEM-DEM), and RFC 9180 HPKE AEAD in v2 (e.g., ChaCha20-Poly1305 in our classic provider).

- **Key separation:** HKDF with context-specific info parameters including role binding.

Not Covered (delegated to RFC 9180 HPKE on Apple 26+):

- Sender authentication modes (Auth, AuthPSK)
- Incremental AEAD for streaming

Used in our handshake (classic v2):

- HPKE exporter for deriving the per-session shared secret with explicit context binding

Format Versions:

The implementation supports two sealed box formats:

v1 (Compatibility KEM-DEM): Used when native HPKE is unavailable. Explicit nonce and tag fields.

Header (17 bytes):

magic	version	suite	flags
4B	1B	2B	2B
encLen	nonceLen	tagLen	ctLen
2B	1B	1B	4B

Body (v1):

encapsulatedKey	nonce	ciphertext	tag
encLen	12B	ctLen	16B

v2 (Native HPKE): Used with CryptoKit HPKE. Nonce and tag are embedded in the AEAD output.

Header (17 bytes):

magic	version	suite	flags
4B	1B	2B	2B
encLen	nonceLen	tagLen	ctLen
2B	0	0	4B

Body (v2):

encapsulatedKey	ciphertext (AEAD output)
encLen	ctLen (includes auth tag)

Version Detection: Parsers distinguish v1 from v2 by checking `nonceLen` and `tagLen`:

- v1: `nonceLen = 12, tagLen = 16`
- v2: `nonceLen = 0, tagLen = 0` (AEAD details encapsulated by library)

Length limits enforce DoS protection:

- `encLen <= 4096` bytes (sufficient for ML-KEM-768’s 1088-byte ciphertext)
- v1: `nonceLen = 12 bytes, tagLen = 16 bytes` (AES-GCM fixed)
- v2: `nonceLen = 0, tagLen = 0` (embedded in ciphertext)

- ctLen <= 64KB (handshake phase, pre-authentication window)
- ctLen <= 256KB (post-authentication)

Parsing uses overflow-safe arithmetic and validates each field before allocation.

4 HANDSHAKE STATE MACHINE

4.1 Design Principles

The handshake subsystem addresses three critical requirements:

- 1) **Race Condition Prevention:** Concurrent message arrival and timeout expiration must not cause double-resume of continuations.
- 2) **Sensitive Material Protection:** Ephemeral private keys and shared secrets must be zeroized on all exit paths.
- 3) **Observability:** All state transitions and failures must emit structured events.

4.2 Actor-Isolated Architecture

The HandshakeDriver actor manages handshake state with compile-time data race prevention:

```
public actor HandshakeDriver {
    private var state: HandshakeState = .idle
    private var pendingContinuation:
        CheckedContinuation<SessionKeys, Error>?
    private var timeoutTask: Task<Void,
        Never>?
    private var pendingResult:
        Result<SessionKeys, Error>?

    public func initiateHandshake(with peer:
        PeerIdentifier)
        async throws -> SessionKeys
    public func handleMessage(_ data: Data,
        from peer: PeerIdentifier) async
    public func cancel() async
}
```

The HandshakeContext actor isolates sensitive cryptographic material:

```
public actor HandshakeContext {
    private var ephemeralPrivateKey:
        SecureBytes?
    private var transcriptHash: SecureBytes?
    private var isZeroized: Bool = false

    public func zeroize()
}
```

Reentrancy Considerations. Swift actors permit method re-entry at suspension points (`await`). While actor isolation prevents data races, it does not prevent interleaving of method executions. Our HandshakeDriver mitigates reentrancy risks through several mechanisms:

- 1) **Single convergence point.** The method `finishOnce(with:)` provides a single point for handshake completion. It guards pendingContinuation access and immediately sets the reference to `nil` after resume, preventing double-resume even if called concurrently from timeout and message handlers. This keeps completion atomic and predictable.

- 2) **Early result buffering:** The `pendingResult` property stores results that arrive before the continuation is established (e.g., if `MessageB` arrives before `withCheckedThrowingContinuation` captures the continuation).
- 3) **Timeout cancellation:** `timeoutTask` is cancelled in `finishOnce`, preventing the race between timeout expiration and successful message receipt.
- 4) **State advancement:** State transitions occur before `await` points where possible, reducing the window for interleaved operations.

Acknowledged Limitation (await window). The `handleMessageB` method awaits `cryptoProvider` operations inside the actor. If a new message arrives during this await, the actor could theoretically process it before the current operation completes. We mitigate this structurally by:

- Advancing state to `.processingMessageB` before the `await`, causing subsequent messages to be rejected or queued
- Copying all necessary immutable inputs before the `await` point
- Validating a monotonic epoch counter after the `await` returns, ensuring the actor state has not been invalidated by concurrent operations
- Emitting security events for any unexpected state transitions

This approach provides structural guarantees against reentrancy hazards rather than relying on timing assumptions. A formal analysis using model checking is planned for future work.

4.3 State Transitions

Fig. 3 illustrates the handshake state machine for both roles.

4.4 Double-Resume Prevention

The `finishOnce` method provides a single convergence point for handshake completion:

```
private func finishOnce(with result:
    Result<SessionKeys, Error>) {
    // Cancel timeout
    timeoutTask?.cancel()
    timeoutTask = nil

    // Guard against double resume
    guard let continuation =
        pendingContinuation else {
            // MessageB arrived before
            continuation established
            pendingResult = result
            return
    }
    pendingContinuation = nil // Immediately
    nil to prevent reuse

    switch result {
        case .success(let keys):
            continuation.resume(returning: keys)
        case .failure(let error):
            continuation.resume(throwing: error)
    }
}
```

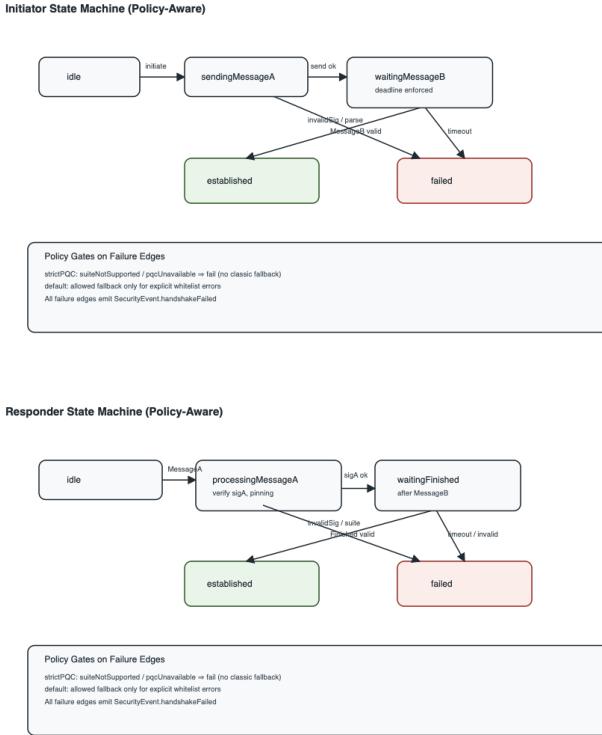


Fig. 3. Handshake state machines for Initiator (top) and Responder (bottom).

This pattern handles the race between timeout expiration and message arrival by: 1. Canceling the timeout task on any completion 2. Guarding continuation access with immediate nil assignment 3. Buffering early results in pendingResult for late continuation establishment

4.5 Secure Zeroization

Swift's standard Data and Array types use copy-on-write (COW) semantics, which can leave uncontrolled copies of sensitive material in memory. The SecureBytes class addresses this by using manual UnsafeMutableRawPointer allocation to maintain exclusive ownership of the memory region, preventing COW-induced secret proliferation.

```

public final class SecureBytes: @unchecked
    Sendable {
    private let pointer:
    UnsafeMutableRawPointer
    private let count: Int

    /// Injectable wiping function for test
    verification
    nonisolated(unsafe) public static var
    wipingFunction:
        (UnsafeMutableRawPointer, Int) -> Void
    = secureZero

    deinit {
        if count > 0 {
            Self.wipingFunction(pointer,
        count)
    }
}
    
```

```

    }
    pointer.deallocate()
}
}
    
```

Design Rationale:

- 1) **Avoiding Copy-on-Write:** The primary motivation for SecureBytes is to prevent COW semantics from creating untracked copies of ephemeral keys and shared secrets. All sensitive material in HandshakeContext uses SecureBytes rather than Data.
- 2) **Explicit Zeroization on Failure Paths:** Because Swift's ARC does not guarantee deinit timing, all failure paths in HandshakeDriver explicitly call context.zeroize() before error propagation. The deinit zeroization serves as a defense-in-depth fallback, not the primary mechanism.
- 3) **Compiler Optimization Resistance:** On Darwin platforms, zeroization uses platform-supported secure wipe primitives where available, or memset followed by withExtendedLifetime as a fallback. We aim for best-effort zeroization; complete guarantees depend on compiler/runtime semantics and are not formally provable in Swift today.
- 4) **Test Verification:** The wipingFunction is a static property that can be replaced during testing. This enables verification that zeroization paths are exercised on all failure modes, as demonstrated in the security-centric evaluation (Section 7).

4.6 Transcript Binding and Signature Separation

The protocol uses domain-separated signatures to prevent cross-message and cross-session replay attacks.

Signature A (MessageA) is computed by the Initiator over the MessageA-local fields, binding suite preference, policy intent, and identity context before any responder data is received:

```

// preimageA: fields known to Initiator at
// → MessageA time
let preimageA = Data()
+ DS("SkyBridge-A")
// Domain separator
+ version.encoded
+ supportedSuites.canonicalEncode()
// Preference order preserved
+ keyShares.canonicalEncode()
// Bound to supportedSuites order
+ clientNonce
// 32 bytes
+ capabilities.canonicalEncode()
+ policy.canonicalEncode()
+ identityPubKey_I

sigA = Sign(preimageA, identityPrivKey_I)

// Optional Secure Enclave binding (prevents
// → SE proof replay)
seSigA = SE_Sign(DS("SkyBridge-SE-A") ||
→ SHA256(preimageA))
    
```

Signature B (MessageB): The Responder signs a transcript that commits to MessageA:

```

// transcriptA: hash of MessageA (excluding
// → sigA and seSigA)
    
```

```

let transcriptA =
→ SHA256(MessageA_without_signatures)

let preimageB = Data()
+ DS("SkyBridge-B")
→ // Domain separator
+ transcriptA
→ // Commits to entire MessageA
+ selectedSuite.wireId.encoded
+ responderEphPubKey
+ serverNonce
→ // 32 bytes, fresh
+ SHA256(encryptedPayload)
→ // Bind payload without bloating sig
+ identityPubKey_R

sigB = Sign(preimageB, identityPrivKey_R)

// Optional Secure Enclave binding
seSigB = SE_Sign(DS("SkyBridge-SE-B") ||
→ SHA256(preimageB))

Key Derivation: Nonces, transcripts, suite binding, and
directional separation are included in the KDF, and the salt is
transcript-bound (non-empty):
let kdfInfo = Data()
+ DS("SkyBridge-KDF")
+ selectedSuite.wireId.encodedLE
+ transcriptA
+ transcriptB                                // e.g.,
→ SHA256(MessageB_without_signatures)
+ clientNonce
+ serverNonce

// Transcript-bound salt (prevents
→ cross-context reuse)
let salt = SHA256(DS("SkyBridge-KDF-Salt-v1|"))
→ || kdfInfo

// Direction-based symmetric key derivation
// Both sides derive the same key for each
→ direction:
// - initiator_to_responder: Initiator's
→ sendKey = Responder's receiveKey
// - responder_to_initiator: Responder's
→ sendKey = Initiator's receiveKey
let i2rInfo = kdfInfo +
→ DS("handshake|initiator_to_responder")
let r2iInfo = kdfInfo +
→ DS("handshake|responder_to_initiator")

// For Initiator: sendKey = I2R, receiveKey =
→ R2I
// For Responder: sendKey = R2I, receiveKey =
→ I2R
let sendKey = HKDF<SHA256>.deriveKey(
  inputKeyMaterial: sharedSecret,
  salt: salt,
  info: role == .initiator ? i2rInfo :
→ r2iInfo,
  outputByteCount: 32
)

let receiveKey = HKDF<SHA256>.deriveKey(
  inputKeyMaterial: sharedSecret,
  salt: salt,
  info: role == .initiator ? r2iInfo :
→ i2rInfo,
  outputByteCount: 32
)

```

This structure ensures: (1) sigB commits to MessageA,

so any tampering breaks verification; (2) domain separators prevent cross-protocol attacks; (3) SE signatures are session-bound and non-replayable.

5 SECURITY MODEL AND GUARANTEES

5.1 Security Model

We assume an active network adversary with full control of the discovery channel (drop, delay, reorder, duplicate, modify, and inject messages) but without breaking standard cryptographic assumptions. The attacker can replay prior handshakes and attempt downgrade by suppressing PQC-related fields. We assume the out-of-band pairing ceremony is trusted and that device key storage (Keychain/Secure Enclave) preserves key integrity. The attacker may compromise a peer after pairing, but cannot retroactively forge signatures for past sessions.

Assumptions:

- The pairing ceremony delivers the correct peer identity key (PIN or visual verification is not bypassed).
- Pinned identity keys stored in Keychain/Secure Enclave retain integrity across normal device operation.
- Devices remain uncompromised (no root or malware control) during handshake execution.

If assumptions fail:

- If pairing is subverted and the pinned identity key is replaced, peer authentication is no longer meaningful; the system must require re-pairing and treat the session as untrusted.
- If device integrity is lost, confidentiality and key secrecy cannot be guaranteed; the system should abort and emit high-severity events such as identity Mismatch or handshakeFailed.

5.2 Security Goals and Proof Sketches

We state the core properties as invariants and provide non-formal proof sketches tied to protocol mechanics:

Property G1 (Negotiation Integrity): The selected suite must be among the Initiator's offered suites and have a corresponding key share.

Proof sketch:

- MessageB includes selectedSuite, and sigB covers MessageA.
- Any modification to supportedSuites[] or keyShares[] breaks sigB verification.
- The Responder validates selectedSuite in supportedSuites[] and checks that keyShares[] contains a matching entry.

Property G2 (Mutual Authentication for Paired Peers): For previously paired devices, the peer identity is authenticated and bound to the handshake transcript.

Proof sketch:

- identityPubKey is pinned during OOB pairing.
- MessageA/MessageB signatures over transcript data must verify under the pinned key; otherwise identityMismatch aborts the handshake.

Property G3 (Session Key Secrecy): The derived session keys remain secret under standard KEM/DH and signature security assumptions.

Proof sketch:

- The shared secret is derived from KEM decapsulation or DH, and keys are extracted via HKDF with transcript-bound salt.
- An attacker without the private key material cannot compute the shared secret or derive session keys.

Property G4 (Replay Resistance): Replayed handshakes do not establish a session.

Proof sketch: handshakeId derives from fresh nonces and suite identifiers; replay detection caches recent IDs and rejects duplicates within the window.

Property G5 (Downgrade Resistance under strictPQC): No fallback to classic is allowed under strict policy.

Proof sketch: TwoAttemptHandshakeManager enforces a policy gate before any fallback attempt; strictPQC forbids all fallback edges regardless of error type. This is validated by policy downgrade benchmarks (Fig. 4).

Property G6 (Safe Fallback under default policy): Fallback can only occur for a whitelisted set of benign errors, and never due to timeout.

Proof sketch: A whitelist/blacklist of error causes controls fallback; timeout is explicitly blocked and per-peer cooldown limits repeated downgrades.

Property G7 (Legacy Acceptance Preconditions): Legacy P-256 signatures are accepted only under authenticated pairing or an existing trust record.

Proof sketch: Legacy acceptance is gated by LegacyTrustP recondition; pure network stranger connections fail. This is validated by the precondition test matrix (Table 10).

Property G8 (Auditability): Cryptographic downgrades and exceptional states are observable.

Proof sketch: The handshake emits handshakeFallback/ cryptoDowngrade events with reason, deviceId, and cooldown context, enabling post-hoc verification of policy adherence.

6 IMPLEMENTATION

6.1 Platform Support Matrix

Fallback semantics: Provider selection is deterministic:

- ApplePQCP provider on macOS/iOS 26+ (CryptoKit ML-KEM/ML-DSA, Secure Enclave backed when available)
- QQSPQCP provider on macOS 14–15 (liboqs ML-KEM-768/ML-DSA-65)
- ClassicProvider (X25519/Ed25519) when PQC is unavailable

Secure Enclave P-256 ECDSA proof-of-possession is optional and orthogonal to the PQC suite.

Note: Apple unified macOS and iOS version numbers starting with version 26 (announced WWDC 2025). macOS 16–25 and iOS 19–25 were never released.

¹ ML-KEM-1024 and ML-DSA-87 are available in CryptoKit on Apple 26+ but not currently used by our implementation. X-Wing hybrid KEM (wireId 0x0001) is reserved for future use. Secure Enclave-backed PQC keys are only

available on Apple 26+; earlier versions fall back to software PQC and P-256 Secure Enclave PoP.

6.2 Apple PQC Integration

The ApplePQCCryptoProvider wraps CryptoKit’s ML-KEM and ML-DSA APIs with a KEM-based authenticated encryption construction:

```
#if HAS_APPLE_PQC_SDK
@available(macOS 26.0, *)
public struct ApplePQCCryptoProvider: CryptoProvider, Sendable {
    public func kemDemSeal(...) async throws
    -> KemDemSealedBox {
        // KEM encapsulation
        let publicKey = try
            MLKEM768.PublicKey(rawRepresentation:
                recipientPublicKey)
        let encapsulationResult = try
            publicKey.encrypt()
        // Key derivation (HKDF-SHA256)
        let salt =
            SHA256(DS("SkyBridge-KDF-Salt-v1")) ||
            info)
        let derivedKey =
            HKDF<SHA256>.deriveKey(
                inputKeyMaterial:
                    encapsulationResult.sharedSecret,
                salt: salt, info: info,
                outputByteCount: 32
            )
        // Authenticated encryption
        (AES-256-GCM)
        let sealedBox = try
            AES.GCM.seal(plaintext, using: derivedKey)
        return KemDemSealedBox(
            encapsulatedKey:
                encapsulationResult.encapsulated,
            nonce: Data(sealedBox.nonce),
            ciphertext: sealedBox.ciphertext,
            tag: sealedBox.tag
        )
    }
}
#endif
```

This construction (KEM -> HKDF -> AEAD) is inspired by HPKE [13] but does not implement the full RFC 9180 specification. On Apple 26+ platforms, CryptoKit exposes HPKE cipher suites including X-Wing (ML-KEM-768 with X25519), enabling a standards-aligned replacement for our compatibility envelope [14]. This layer can then be replaced with direct CryptoKit PQ-HPKE calls.

6.3 Conditional Compilation Strategy

The HAS_APPLE_PQC_SDK flag gates all PQC type references. Importantly, @available only controls *runtime* availability; it does not prevent *compile-time* failures when the SDK lacks the PQC symbols.

For reproducible builds across toolchains, we intentionally **do not** enable HAS_APPLE_PQC_SDK by default in SwiftPM (because .when(platforms: [.macOS]) does not reflect SDK availability and will break older Xcode builds). Instead, projects inject the flag from build settings **only** when compiling with the Apple 26 SDK (Xcode 26+):

TABLE 5
Security Contract (Properties, Enforcement, Evidence).

Property	Enforced at	Evidence
G1 Negotiation integrity	Suite/keyshare validation + transcript-bound <code>sigB</code>	Fig. 1, Table 13, HandshakeDriverTests
G2 Mutual authentication	Identity pinning + signature verification	Table 7 (wrong signature), Table 10
G3 Session key secrecy	KEM/DH + HKDF with transcript-bound salt	Property 1, Table 8
G4 Replay resistance	handshake ID cache + nonce binding	Property-Oriented Testing (Section 7)
G5 strictPQC no-downgrade	Policy gate in TwoAttemptHandshakeManager	Fig. 4, PolicyDowngradeBenchTests
G6 Default safe fallback	Whitelist/blacklist + cooldown	Fig. 5, Table 7
G7 Legacy acceptance precondition	LegacyTrustPrecondition	Table 10
G8 Auditability	Security event emission	Fig. 6, Table 11

TABLE 6
Platform support matrix.

Platform	PQC Provider	Algorithms	Notes
macOS 26+	ApplePQCPProvider	ML-KEM-768, ML-KEM-1024 ¹ , ML-DSA-65, ML-DSA-87 ¹	Native CryptoKit
macOS 14–15	OQSPQCPProvider	ML-KEM-768, ML-DSA-65	liboqs fallback
macOS 14–15	ClassicProvider	X25519, Ed25519	If liboqs unavailable
iOS 26+	ApplePQCPProvider	ML-KEM-768, ML-KEM-1024 ¹ , ML-DSA-65, ML-DSA-87 ¹	Native CryptoKit
iOS 17–18	ClassicProvider	X25519, Ed25519	liboqs not bundled

```
OTHER_SWIFT_FLAGS = \$(inherited)
→ -DHAS_APPLE_PQC_SDK
```

This keeps the codebase buildable on older Xcode versions (classic provider path), while enabling native CryptoKit PQC providers only when the correct SDK is present.

6.4 Security Event Emission

All cryptographic decisions emit structured events:

```
SecurityEventEmitter.emitDetached()
→ SecurityEvent(
  type: .cryptoProviderSelected,
  severity: fallbackFromPreferred ? .warning
→ : .info,
  message: "Crypto provider selected:
→ \(provider.providerName)",
  context: [
    "selectedTier": selectedTier.rawValue,
    "fallbackFromPreferred":
→ String(fallbackFromPreferred),
    "suite":
→ provider.activeSuite.rawValue,
    "osVersion": capability.osVersion
  ]
))
```

The `SecurityEventEmitter` actor implements back-pressure with per-subscriber queues and meta-event rate limiting to prevent recursive overflow.

6.5 Secure Enclave Integration

For hardware-backed signing, the `SigningCallback` protocol enables Secure Enclave integration:

```
public protocol SigningCallback: Sendable {
  func sign(data: Data) async throws -> Data
}

@available(macOS 26.0, iOS 26.0, *)
public struct SecureEnclaveSigningCallback:
→ SigningCallback {
  public func sign(data: Data) async throws
→ -> Data {
```

```
let query: [String: Any] = [
  kSecClass as String: kSecClassKey,
  kSecAttrApplicationTag as String:
→ keyTag,
  kSecAttrKeyType as String:
→ kSecAttrKeyTypeECSECP256R1,
  kSecReturnRef as String: true
]
// ... SecKey operations
}
```

The `HandshakeDriver` prioritizes callback-based signing over raw key material, ensuring private keys never leave the Secure Enclave.

Availability and fallback. Secure Enclave-backed ML-DSA/ML-KEM keys are only available on macOS 26+ via CryptoKit. On macOS 14–15, PQC operations fall back to liboqs (software), and Secure Enclave is used only for P-256 ECDSA proof-of-possession keys. When Secure Enclave PQC is used, the implementation relies on CryptoKit key types `SecureEnclave.MLDsa*` and `SecureEnclave.MLKE*`, which are gated by the macOS 26+ SDK and runtime availability checks.

6.6 Signing Key Hierarchy

The system supports two complementary signing mechanisms:

- 1) **CryptoProvider signing (Protocol Signature):** Uses the active suite's signature algorithm (Ed25519 for classic, ML-DSA-65 for PQC) for protocol-level identity verification. Keys are managed by the `CryptoProvider` and stored in software. This is the primary signature used in `sigA`/`sigB` fields of handshake messages.
- 2) **Secure Enclave signing (Device PoP):** Uses EC P-256 with ECDSA via `SecureEnclaveSigningCallback` to prove the

peer controls a key stored in Secure Enclave. Private keys never leave the Secure Enclave hardware. Note: This provides proof-of-possession of a hardware-backed key, not full device attestation (Apple does not expose a general-purpose attestation API with certificate chains at the application layer). The security value derives from the key being pinned during initial pairing.

Implementation Note. The DeviceIdentityKeyManager creates P-256 keys in Secure Enclave (when available) for hardware-backed device identity. These keys are used for the optional seSigA/seSigB proof-of-possession signatures, NOT for the primary protocol signatures (sigA/sigB). The primary protocol signatures use Ed25519 (classic) or ML-DSA-65 (PQC) keys generated by the CryptoProvider.

The FallbackSigningCallback provides automatic fallback from Secure Enclave to CryptoProvider when hardware signing is unavailable (e.g., on devices without Secure Enclave or when the key has not been provisioned).

Use Case Separation:

- CryptoProvider (Ed25519/ML-DSA): Primary protocol signatures, cross-platform interoperability, suite-negotiated
- Secure Enclave (P-256 ECDSA): Optional hardware-backed proof-of-possession, proving control of a non-exportable key

Both mechanisms can coexist in a single handshake: CryptoProvider for primary protocol signatures (sigA/sigB), Secure Enclave for optional hardware-backed proof-of-possession (seSigA/seSigB).

Signature Verification Rules:

- 1) sigA (Ed25519 or ML-DSA per suite) is mandatory in MessageA and must verify against identityPubKey_I.
- 2) sigB (Ed25519 or ML-DSA per suite) is mandatory in MessageB and must verify against identityPubKey_R; additionally, sigB commits to transcriptA, so Initiator implicitly verifies MessageA was received unmodified.
- 3) For paired peers: identityPubKey MUST match the pinned key from initial pairing; mismatch triggers identityMismatch rejection.
- 4) seSigA/seSigB (P-256 ECDSA from Secure Enclave) are optional; if present and valid, the peer's trust level is elevated. These signatures are domain-separated and session-bound, preventing replay across sessions.
- 5) Verification order: sigA/sigB first, then identity pinning check, then optional SE signature.
- 6) Failure semantics: missing SE signature is acceptable (devices without Secure Enclave); invalid SE signature triggers secureEnclaveSignatureInvalid but may still allow connection at reduced trust level per policy.

6.7 Pre-Negotiation Signature Algorithm Selection and Two-Attempt Strategy

A fundamental challenge in our protocol is the “chicken-and-egg” problem: sigA must be generated *before* suite

negotiation completes, yet the signature algorithm should be consistent with the negotiated suite. We resolve this through **pre-negotiation signature selection** and a **two-attempt strategy**.

Pre-Negotiation Signature Selection:

The signature algorithm for sigA is determined by the offeredSuites in MessageA, not by the final selected Suite:

```
public static func
→ selectForMessageA(offeredSuites:
→ [CryptoSuite]) -> ProtocolSigningAlgorithm
→ {
  let hasPQCOrHybrid =
→ offeredSuites.contains { \$.isPQCGroup }
  return hasPQCOrHybrid ? .mlDSA65 :
→ .ed25519
}
```

Homogeneity Invariant: Each attempt's offeredSuites must be *homogeneous* with respect to sigAAAlgorithm:

- If sigAAAlgorithm is ML-DSA-65, ALL suites in offeredSuites must have isPQCGroup==true.
- If sigAAAlgorithm is Ed25519, ALL suites in offeredSuites must have isPQCGroup==false.

This invariant is enforced at compile-time through the type system (ProtocolSigningAlgorithm excludes P-256) and at runtime through HandshakeDriver initialization validation.

Two-Attempt Strategy:

To support interoperability between PQC-capable and classic-only devices while maintaining the homogeneity invariant, we employ a two-attempt strategy:

- 1) **PQC Attempt (preferPQC=true):** First attempt with offeredSuites containing only PQC/Hybrid suites and sigAAAlgorithm = ML-DSA-65
- 2) **Classic Fallback:** If PQC attempt fails due to provider unavailability or suite negotiation failure, fall back to classic-only offeredSuites with sigAAAlgorithm = Ed25519

```
public static func prepareAttempt(
  strategy: HandshakeAttemptStrategy,
  cryptoProvider: any CryptoProvider
) throws -> AttemptPreparation {
  // 1. Build homogeneous offeredSuites from
  // provider's supported suites
  let buildResult =
  HandshakeOfferedSuites.build(strategy:
  strategy, cryptoProvider: cryptoProvider)

  // 2. Select signature algorithm based on
  // suites
  let sigAAAlgorithm =
  PreNegotiationSignatureSelector.]
  selectForMessageAResult(offeredSuites:
  suites)

  // 3. Get matching signature provider
  let signatureProvider =
  PreNegotiationSignatureSelector.]
  selectProvider(for: sigAAAlgorithm)

  return AttemptPreparation(strategy,
  suites, sigAAAlgorithm, signatureProvider)
}
```

Fallback Security:

Not all failures trigger fallback. The system maintains a whitelist of safe fallback reasons and a blacklist of security-critical failures:

- **Allowed:**
 - pqcProviderUnavailable
 - suiteNotSupported
 - suiteNegotiationFailed
- **Blocked:**
 - timeout
 - suiteSignatureMismatch
 - signatureVerificationFailed
 - identityMismatch
 - replayDetected

Timeout-based fallback is explicitly blocked to prevent attackers from forcing downgrade through packet dropping. Per-peer fallback is rate-limited (5-minute cooldown) to prevent rapid downgrade cycling.

Security Events:

Every fallback emits a handshakeFallback event with full context (reason, deviceId, cooldown), enabling audit and anomaly detection.

7 EVALUATION

7.1 Experimental Setup

We evaluate SkyBridge Compass along two primary tracks: **security-centric evidence** (fault injection, downgrade suppression, legacy precondition enforcement, and auditability) and **cost-centric evidence** (handshake latency, wire overhead, provider selection overhead, and data-plane throughput). All experiments are run on Apple Silicon (ARM64) on macOS 26.x, where CryptoKit PQC is available when the SDK exposes ML-KEM/ML-DSA types.

Test Environment:

- Apple Silicon Macs (M1/M3 class), macOS 26.x (CryptoKit PQC when available; liboqs PQC via library backend)

Build Configuration: Release (-O) with non-essential logging disabled. Timing uses a monotonic clock (`ContinuousClock`) and records warmup iterations discarded, then a fixed number of measured iterations. Reported percentiles are computed directly from samples for benchmarking consistency.

Reproducibility: We ship an opt-in benchmark test suite under `Tests/SkyBridgeCoreTests/`. For a one-shot run, use `Scripts/run_paper_eval.sh`. The following commands reproduce the paper's tables:

- **Handshake Latency (Table 17):**
`SKYBRIDGE_RUN_BENCH=1`
`swift test --filter`
`HandshakeBenchmarkTests`
- **Handshake RTT (Table 18):**
`SKYBRIDGE_RUN_BENCH=1`
`swift test --filter`
`HandshakeBenchmarkTests`
- **Handshake Message Sizes (Table 19):**

- **HandshakeBenchmarkTests**
`SKYBRIDGE_RUN_BENCH=1`
`swift test --filter`
`HandshakeBenchmarkTests`
- **Data-Plane Throughput (Table 20):**
`SKYBRIDGE_RUN_BENCH=1`
`swift test --filter`
`testBench_`
`DataPlaneThroughputAndCPUProxy`
- **Provider Selection (Table 21):**
`SKYBRIDGE_RUN_BENCH=1`
`swift test --filter`
`testBench_`
`ProviderSelectionOverhead`
- **Fault Injection (Table 7):**
`SKYBRIDGE_RUN_FI=1`
`swift test --filter`
`HandshakeFaultInjectionBenchTests`
- **Message Size Breakdown (Fig. 9):**
`SKYBRIDGE_RUN_FI=1`
`swift test --filter`
`MessageSizeSnapshotTests`
- **Policy Downgrade Bench (Fig. 4):**
`SKYBRIDGE_RUN_POLICY_BENCH=1`
`swift test --filter`
`PolicyDowngradeBenchTests`
- **Migration Coverage Bench (Table 10 coverage):**
`SKYBRIDGE_RUN_MIGRATION_BENCH=1`
`swift test --filter`
`MigrationCoverageBenchTests`
- **Downgrade Matrix (Fig. 5):** derived from `TwoAttemptHandshakeManager.shouldAllowFallback` whitelist/blacklist
- **Failure Histogram (Fig. 6):**
`SKYBRIDGE_RUN_FI=1`
`swift test --filter`
`HandshakeFaultInjectionBenchTests`
`SKYBRIDGE_RUN_POLICY_BENCH=1`
`swift test --filter`
`PolicyDowngradeBenchTests`
`Scripts/plot_failure_histogram.py`
- **Audit-Signal Fidelity (Fig. 7 / Table 11):**
`Scripts/derive_audit_signal_fidelity.py`
Inputs: `fault_injection_<date>.csv`
`policy_downgrade_<date>.csv`
Output: `audit_signal_fidelity_<date>.csv`

Results are written to `Artifacts/` as CSV files:

- `handshake_bench_<date>.csv`
- `handshake_rtt_<date>.csv`
- `handshake_wire_<date>.csv`
- `message_sizes_<date>.csv`
- `fault_injection_<date>.csv`
- `policy_downgrade_<date>.csv`
- `migration_coverage_<date>.csv`

Environment Note: CryptoKit PQC rows require macOS 26+ and an SDK that exposes MLKEM768/MLDSA65. The script auto-detects and injects `-DHAS_APPLE_PQC_SDK` when available.

7.2 Security-Centric Evaluation

7.2.1 Failure-Mode Robustness

This experiment validates that the actor-isolated handshake driver provides deterministic failure semantics without

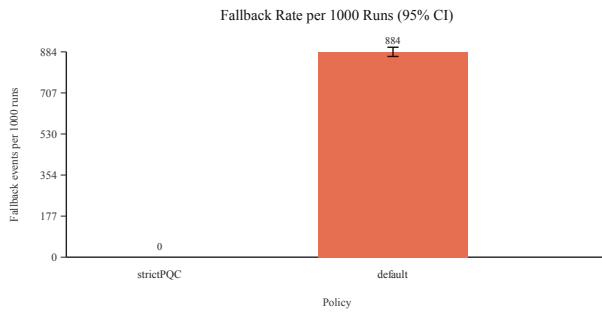


Fig. 4. Policy guard enforces strictPQC: fallback events per 1000 runs (95% CI), macOS 26.x, N=1000 per policy.

unhandled errors, double-resume, or sensitive-material leaks. Each fault-injection scenario is executed under both default and strictPQC policies (n=1000 per policy).

Workloads:

- Timeout (no MessageB delivered)
- Malformed message framing and truncated fields
- Invalid signature on MessageA or MessageB
- Out-of-order delivery and duplicate messages

Metrics:

- NoUnexpectedError: 1 if all injected runs complete without unexpected errors in the harness (`n_unexpected_error = 0`)
- NoDoubleResume: 1 if `finishOnce` never resumes the continuation twice (validated by unit tests)
- ZeroizationVerified: 1 if unit tests covering timeout/cancel/transport failure pass
- `E_handshakeFailed`: count of emitted Security Event Type `.handshakeFailed`
- `E_cryptoDowngrade`: count of emitted Security Event Type `.cryptoDowngrade`

The delay-within-timeout and delay-exceed-timeout scenarios approximate RTT jitter and loss-induced stalls, while drop and duplicate cases approximate packet loss and reordering. The per-scenario event distributions are recorded in `Artifacts/fault_injection_<date>.csv`.

Downgrade events are quantified separately in the policy bench (Fig. 4) to avoid conflating fallback behavior with transport corruption scenarios.

Fig. 4 is generated from `policy_downgrade_<date>.csv`. It demonstrates that strictPQC never emits fallback events even under forced PQC-unavailable errors; default policy shows non-zero downgrade events.

Fig. 5 encodes the explicit downgrade whitelist/blacklist: only PQC-unavailability and suite-selection errors may fallback under default policy; strictPQC denies all fallback edges.

Fig. 6 combines fault-injection counts with the downgrade-acceptance event from the policy bench to visualize observability of failures and downgrades across policy modes.

7.2.2 Property-Oriented Testing

Correctness properties are validated with property-based tests that sweep parameter matrices (multiple timeout configurations, malformed framing variants, replay/downgrade

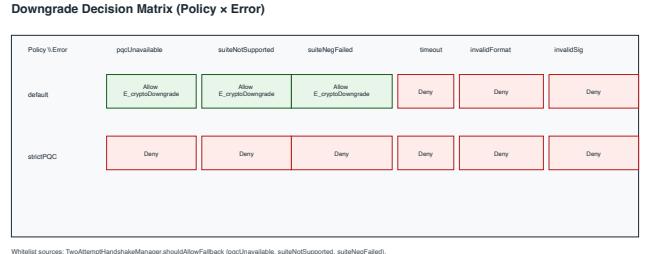


Fig. 5. Downgrade decision matrix (policy x error) with explicit allow/deny semantics, macOS 26.x.

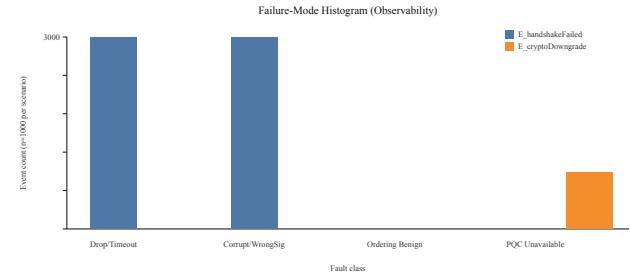


Fig. 6. Failure-mode histogram of security events, macOS 26.x, N=1000 per scenario.

scenarios) and repeat trials for timing-sensitive behavior. Where randomized vectors are used (e.g., KEM-DEM round-trip), the tests fix a reproducible seed and report the number of trials executed.

Property 1 (Round-Trip): For any valid plaintext and key pair, `kemDemOpen(kemDemSeal(plaintext)) == plaintext`. Validated across all three provider implementations with 100 random plaintexts (seed: 0xDEADBEEF).

Property 2 (Signature Verification): For any data and key pair, the signature verifies under the corresponding public key, i.e., `verify(data, sign(data, privateKey), publicKey) == true`. Validated with 100 random payloads per provider.

Property 3 (Zeroization): For any `SecureBytes` instance, deallocation triggers the `wiping` function. Validated via injectable `wipingFunction` that increments a counter; test asserts counter equals allocation count.

Property 4 (State Machine): No sequence of valid inputs causes double-resume of a continuation. Validated via concurrent cancellation/timeout/message-arrival stress tests (500 iterations).

7.2.3 Wire-Format Portability Check

To provide a minimal, non-Swift interoperability check, we include a standalone Python decoder (`Scripts/wire_format_sanity.py`) that parses MessageA/MessageB wire encodings, validates length fields, and extracts transcript bytes without depending on Swift runtime types. This tool accepts hex-encoded captures and ensures that transcript binding and field boundaries are unambiguous outside the Swift implementation.

TABLE 7

Failure-Mode Robustness and Observability. Runs = number of iterations per scenario and policy (n=1000). Table reports default policy; strictPQC counts are recorded separately in `fault_injection_<date>.csv`. All metrics are binary (1 = pass) except event counts. Data from `Artifacts/fault_injection_<date>.csv` produced by `HandshakeFaultInjectionBenchTests`; semantic checks from `HandshakeDriverTests`.

Failure Mode	Runs	No Unexp. Error	No Double Resume	Zero Verified	$(E_{\{handshakeFailed\}})$	$(E_{\{cryptoDowngrade\}})$
Out-of-order	1000	1	1	1	0	0
Duplicate	1000	1	1	1	0	0
Drop	1000	1	1	1	1000	0
Delay within timeout	1000	1	1	1	0	0
Delay exceed timeout	1000	1	1	1	1000	0
Corrupt header	1000	1	1	1	1000	0
Corrupt payload	1000	1	1	1	1000	0
Wrong signature	1000	1	1	1	1000	0
Concurrent cancel	1000	1	1	1	1000	0
Concurrent timeout	1000	1	1	1	1000	0

7.2.4 ML-DSA Key Lifecycle Validation

This experiment validates the ML-DSA-65 key generation, storage, and sign-verify round-trip correctness as implemented in `DeviceIdentityKeyManager`.

Property 5 (ML-DSA Sign-Verify Round Trip): For any message (m) and ML-DSA-65 key pair $((pk, sk))$, $\text{verify}(m, \text{sign}(m, sk), pk) == \text{true}$. Validated with 100 random messages of varying lengths (1–10,000 bytes) per trial.

Property 6 (ML-DSA Signature Integrity): Modifying any byte of the message or signature causes verification to fail. Validated with 50 random modifications each for message tampering and signature tampering.

Property 7 (ML-DSA Key Independence): ML-DSA-65 keys are independent from Ed25519 keys; using the wrong public key for verification always fails. Validated with 50 cross-key verification attempts.

DeviceIdentityKeyManager Integration:

The `DeviceIdentityKeyManager` provides a unified API for protocol signing keys:

```
// Get ML-DSA-65 signing key handle
let keyHandle = try await
  manager.getProtocolSigningKeyHandle(for:
  .mLDSA65)

// Get ML-DSA-65 public key for peer
// verification
let publicKey = try await
  manager.getProtocolSigningPublicKey(for:
  .mLDSA65)
```

Key storage uses Keychain with security attributes:

- `kSecAttrAccessibleAfterFirstUnlockThisDeviceOnly`: Keys accessible after first unlock
- `kSecAttrSynchronizable=false`: Keys do not sync to iCloud Keychain

This ensures ML-DSA keys remain device-local and are protected by the device passcode.

7.2.5 Legacy Fallback Security Precondition Validation

This experiment validates the security preconditions for legacy P-256 signature acceptance during the migration period.

Security Model:

Legacy P-256 signatures are only accepted when one of the following preconditions is satisfied:

- 1) **Authenticated Channel:** The pairing ceremony uses an authenticated out-of-band channel (QR code, PAKE/PIN, or local pairing).
- 2) **Existing Trust Record:** A previously-established `TrustRecord` contains a `legacyP256PublicKey` field.

Pure network stranger connections (no authenticated channel, no existing trust) are rejected to prevent downgrade attacks.

Property 7 (Legacy Fallback Security Precondition): A legacy P-256 signature SHALL only be accepted when a security precondition is satisfied. Pure network stranger connections SHALL be rejected. Validated with 12 test cases covering all precondition combinations.

Coverage Statement: We define the migration state space as the Cartesian product of:

- `authenticatedChannel` in {verified, unverified, none}
- `trustRecord` in {none, withLegacyKey, withoutLegacyKey}
- `discovery` in {network-only, OOB}

The 12 scenarios in Table 10 cover all boundary combinations and security-relevant buckets, yielding 100% coverage of the defined precondition space. The `MigrationCoverageBenchTests` harness records per-scenario outcomes in `Artifacts/migration_coverage_<date>.csv`.

Implementation Components:

- **LegacyTrustPrecondition:** Encapsulates precondition type and satisfaction status

TABLE 8
ML-DSA-65 Key Sizes (FIPS 204 Compliance).

Component	Expected (FIPS 204)	Measured	Status
Public Key	1952 bytes	1952 bytes	OK
Secret Key	4032 bytes	4032 bytes	OK
Signature	3309 bytes	3309 bytes	OK

TABLE 9
ML-DSA-65 Property Test Results. All tests executed via DevicelidentityKeyManagerMLDSATests. N = number of iterations per property.

Property	N	Pass Rate	Notes
Sign-Verify Round Trip	100	100%	Random messages 1–10,000 bytes
Modified Message -> Fail	50	100%	Single byte XOR modification
Modified Signature -> Fail	50	100%	Single byte XOR modification
Wrong Public Key -> Fail	50	100%	Cross-keypair verification
Key Idempotency	2	100%	Multiple calls return same key
Ed25519/ML-DSA Independence	1	100%	Different algorithms, different keys

TABLE 10
Legacy Fallback Precondition Test Results. All tests executed via LegacyFallbackPreconditionTests. Tests validate Property 7: Legacy Fallback Security Precondition.

Scenario	Precondition	Expected Result	Actual Result
Pure network stranger	None	Reject	OK Reject
QR code pairing (verified)	authenticatedChannel	Allow	OK Allow
PAKE pairing (verified)	authenticatedChannel	Allow	OK Allow
Existing TrustRecord with legacy key	existingTrustRecord	Allow	OK Allow
Existing TrustRecord without legacy key	None	Reject	OK Reject
Network discovery	None	Reject	OK Reject
Unverified authenticated channel	None	Reject	OK Reject

- **LegacyTrustPreconditionChecker:** Evaluates preconditions based on TrustRecord and PairingContext
- **FirstContactVerifier:** Routes verification to legacy or modern path based on wire algorithm
- **TrustRecordUpdate:** Suggests TrustRecord updates with requiresUpgrade flag for legacy peers

Event Emission:

When legacy signatures are accepted, the system emits legacySignatureAccepted events with full context:

- preconditionType: Which precondition was satisfied
- deviceId: The peer device identifier
- channelType: The authenticated channel type (if applicable)

This enables audit logging and anomaly detection for legacy fallback patterns.

7.2.6 Audit-Signal Fidelity (Event Traces + TP/FP)

This experiment evaluates whether the emitted security events provide a deterministic, audit-grade explanation of **what happened, why it happened, and how the policy responded**. We treat the fault-injection workloads as labeled

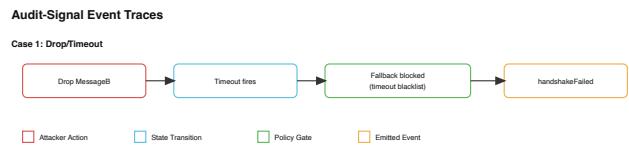


Fig. 7. Audit-signal event trace (representative timeout case) showing attacker action, policy gate, and emitted event.

scenarios and check for correct event semantics rather than classifier performance.

Event Trace Case (Fig. 7):

- **Timeout after drop (representative):** handshakeFailed is emitted. handshakeFallback is blocked due to the timeout blacklist.

Audit-Signal Fidelity (TP/FP):

We compute a TP/FP summary from the labeled fault-injection runs (Table V) and the policy downgrade bench (Fig. 4), stratified by policy. The remaining trace cases are captured in the corresponding TP/FP classes below.

This provides a compact, quantifiable view of audit signal correctness without positioning the system as a detector.

TABLE 11
Audit-Signal Fidelity Summary.

Scenario Class	Expected Signal	N	TP	FP
Drop/Timeout (default)	handshakeFailed=1, handshakeFallback=0	3000	1.00	0.00
Drop/Timeout (strictPQC)	handshakeFailed=1, handshakeFallback=0	3000	1.00	0.00
Corrupt/Wrong Sig (default)	handshakeFailed=1, handshakeFallback=0	3000	1.00	0.00
Corrupt/Wrong Sig (strictPQC)	handshakeFailed=1, handshakeFallback=0	3000	1.00	0.00
Ordering Benign (default)	handshakeFailed=0, handshakeFallback=0	3000	1.00	0.00
Ordering Benign (strictPQC)	handshakeFailed=0, handshakeFallback=0	3000	1.00	0.00
PQC unavailable (default)	handshakeFallback=1	1000	1.00	0.00
PQC unavailable (strictPQC)	handshakeFallback=0	1000	1.00	0.00

7.2.7 Transcript TLV Canonical Encoding Validation

This experiment validates the transcript integrity properties for both V1 (deterministic) and V2 (TLV canonical) encoding formats. The versioned transcript system ensures forward compatibility while maintaining cryptographic binding guarantees.

Transcript Version Design:

TLV Format Specification:

Tag	Length (4B BE)	Value (N B)
1B	UInt32	Variable

Tag ranges:

- 0x01–0x0F: Header tags (protocolVersion, role, domainSeparator, transcriptVersion)
- 0x10–0x1F: Negotiation tags (suiteWireId, capabilities, policy, signatureAlgorithm)
- 0x20–0x2F: Message tags (messageA, messageB, finished)
- 0x30–0x3F: Identity tags (initiatorPublicKey, responderPublicKey, nonces)
- 0xF0–0xFF: Extension tags (reserved)

Property 4 (Transcript Integrity): Modifying ANY field in the transcript SHALL produce a different hash. This property holds for both V1 and V2 encodings. Validated with 14 test cases covering field modifications, determinism, and version negotiation.

Why This Doesn't Break Legacy Devices:

- 1) **Version Negotiation:** Both parties advertise supported versions; the highest common version is selected
- 2) **Fail-Fast on Mismatch:** If versions don't match, handshake fails with explicit error code
- 3) **V1 Default:** Current production uses V1; V2 is opt-in for future deployments
- 4) **Transcript Binding:** Both versions bind the same semantic fields; only encoding differs

Implementation Components:

- `TranscriptVersion`: Enum with V1/V2 cases and version metadata
- `TranscriptTLVTag`: Tag definitions for all transcript fields
- `TLVEncoder/TLVDecoder`: Canonical TLV encoding/decoding
- `VersionedTranscriptBuilder`: Unified builder supporting both versions
- `TranscriptVersionNegotiator`: Version selection and compatibility checking

7.2.8 Regression Test Matrix Validation

This experiment validates the complete regression test matrix covering all protocol signature invariants. The matrix ensures that type system guarantees, fallback behavior, and event emission are correctly implemented.

Property Summary:

- **Property 1 (Type Exclusion):** P-256 CANNOT be used as a protocol signature algorithm. Enforced at compile time.
- **Property 2 (Homogeneity):** PQC attempt uses only PQC suites; Classic attempt uses only Classic suites.
- **Property 3 (Fallback Safety):** Only PQC-unavailability errors trigger fallback; security errors and timeouts do not by design.
- **Property 4 (Legacy Precondition):** Legacy P-256 requires authenticated channel or existing TrustRecord.
- **Property 5 (Event Audit):** All fallback and legacy acceptance events include full context for audit.
- 4) **Transcript Binding:** Both versions bind the same semantic fields; only encoding differs

Implementation Components:

- `TranscriptVersion`: Enum with V1/V2 cases and version metadata
- `TranscriptTLVTag`: Tag definitions for all transcript fields
- `TLVEncoder/TLVDecoder`: Canonical TLV encoding/decoding
- `VersionedTranscriptBuilder`: Unified builder supporting both versions
- `TranscriptVersionNegotiator`: Version selection and compatibility checking

7.3 Cost-Centric Evaluation

7.3.1 Handshake Latency

This experiment measures the end-to-end time to complete a full handshake including explicit key confirmation (Finished_R2I/Finished_I2R exchange). We intentionally isolate cryptographic and state-machine overhead by using an in-memory loopback transport in our harness.

Metrics:

- `T_handshake_ms`: wall-clock from `recordStart()` to verified `finished_I2R` (full handshake completion) as reported by `HandshakeMetricsCollector.handshakeDurationMs`

TABLE 12
Transcript version design.

Version	Encoding	Use Case	Compatibility
V1 (0x01)	Deterministic	Current production	Backward compatible
V2 (0x02)	TLV Canonical	Future extension	Forward compatible

TABLE 13
Transcript Integrity Property Test Results. All tests executed via TranscriptIntegrityPropertyTests. Tests validate Property 4: Transcript Integrity (TLV Canonical).

Test Case	Version	Modification	Expected	Actual
Modify MessageB	V1	Content change	Hash differs	OK Pass
Modify suiteWireId	V2	0x0101->0x1001	Hash differs	OK Pass
Same input determinism	V1/V2	None	Hash identical	OK Pass
V1 vs V2 encoding	Both	Same fields	Hash differs	OK Pass
Modify nonce	V1/V2	Byte flip	Hash differs	OK Pass
Modify public key	V1/V2	Byte flip	Hash differs	OK Pass
Modify signature algorithm	V1/V2	Ed25519->ML-DSA	Hash differs	OK Pass
Random byte modification	V1/V2	XOR 0xFF	Hash differs	OK Pass

TABLE 14
TLV Encoder/Decoder Validation.

Test Case	Expected	Actual
Round-trip encoding	All fields preserved	OK Pass
Length field big-endian	256 = 0x00000100	OK Pass
Version negotiation (both V1+V2)	Select V2	OK Pass
Version negotiation (V1 only common)	Select V1	OK Pass
No common version	Throw error	OK Pass
Version compatibility check	Strict match	OK Pass

TABLE 15
Regression Test Matrix Results. All tests executed via ProtocolSignatureRegressionTests. Tests validate Requirements 12.1-12.6.

Category	Test Case	Expected	Actual
12.1 MessageA Construction	PQC attempt uses ML-DSA-65	sigAAgorithm == .mIDSA65	OK Pass
12.1 MessageA Construction	PQC suites all isPQCGroup	All suites isPQCGroup == true	OK Pass
12.1 MessageA Construction	Classic attempt uses Ed25519	sigAAgorithm == .ed25519	OK Pass
12.1 MessageA Construction	Classic suites all ClassicGroup	All suites isPQCGroup == false	OK Pass
12.2 Type System	P-256 not in ProtocolSigningAlgorithm	Conversion returns nil	OK Pass
12.2 Type System	ClassicSignatureProvider has ed25519	algorithm == .ed25519	OK Pass
12.2 Type System	PQCSignatureProvider has mIDSA65	algorithm == .mIDSA65	OK Pass
12.3 Key Mismatch	Wrong key length throws	Error thrown	OK Pass
12.4 Timeout Fallback	Timeout does not trigger fallback	isPQCUnavailableError == false	OK Pass
12.4 Timeout Fallback	signatureVerificationFailed no fallback	isPQCUnavailableError == false	OK Pass
12.4 Timeout Fallback	pqcProviderUnavailable triggers fallback	isPQCUnavailableError == true	OK Pass
12.5 Legacy First Contact	Authenticated channel allows legacy	precondition.isSatisfied == true	OK Pass
12.5 Legacy First Contact	No auth channel rejects legacy	precondition.isSatisfied == false	OK Pass
12.6 Event Emission	handshakeFallback has context	All context fields present	OK Pass
12.6 Event Emission	legacySignatureAccepted has preconditionType	preconditionType in context	OK Pass

TABLE 16
Final Gate Validation.

Gate	Criteria	Result
Compile-Fail Harness	All 3 negative tests fail to compile	OK 3/3 Pass
P256AsProtocolSignatureProvider	P-256 cannot conform to ProtocolSignatureProvider	OK Compile Error
CryptoProviderAsSignatureParam	CryptoProvider cannot be passed as signature param	OK Compile Error
LegacyVerifierHasNoSign	LegacySignatureVerifier has no sign method	OK Compile Error
Regression Matrix	All 15 regression tests pass	OK 15/15 Pass

- B_total: total bytes transferred for MessageA + MessageB + Finished_R2I + Finished_I2R.

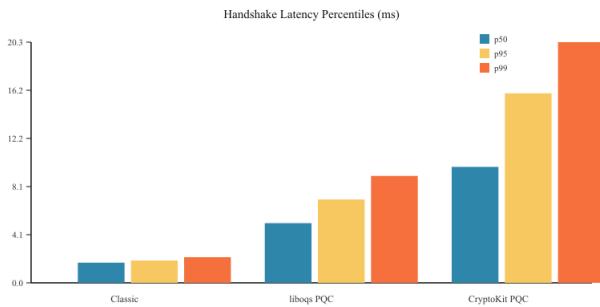


Fig. 8. Handshake latency percentiles for Classic vs liboqs PQC vs CryptoKit PQC (N=1000).

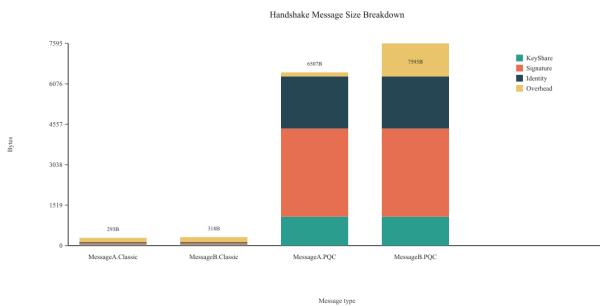


Fig. 9. Wire-format size breakdown (signature, keyshare, identity fields, framing overhead) for MessageA/MessageB.

Computed from serialized lengths observed on the transport.

- B_msgA, B_msgB, B_finished: per-message byte totals from serialized on-wire encoding

Each configuration reports (p50/p95/p99) over (N=1000) iterations after 10 warmup runs.

Note: X-Wing is a hybrid suite. The current benchmark harness covers only pqcOnly/classicOnly paths. The hybrid path will be measured after integration into HandshakeBenchmarkTests, so the main table omits the projected row. In Table 19, CryptoKit PQC and liboqs PQC sizes are very close; differences come from provider metadata and encoding details. The X-Wing projection appears in Appendix C.

The size breakdown is generated from `message_sizes_<date>.csv`, emitted by `MessageSizeSnapshotTests` using deterministic snapshot messages (minimal capability set). Totals can be slightly smaller than the end-to-end wire sizes in Table 19.

We additionally report a breakdown by dominant cost contributors, including KEM encapsulation/decapsulation, signature sign/verify, and serialization, using instrumented timing around provider calls in the benchmark harness.

7.3.2 Data-Plane Throughput and CPU Proxy

Handshake cost is not the only performance concern for remote desktop and file transfer. This experiment measures cryptographic throughput and a CPU proxy for the data plane.

Workloads:

- Symmetric AEAD encryption/decryption using session keys derived by the handshake (`SessionKeys.sendKey` / `SessionKeys.receiveKey`)
- Payload sizes: 1 KiB, 16 KiB, 64 KiB, 1 MiB

Metrics:

- `Throughput_MBps`: bytes processed / elapsed time for encrypt+decrypt
- `CPU_proxy_ns_per_byte`: elapsed ns / bytes processed in a fixed performance mode

7.3.3 Provider Selection Overhead

This experiment isolates the overhead of capability detection and provider instantiation. It distinguishes cold-start behavior (first call, caches empty) from steady-state behavior (hot path, cached result).

Metrics:

- `T_select_cold_us`: elapsed time for `CryptoProviderSelector.shared.bestAvailableProvider` on first call after `clearCache()`
- `T_select_hot_us`: elapsed time for subsequent calls with warm caches

8 LIMITATIONS AND FUTURE WORK

8.1 Current Limitations

- 1) **iOS liboqs Bundling:** The current implementation does not bundle liboqs for iOS, limiting PQC availability to iOS 26+ devices.
- 2) **X-Wing Hybrid KEM:** We have reserved wire-format identifiers for X-Wing hybrid KEM (wireId 0x0001, combining X25519 + ML-KEM-768). CryptoKit on Apple 26+ exposes HPKE cipher suites including X-Wing (ML-KEM-768 with X25519), enabling a standards-aligned replacement for our compatibility envelope [14]. Our current implementation uses pure ML-KEM-768 (wireId 0x0101); the X-Wing provider mapping is planned for a future release once we complete integration testing with CryptoKit's PQ-HPKE API.
- 3) **Key Rotation:** Session key rotation during long-lived connections is not addressed in the current design.
- 4) **Cross-Platform Interoperability:** The wire format is documented but interoperability with non-Apple platforms requires additional validation.

8.2 Future Directions

- 1) **Android PQC Integration:** Extend the Crypto-Provider architecture to support Android's BouncyCastle PQC implementations.
- 2) **Formal Verification:** Apply model checking to the handshake state machine to prove absence of deadlocks and race conditions.
- 3) **Performance Optimization:** Profile ML-KEM-768 encapsulation latency and explore hardware acceleration opportunities.
- 4) **Certificate-Based Identity:** Integrate with device certificates for enterprise deployment scenarios.

TABLE 17

Handshake latency. Latency measured from handshake initiation to verified Finished_I2R. Includes event emission overhead. N=1000 iterations after 10 warmup runs.

Configuration	OS Stratum	N	mean (ms)	std (ms)	p50 (ms)	p95 (ms)	p99 (ms)
Classic (X25519 + Ed25519)	macOS 26.x	1000	1.648	0.083	1.644	1.794	1.962
liboqs PQC (ML-KEM-768 + ML-DSA-65)	macOS 26.x	1000	2.526	0.366	2.443	3.241	3.636
CryptoKit PQC (ML-KEM-768 + ML-DSA-65)	macOS 26.x	1000	10.104	2.672	9.423	15.418	18.940

TABLE 18

Handshake RTT. RTT measured as $t_B - t_A$ (MessageB receive time minus MessageA send time). N=1000 iterations after 10 warmup runs.

Configuration	OS Stratum	N	mean (ms)	std (ms)	p50 (ms)	p95 (ms)	p99 (ms)
Classic (X25519 + Ed25519)	macOS 26.x	1000	0.624	0.073	0.610	0.710	0.966
liboqs PQC (ML-KEM-768 + ML-DSA-65)	macOS 26.x	1000	1.090	0.262	1.014	1.598	1.974
CryptoKit PQC (ML-KEM-768 + ML-DSA-65)	macOS 26.x	1000	5.155	1.358	4.925	7.304	9.676

TABLE 19

Handshake message sizes. All sizes in bytes. $B_{finished} = 2 \times 38 = 76$ bytes (Finished_R2I + Finished_I2R). $B_{total} = B_{msgA} + B_{msgB} + B_{finished}$.

Configuration	B_msgA (bytes)	B_msgB (bytes)	B_finished (bytes)	B_total (bytes)
Classic	337	380	76	793
liboqs PQC	6560	5493	76	12129
CryptoKit PQC	6577	5510	76	12163

TABLE 20

Data-plane throughput. Throughput measured for symmetric AEAD (AES-256-GCM) encrypt+decrypt cycle using session keys derived from handshake. Does not include handshake overhead. N=200 iterations after warmup.

Configuration	Payload Size	Throughput (MB/s)	CPU Proxy (ns/byte)
Classic	1 KiB	404.1	2.36
Classic	16 KiB	2918.4	0.33
Classic	64 KiB	3000.0	0.32
Classic	1 MiB	3755.3	0.25

TABLE 21

Provider selection overhead. Time measured using ContinuousClock. Cold = after clearCache(); Hot = cached path. N=200 iterations.

Scenario	p50 (us)	p95 (us)	Notes
Cold start	0.584	0.750	Includes OS/version checks and API probing/self-test
Hot path	0.167	0.209	Cached selection
PQC unavailable fallback	2.542	5.125	Provider tier downgrade
Self-test failure recovery	2.500	5.833	Native PQC probe fails, fallback engages

9 CONCLUSION

SkyBridge Compass demonstrates that cryptographic agility and post-quantum readiness can be achieved in production P2P systems without sacrificing API stability or operational transparency. The layered CryptoProvider architecture enables seamless adoption of new primitives as platforms

evolve, while the actor-isolated handshake state machine provides strong guarantees against concurrency bugs and sensitive material exposure.

Our implementation on Apple platforms shows that native PQC APIs can be integrated with minimal overhead when available, with graceful fallback to library-based or classic

implementations on older systems. The structured security event model ensures that all cryptographic decisions are auditable, supporting both real-time monitoring and post-incident analysis.

As post-quantum cryptography transitions from standardization to deployment, systems like SkyBridge Compass provide a practical template for managing this transition while maintaining security and usability across heterogeneous device fleets.

The limitations noted in Section 8 do not change the core contribution: an auditable migration contract with concurrency-safe handshake semantics that are reproducible from released artifacts.

APPENDIX A KEY SIZE REFERENCE

¹ Apple CryptoKit uses `integrityCheckedRepresentation` for private key serialization, which employs a seed-based compact format. This is more storage-efficient than the FIPS 203/204 expanded format. Public keys use `rawRepresentation` which matches FIPS standard sizes. Measurements performed on macOS 26.0 (Tahoe) SDK.

² Estimated based on seed-based representation pattern; actual sizes may vary.

APPENDIX B SECURITY EVENT TYPES

APPENDIX C X-WING WIRE-SIZE PROJECTION

We exclude X-Wing from the main tables because the benchmark harness currently exercises only `pqcOnly/classicOnly` paths today.

For a conservative wire-size estimate, we start from Table 19 (pure ML-KEM-768 + ML-DSA-65) and adjust only the KEM keyshare lengths:

$$\Delta_{KEM} = (1216 \text{ B}) - (1088 \text{ B}) = 128 \text{ B}$$

$$B_{\text{msgA}}(\text{xwing}) \approx 6556 + 128 = 6684 \text{ B}$$

$$B_{\text{msgB}}(\text{xwing}) \approx 5489 + 128 = 5617 \text{ B}$$

$$B_{\text{total}}(\text{xwing}) \approx 6684 + 5617 + 76 = 12,377 \text{ B}$$

This yields an estimated total wire size of **approx12.4 KB** for the full handshake, assuming the same signature/identity sizes (ML-DSA-65) as the PQC-only suites. If X-Wing is integrated via native CryptoKit HPKE (removing the compatibility envelope header/nonce/tag overhead), the total is expected to drop slightly; we will report the measured figure once the hybrid path is benchmarked.

TABLE 22
Key size reference.

Algorithm	Public Key	Private Key (Apple) ¹	Private Key (FIPS)	Ciphertext/Signature
ML-KEM-768	1184 B	96 B	2400 B	1088 B
ML-KEM-1024	1568 B	128 B ²	3168 B	1568 B
ML-DSA-65	1952 B	64 B	4032 B	~3309 B
ML-DSA-87	2592 B	96 B ²	4896 B	~4627 B
X25519	32 B	32 B	-	32 B
Ed25519	32 B	32 B	-	64 B

TABLE 23
Security event types.

Event Type	Severity	Trigger
cryptoProviderSelected	info/warning	Provider factory selection
cryptoDowngrade	warning	PQC to classic fallback
handshakeFailed	warning	Any handshake failure
signatureVerificationFailed	high	Invalid peer protoSignature
secureEnclaveVerificationFailed	warning	Invalid secureEnclaveSignature
identityMismatch	high	identityPubKey does not match pinned key
contextZeroized	info	Sensitive material cleared
suiteNegotiationFailed	warning	No common suite found
unexpectedStateTransition	high	Actor reentrancy detected

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AUTHOR CONTRIBUTIONS

Single-author paper. The author performed conceptualization, protocol and system design, implementation, experimentation, data analysis, and manuscript writing.

DATA AND ARTIFACT AVAILABILITY

The artifact package includes the implementation, reproducible test harnesses, and scripts that regenerate primary figures and tables. Running the provided test filters produces CSV outputs under Artifacts/ (e.g., handshake latency/RTT, wire sizes, fault injection outcomes, and downgrade-policy traces), and the included scripts derive aggregate plots and audit-signal fidelity summaries from these traces.

Artifact release (for review):

- URL: <https://github.com/billlza/Skybridge-Compa ss>
- Tag: artifact-v1
- Commit: 8a68fa6e0fe78147d2b18d3287681f5d07c74af

Environment: macOS 26.2 (25C56), Swift 6.2.3, Python 3.14.2. A standalone wire-format sanity checker is provided at `scripts/wire_format_sanity.py`.

CSV data dictionary (header fields):

handshake_bench_<date>.csv	configuration, iteration_count, mean_ms, stddev_ms, p50_ms, p95_ms, p99_ms
handshake_rtt_<date>.csv	configuration, iteration_count, mean_ms, stddev_ms, p50_ms, p95_ms, p99_ms
handshake_wire_<date>.csv	configuration, messageA_bytes, messageB_bytes, finished_bytes, total_bytes
message_sizes_<date>.csv	message, total_bytes, signature_bytes, keyshare_bytes, identity_bytes, overhead_bytes
fault_injection_<date>.csv	policy, scenario, n_runs, n_success, n_fail, n_unexpected_error, n_double_resume, zeroization_called_pct, E_handshakeFailed, E_cryptoDowngrade
policy_downgrade_<date>.csv	policy, iterations, classic_attempts, fallback_events
migration_coverage_<date>.csv	scenario, precondition_type, pairing_channel, pairing_verified, has_trust_record, has_legacy_key, expected_satisfied, iterations, allowed_count, rejected_count
provider_selection_<date>.csv	scenario, p50_us, p95_us
audit_signal_fidelity_<date>.csv	scenario_class, expected_signal, total_runs, tp_rate, fp_rate

CONFLICT OF INTEREST

The author declares no competing interests.

REFERENCES

- [1] Apple Inc., "CryptoKit Framework," Apple Developer Documentation, 2025. [Online]. Available: <https://developer.apple.com/documentation/cryptokit>. Accessed: Dec. 2025.
- [2] Bluetooth SIG, "Bluetooth Core Specification v5.4," 2023.
- [3] Apple Inc., "Continuity," Apple Platform Security Guide, 2024.
- [4] T. Taubert and C. A. Wood, "SPAKE2+, an Augmented PAKE," RFC 9383, IETF, Sept. 2023. [Online]. Available: <https://datatracker.ietf.org/doc/rfc9383/>
- [5] D. McGrew, "Achieving Crypto Agility," in Proc. RSA Conference, 2019.
- [6] E. Rescorla, "The Transport Layer Security (TLS) Protocol Version 1.3," RFC 8446, IETF, 2018.
- [7] E. Barker and A. Roginsky, "Transitioning the Use of Cryptographic Algorithms and Key Lengths," NIST SP 800-131A Rev. 2, 2019.
- [8] NIST, "Post-Quantum Cryptography Standardization," 2024. [Online]. Available: <https://csrc.nist.gov/projects/post-quantum-cryptography>. Accessed: Dec. 2025.
- [9] Signal Foundation, "PQXDH Key Agreement Protocol," Signal Technical Documentation, 2023.
- [10] Cloudflare, "Post-Quantum Cryptography Goes GA," Cloudflare Blog, Sept. 29, 2023. [Online]. Available: <https://blog.cloudflare.com/post-quantum-cryptography-ga/>. Accessed: Dec. 2025.
- [11] D. Beyer et al., "Software Model Checking," in Handbook of Model Checking, Springer, 2018.
- [12] Apple Inc., "Swift Concurrency," The Swift Programming Language, 2024.
- [13] R. Barnes, K. Bhargavan, B. Lipp, and C. Wood, "Hybrid Public Key Encryption," RFC 9180, IETF, Feb. 2022. [Online]. Available: <https://datatracker.ietf.org/doc/rfc9180/>
- [14] Apple Inc., "Get ahead with quantum-secure cryptography," WWDC 2025 Session 314, June 2025. [Online]. Available: <https://developer.apple.com/videos/play/wwdc2025/314/>. Accessed: Dec. 2025.
- [15] NIST, "Module-Lattice-Based Key-Encapsulation Mechanism Standard," FIPS 203, Aug. 2024. [Online]. Available: <https://csrc.nist.gov/pubs/fips/203/final>
- [16] NIST, "Module-Lattice-Based Digital Signature Standard," FIPS 204, Aug. 2024. [Online]. Available: <https://csrc.nist.gov/pubs/fips/204/final>
- [17] M. Barbosa, D. Connolly, J. Duarte, A. Kaiser, P. Schwabe, K. Varber, and B. Westerbaan, "X-Wing: The Hybrid KEM You've Been Looking For," IETF Internet-Draft, 2024. [Online]. Available: <https://datatracker.ietf.org/doc/draft-connolly-cfrg-xwing-kem/>
- [18] J. Iyengar and M. Thomson, "QUIC: A UDP-Based Multiplexed and Secure Transport," RFC 9000, IETF, 2021. [Online]. Available: <https://datatracker.ietf.org/doc/rfc9000/>
- [19] T. Perrin, "The Noise Protocol Framework," 2018. [Online]. Available: <https://noiseprotocol.org/noise.pdf>