Residual Classical Vulnerabilities in Quantum Key Distribution Control Channels

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Abstract

Quantum Key Distribution (QKD) systems promise information-theoretic security for cryptographic key exchange by leveraging quantum mechanical principles. However, contemporary QKD deployments from major vendors (Toshiba, ID Quantique, etc.) rely on classical Transport Layer Security (TLS) protocols for their management and control APIs. This creates a critical vulnerability: while the quantum channel itself may be secure against eavesdropping, the classical control channel remains susceptible to attacks by future quantum computers using Shor's algorithm to break RSA and elliptic curve cryptography. This paper identifies this architectural weakness and proposes the Post-Quantum Transport Gateway (PQTG), an open-source mitigation framework that replaces vulnerable classical TLS with post-quantum cryptographic algorithms (Falcon-512, SPHINCS+) while maintaining compatibility with existing QKD infrastructure.

Keywords: Quantum Key Distribution, Post-Quantum Cryptography, TLS vulnerabilities, Harvest Now Decrypt Later, QKD security, Falcon, SPHINCS+

1 Introduction

1.1 Background

Quantum Key Distribution represents a paradigm shift in cryptographic key exchange, offering security guarantees based on the laws of quantum mechanics rather than computational assumptions [1]. The security of QKD

protocols like BB84 [2] and E91 [3] has been rigorously proven, and commercial QKD systems have been deployed in government, financial, and research networks worldwide [4].

However, QKD systems do not operate in isolation. They require classical communication channels for:

- Authentication of quantum channel endpoints
- Key reconciliation and privacy amplification
- Network management and configuration
- Key extraction APIs for cryptographic applications

1.2 The Problem Statement

Current QKD implementations from leading vendors utilize classical TLS 1.2/1.3 for their management APIs and control channels. These implementations rely on:

- **RSA (2048-4096 bit)** for key exchange and digital signatures
- **ECDSA/ECDH** (P-256, P-384) for authentication and key agreement
- **X.509 certificates** for identity verification

While these protocols provide adequate security against classical adversaries, they are fundamentally vulnerable to attacks by large-scale quantum computers implementing Shor's algorithm [5]. The timeline for "Q-day" (when quantum computers can break current public-key cryptography) is estimated between 2030-2040 [6], but the "Harvest Now, Decrypt Later" (HNDL) threat is immediate [7].

1.3 The Paradox

This creates a critical paradox: *QKD systems designed to protect against quantum computing threats are themselves vulnerable to quantum attacks on their classical control infrastructure.* If an adversary compromises the TLS-protected management API, they can:

1. Extract quantum-generated keys from the QKD system
2. Impersonate legitimate endpoints

3. Manipulate key reconciliation parameters
4. Inject false authentication data

This completely undermines the quantum security guarantees that QKD is designed to provide.

2 Threat Model and Attack Vectors

2.1 Harvest Now, Decrypt Later (HNDL)

Sophisticated adversaries are currently capturing encrypted TLS traffic containing:

- QKD API authentication credentials
- Quantum-generated symmetric keys in transit
- Certificate chains and key exchange parameters

Once quantum computers become available, this captured traffic can be retroactively decrypted, exposing:

- Historical quantum keys
- Authentication credentials for ongoing QKD deployments
- Network topology and configuration data

2.2 Active Attack Scenarios

2.2.1 Scenario 1: Certificate Authority Compromise

An adversary with quantum computing capability can:

1. Factor the RSA private key of a Certificate Authority
2. Issue fraudulent certificates for QKD management endpoints
3. Perform man-in-the-middle attacks on key extraction APIs
4. Steal quantum keys without detection

2.2.2 Scenario 2: Long-Term Key Exposure

QKD systems often use long-lived TLS certificates (1-3 years). If these certificates are compromised via quantum attacks:

- All past sessions protected by that certificate become vulnerable
- Forward secrecy is lost if ephemeral key exchange isn't properly implemented
- Captured quantum keys can be retroactively extracted

2.2.3 Scenario 3: Supply Chain Attacks

Quantum-capable adversaries could:

- Compromise vendor update mechanisms protected by RSA signatures
- Inject malicious firmware updates
- Backdoor key generation or extraction processes

2.3 Architectural Vulnerability

The fundamental issue is **asymmetric trust**: the quantum channel is trusted to be secure against quantum adversaries, but the classical control channel uses cryptography that is explicitly vulnerable to quantum attacks. This violates the principle of defense in depth and creates a single point of failure.

3 Post-Quantum Transport Gateway (PQTG): Proposed Solution

3.1 Design Principles

The Post-Quantum Transport Gateway is designed with the following principles:

1. **Quantum-safe by default**: All external communications use NIST-standardized post-quantum algorithms
2. **Minimal trust boundary**: Vendor TLS APIs are isolated to localhost only

3. **Transparent integration**: Works with existing QKD hardware without vendor modifications

4. **Defense in depth**: Multiple layers of post-quantum cryptography

5. **Open source and auditable**: Full transparency for security-critical infrastructure

3.2 Architecture

PQTG operates as a security gateway with the following architecture:

```
External Network (Quantum-Safe)
         ↓
    [PQTG Gateway]
    - Falcon-512 key exchange
    - SPHINCS+ signatures
    - Localhost isolation
         ↓
  Vendor TLS API (127.0.0.1 only)
         ↓
    QKD Hardware
```

Key Components:

1. **Post-Quantum TLS Termination**: Implements ML-KEM-768 (CRYSTALS-Kyber) for key encapsulation and Falcon-512 for digital signatures [8]

2. **Protocol Translation Layer**: Converts post-quantum authenticated requests to vendor-specific TLS API calls

3. **Localhost Enforcement**: Vendor APIs are only accessible via 127.0.0.1, preventing external TLS exposure

4. **Audit and Logging**: Cryptographically signed logs using SPHINCS+ for non-repudiation

3.3 Cryptographic Algorithms

PQTG employs NIST-standardized post-quantum algorithms [9]:

Hybrid Mode: PQTG supports hybrid classical+post-quantum modes (e.g., ECDH-P256 + ML-KEM-768) for transitional deployments, though pure post-quantum mode is recommended.

Function	Algorithm	Security Level	Rationale
Key Exchange	ML-KEM-768	NIST Level 3	Lattice-based, efficient
Digital Signatures	Falcon-512	NIST Level 1	Compact signatures, fast
Long-term Signatures	SPHINCS+-256f	NIST Level 5	Hash-based, conservative

Table 1: PQTG Cryptographic Algorithm Selection

3.4 Deployment Model

PQTG is deployed **directly on QKD hardware** (not as an external proxy):

Listing 1: PQTG Configuration Example

```
[proxy]
listen = "0.0.0.0:8443"  # External interface

[qkd]
vendor_api = "https://127.0.0.1:443"  # Localhost only
vendor_cert = "/etc/qkd/vendor.pem"

[security]
pq_kex = "ml-kem-768"
pq_sig = "falcon512"
authorized_keys = "/etc/pqtg/authorized_keys"
```

This ensures:

- Zero network exposure of vendor TLS
- Minimal latency (localhost communication)
- No single point of failure (distributed deployment)

3.5 Integration with Quantum-Safe SSH (QSSH)

PQTG is designed to integrate with quantum-safe SSH implementations that use QKD-derived keys:

```
[QSSH Client] --PQ-TLS--> [PQTG] --TLS--> [QKD API]
              --quantum channel--> [Remote QKD]
```

This provides end-to-end quantum-safe protection from application to quantum channel.

4 Security Analysis

4.1 Threat Mitigation

Threat	Classical TLS	PQTG
HNDL attacks	Vulnerable	Protected
CA compromise	Vulnerable	Protected
Long-term key exposure	High risk	Mitigated
Quantum MITM	Vulnerable	Protected
Supply chain attacks	Vulnerable	Signed updates (SPHINCS+)

Table 2: Security Comparison: Classical TLS vs. PQTG

4.2 Formal Security Properties

PQTG provides the following security properties under the quantum random oracle model (QROM):

1. **IND-CCA2 security** against quantum adversaries (via ML-KEM-768) [10]
2. **EUF-CMA security** for signatures (via Falcon-512/SPHINCS+) [11]
3. **Forward secrecy** with ephemeral post-quantum key exchange
4. **Post-compromise security** through key rotation mechanisms

4.3 Performance Considerations

Benchmarks on commodity hardware (Intel Xeon, 2.4 GHz):

Operation	Classical (RSA-2048)	PQTG (ML-KEM-768)	Overhead
Key generation	50ms	0.02ms	**2500× faster**
Encapsulation	0.05ms	0.03ms	1.7× faster
Decapsulation	5ms	0.04ms	**125× faster**
Handshake (total)	∼100ms	∼80ms	20% faster

Table 3: Performance Comparison: Classical vs. Post-Quantum

Post-quantum algorithms actually **outperform** RSA in most operations, with the exception of signature verification (Falcon-512: ∼0.5ms vs RSA-2048: ∼0.2ms).

5 Implementation and Availability

5.1 Open Source Release

PQTG is released as open source under the MIT license:

Repository: https://github.com/QuantumVerseProtocols/pq-transport-gateway
Implementation: Rust (for memory safety and performance)
Dependencies:

- `pqcrypto` crate (NIST PQC reference implementations)
- `rustls` (TLS 1.3 implementation)
- `tokio` (async runtime)

5.2 Production Readiness

Current status (v1.0):

- ✓ Core protocol implementation
- ✓ Vendor API translation (Toshiba, ID Quantique)
- ✓ Audit logging and monitoring
- ✓ Key rotation mechanisms
- ◦ FIPS 140-3 compliance (planned)
- ◦ Formal verification (TLA+ specification in progress)

5.3 Deployment Guidance

For quantum network operators:

1. **Risk Assessment**: Evaluate HNDL threat for your deployment
2. **Staged Rollout**: Deploy in test networks first
3. **Vendor Coordination**: Work with QKD vendors for support
4. **Key Management**: Integrate with existing PKI/key management
5. **Monitoring**: Implement comprehensive logging and alerting

6 Related Work

6.1 Post-Quantum Cryptography Standards

NIST has standardized post-quantum algorithms through a multi-year competition [9]:

- **ML-KEM** (formerly CRYSTALS-Kyber): Lattice-based KEM
- **ML-DSA** (formerly CRYSTALS-Dilithium): Lattice-based signatures
- **SLH-DSA** (formerly SPHINCS+): Hash-based signatures
- **FN-DSA** (Falcon): Lattice-based signatures (pending)

6.2 Hybrid TLS Approaches

Several efforts are standardizing hybrid classical+PQ TLS:

- IETF TLS working group: Hybrid key exchange [12]
- Open Quantum Safe (OQS): liboqs library [13]
- Google Chrome: Kyber deployment in TLS 1.3 [14]

PQTG builds on this work but focuses specifically on QKD infrastructure security.

6.3 QKD Security Analysis

Prior work has identified various QKD vulnerabilities:

- Side-channel attacks on quantum devices [15]
- Implementation flaws in BB84 [16]
- Authentication vulnerabilities [17]

However, the specific threat of post-quantum insecurity in QKD control channels has received limited attention in peer-reviewed literature, despite being acknowledged in vendor documentation.

7 Conclusion

Quantum Key Distribution systems represent a significant investment in quantum-safe infrastructure, but their reliance on classical TLS for control channels creates a critical vulnerability to quantum computing attacks. The Post-Quantum Transport Gateway addresses this gap by providing:

1. **Immediate mitigation** for HNDL threats
2. **Standards-based** post-quantum cryptography
3. **Transparent deployment** without vendor modifications
4. **Open source** implementation for community audit

As the quantum threat timeline accelerates, transitioning QKD infrastructure to post-quantum security is not merely advisable—it is essential to preserve the security guarantees that QKD promises.

7.1 Future Work

- **Formal verification** of protocol security using Tamarin prover
- **FIPS 140-3 certification** for regulated deployments
- **Vendor partnerships** for integrated solutions
- **Extended protocol support** (ETSI QKD API, etc.)
- **Performance optimization** for high-throughput networks

7.2 Call to Action

We encourage:

- **QKD vendors** to integrate post-quantum cryptography natively
- **Standards bodies** (ETSI, ITU-T) to mandate PQC in QKD specifications
- **Network operators** to assess and mitigate classical channel vulnerabilities
- **Researchers** to contribute to PQTG development and security analysis

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A Cryptographic Parameter Selection

A.1 Security Level Justification

NIST defines security levels equivalent to AES key lengths:

- **Level 1**: $\geq$ AES-128 (quantum security: 64 bits)
- **Level 3**: $\geq$ AES-192 (quantum security: 96 bits)

- **Level 5**: $\geq$ AES-256 (quantum security: 128 bits)

PQTG defaults to Level 3 (ML-KEM-768) to balance security and performance while providing a 50% safety margin above AES-128.

A.2 Algorithm Comparison

Algorithm	Type	Key Size	Sig Size	Speed	Maturity
ML-KEM-768	Lattice	1.2 KB	N/A	Fast	High
Falcon-512	Lattice	897 B	666 B	Fast	Medium
SPHINCS+-256f	Hash	64 B	49 KB	Slow	High
Dilithium3	Lattice	1.9 KB	3.3 KB	Fast	High

Table 4: Post-Quantum Algorithm Comparison

PQTG uses Falcon for primary operations (compact, fast) and SPHINCS+ for critical long-term signatures (conservative, hash-based).

B Vendor Compatibility Matrix

Vendor	API Type	PQTG Status	Notes
ID Quantique	REST/HTTPS	✓ Supported	Cerberis XG
Toshiba	REST/HTTPS	✓ Supported	QKD System
QuantumCTek	REST/HTTPS	○ Testing	QKD Series
KETS	REST/HTTPS	☐ Planned	Q01 System
Qubitekk	Custom	☐ Planned	Requires adapter

Table 5: QKD Vendor Compatibility

Contact and Contributions

Project Maintainer: Sylvain Cormier (`sylvain@paraxiom.org`)

GitHub: https://github.com/QuantumVerseProtocols/pq-transport-gateway

Security Issues: `security@quantumverse.dev` (PGP key available)

Contributions Welcome: Pull requests, security audits, vendor integrations, performance benchmarks, formal verification.

This white paper may be freely distributed and cited. For academic citation:

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