Post-Quantum Cryptographic Engineering in WireGuard: ML-KEM-768

Hybrid Noise Protocol Ratcheting, MTU Fragmentation Dynamics, and Line-Rate Linux Kernel Offloading

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EXECUTIVE ABSTRACT: *WireGuard's modern 1-RTT cryptographic handshake relies on Curve25519 Elliptic Curve Diffie-Hellman, which is fully vulnerable to future quantum cryptanalysis via Shor's algorithm. To neutralize 'Store-Now-Decrypt-Later' (SNDL) state adversary threats, the WireGuard Noise_IKpsk2 state machine is augmented with NIST FIPS 203 ML-KEM-768 (Kyber). This technical dossier examines hybrid key encapsulation, wire format byte expansion, MTU fragmentation mitigation, and AVX2/AVX-512 kernel acceleration.*

Cryptographic Parameter	Standard WireGuard (Classical)	Hybrid Post-Quantum WireGuard	Legacy IPsec IKEv2 (Classic)
Key Exchange Primitive	Curve25519 (ECDH, 32B)	Curve25519 + ML-KEM-768 (1088B)	DH Group 14 (MODP 2048B)
Quantum Security Level	0 (Vulnerable to Shor's)	NIST Level 3 (~AES-192 security)	0 (Vulnerable to Shor's)
Handshake Packet Size	148 Bytes (Single UDP frame)	1,236 Bytes (Fits within MTU 1420)	1,800+ Bytes (Fragmented)
Handshake CPU Computation	8.2 us (Curve25519 scalar mul)	42.5 us (AVX2 ML-KEM + ECDH)	1,450 us (Heavy modular exp)

1. Store-Now-Decrypt-Later (SNDL) Threat Vector

Hostile intelligence entities are actively archiving encrypted enterprise network traffic. When cryptanalytically relevant quantum computers (CRQC) emerge, all classical Diffie-Hellman shared secrets will be compromised retrospectively. VPN tunnels protecting high-value industrial, defense, and medical infrastructure must transition to post-quantum hybrid key encapsulation immediately.

2. Noise_IKpsk2 Hybrid State Machine Extension

Rather than discarding battle-tested classical cryptography, hybrid post-quantum WireGuard blends Curve25519 ECDH with lattice-based ML-KEM-768. The client encapsulates an ephemeral lattice secret, transmitting the 1088-byte ciphertext within the handshake initiation message. The shared secret is derived through sequential HKDF hashing: SS = HKDF(SS_classical || SS_quantum), ensuring security against both classical and quantum adversaries.

3. MTU Overhead and Packet Fragmentation Defense

Standard WireGuard handshakes require only 148 bytes. Injecting an ML-KEM-768 public key (1,184 bytes) and ciphertext (1,088 bytes) expands initiation frames to 1,236 bytes. Because common WAN links enforce 1500-byte MTUs (and 1420-byte tunnel MTUs), this payload must not trigger IP fragmentation. By strictly packing hybrid tokens into a single atomic UDP frame, packet drops caused by carrier middlebox fragmentation filters are averted.

4. Kernel Acceleration & Throughput Telemetry

Vectorized ML-KEM implementations utilizing Intel AVX2 and ARM Neon instructions compute NTT (Number Theoretic Transform) polynomial multiplications in sub-30 microsecond bursts. Once the 120-second session handshake completes, symmetric data encryption defaults to ChaCha20-Poly1305, maintaining full 9.4 Gbps line-rate forwarding across 10GbE network interfaces without CPU core saturation.

Key Strategic Architecture Takeaways

- Hybrid Curve25519 + ML-KEM-768 preserves classical security while providing NIST Level 3 quantum resistance.
- Packing the complete hybrid handshake into a 1,236-byte UDP frame avoids IP fragmentation across restrictive WAN MTUs.
- AVX2/AVX-512 NTT kernel optimizations keep hybrid handshake compute under 45 us per session renewal.
- Zero impact on data path forwarding: ChaCha20-Poly1305 symmetric throughput continues at full line rate (>9.4 Gbps).