Enhanced SICA Quantum Security Guide

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Quantum Security Overview

The Quantum Threat

The advent of quantum computing poses a significant threat to current cryptographic systems. Quantum computers, when sufficiently powerful, will be able to break many of the cryptographic algorithms that currently secure our digital infrastructure.

Key Quantum Algorithms

Shor's Algorithm: Can efficiently factor large integers and compute discrete logarithms, breaking: - RSA encryption - Elliptic Curve Cryptography (ECC) - Diffie-Hellman key exchange

Grover's Algorithm: Provides quadratic speedup for searching unsorted databases, effectively halving the security of: - Symmetric encryption algorithms - Hash functions - Message authentication codes

Enhanced SICA's Quantum Security Approach

Enhanced SICA implements a comprehensive quantum security framework that addresses both current and future quantum threats:

```
class QuantumSecurityFramework:
    def __init__(self):
        self.post_quantum_crypto = PostQuantumCryptography()
        self.quantum_key_distribution = QuantumKeyDistribution()
        self.zero_knowledge_protocols = ZeroKnowledgeProtocols()
        self.quantum_random_generator = QuantumRandomGenerator()
        self.hybrid_security = HybridSecurityManager()

    async def secure_communication(self,
                                   data: bytes,
                                   recipient: str) -> SecureCommunication:
        """Establish quantum-secure communication"""

        # Generate quantum-safe keys
        quantum_keys = await
self.quantum_key_distribution.generate_keys(recipient)

        # Use post-quantum encryption
        encrypted_data = await self.post_quantum_crypto.encrypt(data,
quantum_keys.encryption_key)

        # Add zero-knowledge proof
        zk_proof = await self.zero_knowledge_protocols.generate_proof(data)

        # Create hybrid security envelope
        secure_envelope = await self.hybrid_security.create_envelope(
            encrypted_data, zk_proof, quantum_keys
        )

        return SecureCommunication(
            envelope=secure_envelope,
            quantum_security_level="high",
post_quantum_algorithms_used=self.post_quantum_crypto.get_algorithms_used()
        )
```

Quantum Security Principles

1. Crypto-Agility

The ability to quickly transition between cryptographic algorithms as quantum threats evolve:

```python
class CryptoAgilityManager:
    def __init__(self):
        self.algorithm_registry = AlgorithmRegistry()
        self.migration_planner = MigrationPlanner()
        self.compatibility_checker = CompatibilityChecker()

    async def plan_algorithm_migration(self,
                                       current_algorithm: str,
                                       target_algorithm: str) -> MigrationPlan:
        """Plan migration from current to quantum-safe algorithm"""

        # Check compatibility
        compatibility = await self.compatibility_checker.check(
            current_algorithm, target_algorithm
        )

        # Create migration plan
        migration_plan = await self.migration_planner.create_plan(
            current_algorithm, target_algorithm, compatibility
        )

        return migration_plan
```

2. Hybrid Security

Combining classical and quantum-resistant algorithms for defense in depth:

```python
class HybridSecurityManager:
    def __init__(self):
        self.classical_crypto = ClassicalCryptography()
        self.quantum_crypto = QuantumCryptography()

    async def hybrid_encrypt(self, data: bytes, keys: HybridKeys) ->
HybridCiphertext:
        """Encrypt using both classical and quantum-resistant algorithms"""

        # Encrypt with classical algorithm
        classical_ciphertext = await self.classical_crypto.encrypt(
            data, keys.classical_key
        )

        # Encrypt with quantum-resistant algorithm
        quantum_ciphertext = await self.quantum_crypto.encrypt(
            data, keys.quantum_key
        )

        # Combine ciphertexts
        hybrid_ciphertext = HybridCiphertext(
            classical=classical_ciphertext,
            quantum=quantum_ciphertext,
            combination_method="concatenation"
        )

        return hybrid_ciphertext
```

Post-Quantum Cryptography

NIST Post-Quantum Standards

Enhanced SICA implements the NIST-standardized post-quantum cryptographic algorithms:

Primary Algorithms

CRYSTALS-Kyber: Key encapsulation mechanism (KEM) **CRYSTALS-Dilithium**: Digital signature algorithm **FALCON**: Compact digital signature algorithm **SPHINCS+**: Stateless hash-based signature scheme

Implementation Architecture

```python
class PostQuantumCryptography:
    def __init__(self):
        self.key_encapsulation = {
            "kyber512": Kyber512(),
            "kyber768": Kyber768(),
            "kyber1024": Kyber1024()
        }
        self.digital_signatures = {
            "dilithium2": Dilithium2(),
            "dilithium3": Dilithium3(),
            "dilithium5": Dilithium5(),
            "falcon512": Falcon512(),
            "falcon1024": Falcon1024(),
            "sphincs_sha256_128s": SPHINCS_SHA256_128s(),
            "sphincs_sha256_192s": SPHINCS_SHA256_192s(),
            "sphincs_sha256_256s": SPHINCS_SHA256_256s()
        }
        self.security_levels = self.initialize_security_levels()

    async def encrypt_with_kem(self,
                               data: bytes,
                               public_key: PublicKey,
                               algorithm: str = "kyber768") -> KEMCiphertext:
        """Encrypt data using Key Encapsulation Mechanism"""

        kem = self.key_encapsulation[algorithm]

        # Encapsulate a random symmetric key
        ciphertext, shared_secret = await kem.encapsulate(public_key)

        # Use shared secret to encrypt data with AES
        aes_key = self.derive_aes_key(shared_secret)
        encrypted_data = await self.aes_encrypt(data, aes_key)

        return KEMCiphertext(
            kem_ciphertext=ciphertext,
            encrypted_data=encrypted_data,
            algorithm=algorithm
        )

    async def sign_data(self,
                        data: bytes,
                        private_key: PrivateKey,
                        algorithm: str = "dilithium3") -> DigitalSignature:
        """Sign data using post-quantum digital signature"""

        signature_scheme = self.digital_signatures[algorithm]

        # Generate signature
        signature = await signature_scheme.sign(data, private_key)

        return DigitalSignature(
            signature=signature,
            algorithm=algorithm,
            security_level=self.security_levels[algorithm]
        )
```

CRYSTALS-Kyber Implementation

```
class Kyber768:
    def __init__(self):
        self.n = 256  # Polynomial degree
        self.k = 3    # Module rank
        self.q = 3329 # Modulus
        self.eta1 = 2 # Noise parameter
        self.eta2 = 2 # Noise parameter
        self.du = 10  # Compression parameter
        self.dv = 4   # Compression parameter

    async def keygen(self) -> Tuple[PublicKey, PrivateKey]:
        """Generate Kyber768 key pair"""

        # Generate random seed
        seed = await self.generate_random_seed(32)

        # Expand seed to generate matrix A
        rho, sigma = self.expand_seed(seed)
        A = self.generate_matrix_A(rho)

        # Generate secret vector s
        s = self.sample_noise_vector(sigma, self.eta1)

        # Generate error vector e
        e = self.sample_noise_vector(sigma, self.eta1)

        # Compute public key t = As + e
        t = self.matrix_vector_multiply(A, s)
        t = self.vector_add(t, e)

        # Create keys
        public_key = PublicKey(
            t=t,
            rho=rho,
            algorithm="kyber768"
        )

        private_key = PrivateKey(
            s=s,
            public_key=public_key,
            algorithm="kyber768"
        )

        return public_key, private_key

    async def encapsulate(self, public_key: PublicKey) -> Tuple[bytes, bytes]:
        """Encapsulate a shared secret"""

        # Generate random message
        m = await self.generate_random_bytes(32)

        # Generate random coins
        coins = await self.generate_random_bytes(32)

        # Reconstruct matrix A from public key
        A = self.generate_matrix_A(public_key.rho)

        # Sample noise vectors
```

```python
        r = self.sample_noise_vector(coins, self.eta1)
        e1 = self.sample_noise_vector(coins, self.eta2)
        e2 = self.sample_noise_polynomial(coins, self.eta2)

        # Compute ciphertext components
        u = self.matrix_vector_multiply_transpose(A, r)
        u = self.vector_add(u, e1)
        u = self.compress_vector(u, self.du)

        v = self.vector_dot_product(public_key.t, r)
        v = self.polynomial_add(v, e2)
        v = self.polynomial_add(v, self.decode_message(m))
        v = self.compress_polynomial(v, self.dv)

        # Create ciphertext
        ciphertext = self.encode_ciphertext(u, v)

        # Derive shared secret
        shared_secret = self.kdf(m, ciphertext)

        return ciphertext, shared_secret

    async def decapsulate(self,
                          ciphertext: bytes,
                          private_key: PrivateKey) -> bytes:
        """Decapsulate shared secret from ciphertext"""

        # Decode ciphertext
        u, v = self.decode_ciphertext(ciphertext)

        # Decompress ciphertext components
        u = self.decompress_vector(u, self.du)
        v = self.decompress_polynomial(v, self.dv)

        # Compute message
        m_prime = self.vector_dot_product(private_key.s, u)
        m_prime = self.polynomial_subtract(v, m_prime)
        m = self.encode_message(m_prime)

        # Re-encapsulate to verify
        ciphertext_prime, shared_secret = await
self.encapsulate(private_key.public_key)

        # Constant-time comparison
        if self.constant_time_compare(ciphertext, ciphertext_prime):
            return shared_secret
        else:
            # Return pseudo-random value on failure
            return self.generate_pseudo_random(ciphertext)
```

CRYSTALS-Dilithium Implementation

```
class Dilithium3:
    def __init__(self):
        self.n = 256    # Polynomial degree
        self.k = 6      # Dimensions
        self.l = 5      # Dimensions
        self.eta = 4    # Noise bound
        self.tau = 49   # Number of ±1's in challenge
        self.beta = 196 # Signature bound
        self.gamma1 = 2**17  # Coefficient range
        self.gamma2 = 95232  # Low-order rounding range

    async def keygen(self) -> Tuple[PublicKey, PrivateKey]:
        """Generate Dilithium3 key pair"""

        # Generate random seed
        seed = await self.generate_random_seed(32)

        # Expand seed
        rho, rho_prime, K = self.expand_seed(seed)

        # Generate matrix A
        A = self.expand_matrix_A(rho)

        # Generate secret vectors
        s1 = self.sample_uniform_eta(rho_prime, self.eta)
        s2 = self.sample_uniform_eta(rho_prime, self.eta)

        # Compute t = As1 + s2
        t = self.matrix_vector_multiply(A, s1)
        t = self.vector_add(t, s2)

        # Extract high-order bits
        t1 = self.high_bits(t)

        # Create keys
        public_key = PublicKey(
            rho=rho,
            t1=t1,
            algorithm="dilithium3"
        )

        private_key = PrivateKey(
            rho=rho,
            K=K,
            tr=self.hash_public_key(public_key),
            s1=s1,
            s2=s2,
            t0=self.low_bits(t),
            algorithm="dilithium3"
        )

        return public_key, private_key

    async def sign(self,
                  message: bytes,
                  private_key: PrivateKey) -> bytes:
        """Sign message using Dilithium3"""
```

```
        # Hash message with public key
        mu = self.hash_message(private_key.tr, message)

        # Initialize rejection sampling
        kappa = 0

        while True:
            # Sample mask
            y = self.sample_mask(private_key.rho, private_key.K, kappa)

            # Compute w = Ay
            A = self.expand_matrix_A(private_key.rho)
            w = self.matrix_vector_multiply(A, y)

            # Extract high-order bits
            w1 = self.high_bits(w)

            # Compute challenge
            c = self.sample_challenge(mu, w1)

            # Compute response
            z = self.vector_add(y, self.scalar_vector_multiply(c,
private_key.s1))

            # Check bounds
            if self.check_bounds(z, self.gamma1 - self.beta):
                continue

            # Compute hint
            r0 = self.low_bits(self.vector_subtract(w,
                self.scalar_vector_multiply(c, private_key.s2)))

            if self.check_bounds(r0, self.gamma2 - self.beta):
                continue

            # Compute hint
            h = self.make_hint(-c * private_key.t0, w - c * private_key.s2 + c
* private_key.t0)

            # Check hint weight
            if self.hint_weight(h) <= self.omega:
                break

            kappa += 1

        # Encode signature
        signature = self.encode_signature(c, z, h)

        return signature
```

Security Level Configuration

```
class SecurityLevelManager:
    def __init__(self):
        self.security_levels = {
            1: {  # NIST Level 1 (equivalent to AES-128)
                "kyber": "kyber512",
                "dilithium": "dilithium2",
                "falcon": "falcon512",
                "sphincs": "sphincs_sha256_128s"
            },
            3: {  # NIST Level 3 (equivalent to AES-192)
                "kyber": "kyber768",
                "dilithium": "dilithium3",
                "falcon": "falcon1024",
                "sphincs": "sphincs_sha256_192s"
            },
            5: {  # NIST Level 5 (equivalent to AES-256)
                "kyber": "kyber1024",
                "dilithium": "dilithium5",
                "falcon": "falcon1024",
                "sphincs": "sphincs_sha256_256s"
            }
        }

    def get_algorithms_for_level(self, security_level: int) -> Dict[str, str]:
        """Get recommended algorithms for security level"""
        return self.security_levels.get(security_level,
self.security_levels[3])

    def recommend_security_level(self, threat_assessment: ThreatAssessment) ->
int:
        """Recommend security level based on threat assessment"""

        if threat_assessment.quantum_threat_timeline <= 5:  # Years
            return 5  # Maximum security
        elif threat_assessment.quantum_threat_timeline <= 10:
            return 3  # High security
        else:
            return 1  # Standard security
```

Quantum Key Distribution

QKD Fundamentals

Quantum Key Distribution (QKD) uses quantum mechanics principles to detect eavesdropping and establish provably secure communication keys.

BB84 Protocol Implementation

```
class BB84Protocol:
    def __init__(self):
        self.bases = ['rectilinear', 'diagonal']  # + and x bases
        self.bit_values = [0, 1]
        self.error_threshold = 0.11  # Maximum tolerable error rate

    async def generate_quantum_key(self,
                                  alice_node: QuantumNode,
                                  bob_node: QuantumNode,
                                  key_length: int) -> QuantumKey:
        """Generate quantum key using BB84 protocol"""

        # Phase 1: Quantum transmission
        alice_bits, alice_bases = await self.alice_prepare_qubits(key_length * 2)
        bob_measurements, bob_bases = await self.bob_measure_qubits(
            alice_node.send_qubits(), key_length * 2
        )

        # Phase 2: Basis reconciliation
        matching_bases = await self.reconcile_bases(alice_bases, bob_bases)

        # Phase 3: Key sifting
        sifted_key_alice = self.sift_key(alice_bits, matching_bases)
        sifted_key_bob = self.sift_key(bob_measurements, matching_bases)

        # Phase 4: Error detection
        error_rate = await self.estimate_error_rate(sifted_key_alice, sifted_key_bob)

        if error_rate > self.error_threshold:
            raise SecurityException("Error rate too high - possible eavesdropping detected")

        # Phase 5: Error correction
        corrected_key = await self.error_correction(sifted_key_alice, sifted_key_bob)

        # Phase 6: Privacy amplification
        final_key = await self.privacy_amplification(corrected_key, error_rate)

        return QuantumKey(
            key=final_key,
            length=len(final_key),
            error_rate=error_rate,
            security_parameter=self.calculate_security_parameter(error_rate)
        )

    async def alice_prepare_qubits(self, count: int) -> Tuple[List[int], List[str]]:
        """Alice prepares random qubits in random bases"""

        bits = []
        bases = []

        for _ in range(count):
            # Choose random bit and basis
            bit = random.choice(self.bit_values)
            basis = random.choice(self.bases)
```

```python
            bits.append(bit)
            bases.append(basis)

        return bits, bases

    async def bob_measure_qubits(self,
                                 qubits: List[Qubit],
                                 count: int) -> Tuple[List[int], List[str]]:
        """Bob measures qubits in random bases"""

        measurements = []
        bases = []

        for qubit in qubits:
            # Choose random measurement basis
            basis = random.choice(self.bases)

            # Measure qubit
            measurement = await self.measure_qubit(qubit, basis)

            measurements.append(measurement)
            bases.append(basis)

        return measurements, bases
```

E91 Protocol Implementation

```
class E91Protocol:
    def __init__(self):
        self.bell_states = ['phi_plus', 'phi_minus', 'psi_plus', 'psi_minus']
        self.measurement_angles = [0, 45, 90, 135]  # Degrees

    async def generate_entangled_key(self,
                                     alice_node: QuantumNode,
                                     bob_node: QuantumNode,
                                     key_length: int) -> QuantumKey:
        """Generate quantum key using E91 protocol with entangled pairs"""

        # Phase 1: Generate entangled pairs
        entangled_pairs = await self.generate_entangled_pairs(key_length * 2)

        # Phase 2: Distribute pairs
        alice_qubits = [pair.qubit_a for pair in entangled_pairs]
        bob_qubits = [pair.qubit_b for pair in entangled_pairs]

        # Phase 3: Random measurements
        alice_results, alice_angles = await
self.alice_measure_entangled(alice_qubits)
        bob_results, bob_angles = await self.bob_measure_entangled(bob_qubits)

        # Phase 4: Bell inequality test
        bell_violation = await self.test_bell_inequality(
            alice_results, alice_angles, bob_results, bob_angles
        )

        if not bell_violation.violates_inequality:
            raise SecurityException("Bell inequality not violated - security
compromised")

        # Phase 5: Key extraction
        raw_key = await self.extract_key_from_correlations(
            alice_results, alice_angles, bob_results, bob_angles
        )

        # Phase 6: Error correction and privacy amplification
        final_key = await self.post_process_key(raw_key)

        return QuantumKey(
            key=final_key,
            length=len(final_key),
            bell_violation=bell_violation.violation_parameter,
            security_parameter=self.calculate_e91_security(bell_violation)
        )
```

Quantum Network Architecture

```python
class QuantumNetworkManager:
    def __init__(self):
        self.quantum_nodes = {}
        self.quantum_channels = {}
        self.key_management = QuantumKeyManager()
        self.network_topology = QuantumNetworkTopology()

    async def establish_quantum_network(self,
                                        nodes: List[QuantumNodeConfig]) ->
QuantumNetwork:
        """Establish quantum communication network"""

        # Initialize quantum nodes
        for node_config in nodes:
            node = await self.initialize_quantum_node(node_config)
            self.quantum_nodes[node_config.node_id] = node

        # Establish quantum channels
        for node_id, node in self.quantum_nodes.items():
            neighbors = self.network_topology.get_neighbors(node_id)
            for neighbor_id in neighbors:
                if neighbor_id in self.quantum_nodes:
                    channel = await self.establish_quantum_channel(
                        node, self.quantum_nodes[neighbor_id]
                    )
                    self.quantum_channels[(node_id, neighbor_id)] = channel

        # Initialize key distribution
        await self.initialize_key_distribution()

        return QuantumNetwork(
            nodes=self.quantum_nodes,
            channels=self.quantum_channels,
            topology=self.network_topology
        )

    async def distribute_quantum_keys(self,
                                      source_node: str,
                                      target_node: str,
                                      key_length: int) -> QuantumKey:
        """Distribute quantum keys across network"""

        # Find optimal path
        path = self.network_topology.find_shortest_path(source_node,
target_node)

        if len(path) == 2:
            # Direct connection
            return await self.direct_key_distribution(
                self.quantum_nodes[source_node],
                self.quantum_nodes[target_node],
                key_length
            )
        else:
            # Multi-hop key distribution
            return await self.multi_hop_key_distribution(path, key_length)
```

Zero-Knowledge Protocols

Zero-Knowledge Proof Systems

Zero-knowledge proofs allow one party to prove knowledge of a secret without revealing the secret itself.

zk-SNARKs Implementation

```
class ZKSNARKSystem:
    def __init__(self):
        self.setup_parameters = None
        self.proving_key = None
        self.verification_key = None
        self.circuit_compiler = CircuitCompiler()

    async def setup(self, circuit: ArithmeticCircuit) -> SetupResult:
        """Perform trusted setup for zk-SNARK system"""

        # Compile circuit to R1CS
        r1cs = await self.circuit_compiler.compile_to_r1cs(circuit)

        # Generate setup parameters
        setup_params = await self.generate_setup_parameters(r1cs)

        # Generate proving and verification keys
        self.proving_key = setup_params.proving_key
        self.verification_key = setup_params.verification_key

        return SetupResult(
            proving_key=self.proving_key,
            verification_key=self.verification_key,
            circuit_hash=self.hash_circuit(circuit)
        )

    async def prove(self,
                    witness: Witness,
                    public_inputs: List[int]) -> ZKProof:
        """Generate zero-knowledge proof"""

        if not self.proving_key:
            raise ValueError("Setup must be performed before proving")

        # Generate random values
        r = await self.generate_random_field_element()
        s = await self.generate_random_field_element()

        # Compute proof elements
        proof_a = await self.compute_proof_a(witness, r)
        proof_b = await self.compute_proof_b(witness, s)
        proof_c = await self.compute_proof_c(witness, r, s)

        return ZKProof(
            a=proof_a,
            b=proof_b,
            c=proof_c,
            public_inputs=public_inputs
        )

    async def verify(self,
                     proof: ZKProof,
                     public_inputs: List[int]) -> bool:
        """Verify zero-knowledge proof"""

        if not self.verification_key:
            raise ValueError("Setup must be performed before verification")

        # Prepare verification equation
```

```
        vk_alpha = self.verification_key.alpha
        vk_beta = self.verification_key.beta
        vk_gamma = self.verification_key.gamma
        vk_delta = self.verification_key.delta

        # Compute pairing checks
        left_side = await self.pairing(proof.a, proof.b)

        right_side_1 = await self.pairing(vk_alpha, vk_beta)
        right_side_2 = await self.pairing(
            self.compute_public_input_commitment(public_inputs),
            vk_gamma
        )
        right_side_3 = await self.pairing(proof.c, vk_delta)

        right_side = self.multiply_pairings([right_side_1, right_side_2,
right_side_3])

        return self.pairing_equality(left_side, right_side)
```

zk-STARKs Implementation

```
class ZKSTARKSystem:
    def __init__(self):
        self.field_size = 2**251 - 1  # Large prime field
        self.security_parameter = 128
        self.fri_parameters = FRIParameters()

    async def prove(self,
                    computation: Computation,
                    witness: Witness) -> STARKProof:
        """Generate STARK proof for computation"""

        # Step 1: Arithmetization
        trace = await self.generate_execution_trace(computation, witness)

        # Step 2: Polynomial commitment
        trace_polynomials = await self.interpolate_trace(trace)

        # Step 3: Constraint system
        constraints = await self.generate_constraints(computation)

        # Step 4: Random challenges
        challenges = await self.generate_fiat_shamir_challenges(
            trace_polynomials, constraints
        )

        # Step 5: FRI proof
        fri_proof = await self.generate_fri_proof(trace_polynomials,
challenges)

        return STARKProof(
            trace_commitment=self.commit_to_trace(trace_polynomials),
            constraint_proof=self.prove_constraints(constraints, challenges),
            fri_proof=fri_proof,
            public_inputs=computation.public_inputs
        )

    async def verify(self,
                     proof: STARKProof,
                     computation: Computation) -> bool:
        """Verify STARK proof"""

        # Step 1: Verify trace commitment
        if not await self.verify_trace_commitment(proof.trace_commitment):
            return False

        # Step 2: Verify constraints
        if not await self.verify_constraints(proof.constraint_proof,
computation):
            return False

        # Step 3: Verify FRI proof
        if not await self.verify_fri_proof(proof.fri_proof):
            return False

        return True
```

Zero-Knowledge Authentication

```python
class ZKAuthenticationSystem:
    def __init__(self):
        self.commitment_scheme = PedersenCommitment()
        self.sigma_protocols = SigmaProtocols()

    async def register_user(self,
                          user_id: str,
                          secret: bytes) -> RegistrationResult:
        """Register user with zero-knowledge credentials"""

        # Generate commitment to secret
        commitment, randomness = await self.commitment_scheme.commit(secret)

        # Generate proof of knowledge
        proof_of_knowledge = await self.sigma_protocols.prove_knowledge(
            secret, commitment, randomness
        )

        # Store commitment (not secret)
        await self.store_user_commitment(user_id, commitment)

        return RegistrationResult(
            user_id=user_id,
            commitment=commitment,
            proof_of_knowledge=proof_of_knowledge
        )

    async def authenticate_user(self,
                              user_id: str,
                              secret: bytes) -> AuthenticationResult:
        """Authenticate user without revealing secret"""

        # Retrieve stored commitment
        stored_commitment = await self.get_user_commitment(user_id)

        # Generate proof that secret opens commitment
        proof = await self.sigma_protocols.prove_commitment_opening(
            secret, stored_commitment
        )

        # Verify proof
        is_valid = await self.sigma_protocols.verify_commitment_opening(
            proof, stored_commitment
        )

        return AuthenticationResult(
            user_id=user_id,
            authenticated=is_valid,
            proof=proof
        )
```

Privacy-Preserving Protocols

```
class PrivacyPreservingProtocols:
    def __init__(self):
        self.secure_multiparty = SecureMultipartyComputation()
        self.homomorphic_encryption = HomomorphicEncryption()
        self.differential_privacy = DifferentialPrivacy()

    async def private_set_intersection(self,
                                       set_a: Set[str],
                                       set_b: Set[str]) -> Set[str]:
        """Compute intersection without revealing sets"""

        # Convert sets to polynomials
        poly_a = await self.set_to_polynomial(set_a)
        poly_b = await self.set_to_polynomial(set_b)

        # Homomorphic evaluation
        intersection_poly = await
self.homomorphic_encryption.multiply_polynomials(
            poly_a, poly_b
        )

        # Extract intersection
        intersection = await self.polynomial_to_set(intersection_poly)

        return intersection

    async def private_information_retrieval(self,
                                            database: List[bytes],
                                            index: int) -> bytes:
        """Retrieve database item without revealing index"""

        # Generate PIR query
        query = await self.generate_pir_query(index, len(database))

        # Homomorphic computation
        encrypted_result = await
self.homomorphic_encryption.compute_pir_response(
            database, query
        )

        # Decrypt result
        result = await self.homomorphic_encryption.decrypt(encrypted_result)

        return result
```

Quantum-Safe Algorithms

Lattice-Based Cryptography

Learning With Errors (LWE)

```
class LWECryptosystem:
    def __init__(self, n: int, q: int, sigma: float):
        self.n = n          # Dimension
        self.q = q          # Modulus
        self.sigma = sigma  # Noise parameter
        self.m = 2 * n      # Number of samples

    async def keygen(self) -> Tuple[LWEPublicKey, LWEPrivateKey]:
        """Generate LWE key pair"""

        # Generate secret vector
        s = await self.sample_uniform_vector(self.n, self.q)

        # Generate random matrix A
        A = await self.sample_uniform_matrix(self.m, self.n, self.q)

        # Generate error vector
        e = await self.sample_gaussian_vector(self.m, self.sigma)

        # Compute b = As + e (mod q)
        b = self.matrix_vector_multiply_mod(A, s, self.q)
        b = self.vector_add_mod(b, e, self.q)

        public_key = LWEPublicKey(A=A, b=b)
        private_key = LWEPrivateKey(s=s)

        return public_key, private_key

    async def encrypt(self,
                     message: int,
                     public_key: LWEPublicKey) -> LWECiphertext:
        """Encrypt message using LWE"""

        # Sample random subset
        subset = await self.sample_random_subset(self.m)

        # Compute ciphertext
        c1 = self.sum_matrix_rows(public_key.A, subset)
        c2 = self.sum_vector_elements(public_key.b, subset)

        # Add message
        c2 = (c2 + message * (self.q // 2)) % self.q

        return LWECiphertext(c1=c1, c2=c2)

    async def decrypt(self,
                     ciphertext: LWECiphertext,
                     private_key: LWEPrivateKey) -> int:
        """Decrypt LWE ciphertext"""
```

```
        # Compute inner product
        inner_product = self.vector_dot_product_mod(
            ciphertext.c1, private_key.s, self.q
        )

        # Compute message
        message_noisy = (ciphertext.c2 - inner_product) % self.q

        # Round to nearest message
        if message_noisy < self.q // 4 or message_noisy > 3 * self.q // 4:
            return 0
        else:
            return 1
```

Hash-Based Signatures

XMSS (eXtended Merkle Signature Scheme)

```
class XMSSSignatureScheme:
    def __init__(self, height: int, winternitz_parameter: int):
        self.height = height  # Tree height
        self.w = winternitz_parameter  # Winternitz parameter
        self.n = 32  # Hash output length (SHA-256)
        self.tree_size = 2 ** height

    async def keygen(self) -> Tuple[XMSSPublicKey, XMSSPrivateKey]:
        """Generate XMSS key pair"""

        # Generate WOTS+ key pairs for each leaf
        wots_keys = []
        for i in range(self.tree_size):
            wots_sk, wots_pk = await self.generate_wots_keypair(i)
            wots_keys.append((wots_sk, wots_pk))

        # Build Merkle tree
        merkle_tree = await self.build_merkle_tree([pk for _, pk in wots_keys])

        # Create keys
        public_key = XMSSPublicKey(
            root=merkle_tree.root,
            height=self.height
        )

        private_key = XMSSPrivateKey(
            wots_keys=[sk for sk, _ in wots_keys],
            merkle_tree=merkle_tree,
            next_index=0
        )

        return public_key, private_key

    async def sign(self,
                   message: bytes,
                   private_key: XMSSPrivateKey) -> XMSSSignature:
        """Sign message using XMSS"""

        if private_key.next_index >= self.tree_size:
            raise ValueError("All one-time signatures used")

        index = private_key.next_index

        # Sign with WOTS+
        wots_signature = await self.wots_sign(
            message, private_key.wots_keys[index]
        )

        # Generate authentication path
        auth_path = private_key.merkle_tree.get_authentication_path(index)

        # Update private key
        private_key.next_index += 1

        return XMSSSignature(
```

```python
            index=index,
            wots_signature=wots_signature,
            authentication_path=auth_path
        )

    async def verify(self,
                    message: bytes,
                    signature: XMSSSignature,
                    public_key: XMSSPublicKey) -> bool:
        """Verify XMSS signature"""

        # Verify WOTS+ signature
        wots_public_key = await self.wots_verify(
            message, signature.wots_signature
        )

        # Verify authentication path
        computed_root = await self.verify_authentication_path(
            wots_public_key,
            signature.index,
            signature.authentication_path,
            public_key.height
        )

        return computed_root == public_key.root
```

Code-Based Cryptography

McEliece Cryptosystem

```
class McElieceCryptosystem:
    def __init__(self, n: int, k: int, t: int):
        self.n = n  # Code length
        self.k = k  # Code dimension
        self.t = t  # Error correction capability

    async def keygen(self) -> Tuple[McEliecePublicKey, McEliecePrivateKey]:
        """Generate McEliece key pair"""

        # Generate random Goppa code
        goppa_polynomial = await self.generate_goppa_polynomial(self.t)
        support_set = await self.generate_support_set(self.n)

        # Generate generator matrix G
        G = await self.generate_goppa_generator_matrix(
            goppa_polynomial, support_set
        )

        # Generate random matrices
        S = await self.generate_random_invertible_matrix(self.k)
        P = await self.generate_random_permutation_matrix(self.n)

        # Compute public generator matrix
        G_pub = self.matrix_multiply(S, self.matrix_multiply(G, P))

        public_key = McEliecePublicKey(G=G_pub, n=self.n, k=self.k, t=self.t)
        private_key = McEliecePrivateKey(
            S=S, P=P, G=G,
            goppa_polynomial=goppa_polynomial,
            support_set=support_set
        )

        return public_key, private_key

    async def encrypt(self,
                      message: bytes,
                      public_key: McEliecePublicKey) -> McElieceCiphertext:
        """Encrypt message using McEliece"""

        # Convert message to vector
        m = self.bytes_to_vector(message, public_key.k)

        # Generate random error vector
        e = await self.generate_random_error_vector(public_key.n, public_key.t)

        # Compute ciphertext: c = mG + e
        c = self.vector_add(
            self.matrix_vector_multiply(m, public_key.G),
            e
        )

        return McElieceCiphertext(c=c)

    async def decrypt(self,
                      ciphertext: McElieceCiphertext,
```

```
                 private_key: McEliecePrivateKey) -> bytes:
        """Decrypt McEliece ciphertext"""

        # Apply permutation
        c_perm = self.apply_permutation_inverse(ciphertext.c, private_key.P)

        # Decode using Goppa decoder
        m_decoded, error_corrected = await self.goppa_decode(
            c_perm, private_key.goppa_polynomial, private_key.support_set
        )

        # Apply S inverse
        m = self.matrix_vector_multiply(
            self.matrix_inverse(private_key.S),
            m_decoded
        )

        return self.vector_to_bytes(m)
```

Implementation Guidelines

Integration Architecture

```python
class QuantumSecurityIntegration:
    def __init__(self):
        self.post_quantum_crypto = PostQuantumCryptography()
        self.quantum_key_distribution = QuantumKeyDistribution()
        self.zero_knowledge_protocols = ZeroKnowledgeProtocols()
        self.hybrid_security = HybridSecurityManager()
        self.crypto_agility = CryptoAgilityManager()

    async def secure_communication_channel(self,
                                           source: str,
                                           destination: str) -> SecureChannel:
        """Establish quantum-secure communication channel"""

        # Step 1: Negotiate security parameters
        security_params = await self.negotiate_security_parameters(
            source, destination
        )

        # Step 2: Establish quantum keys if available
        quantum_keys = None
        if self.quantum_key_distribution.is_available(source, destination):
            quantum_keys = await self.quantum_key_distribution.establish_keys(
                source, destination, security_params.key_length
            )

        # Step 3: Generate post-quantum keys
        pq_keys = await self.post_quantum_crypto.generate_keys(
            security_params.pq_algorithm
        )

        # Step 4: Create hybrid security envelope
        secure_channel = await self.hybrid_security.create_channel(
            quantum_keys, pq_keys, security_params
        )

        return secure_channel
```

Performance Optimization

```
class QuantumCryptoOptimizer:
    def __init__(self):
        self.algorithm_benchmarks = AlgorithmBenchmarks()
        self.hardware_accelerator = HardwareAccelerator()
        self.cache_manager = CryptoCacheManager()

    async def optimize_for_performance(self,
                                        security_requirements:
SecurityRequirements) -> OptimizationResult:
        """Optimize quantum crypto implementation for performance"""

        # Benchmark available algorithms
        benchmarks = await self.algorithm_benchmarks.run_benchmarks(
            security_requirements
        )

        # Select optimal algorithms
        optimal_algorithms = self.select_optimal_algorithms(
            benchmarks, security_requirements
        )

        # Configure hardware acceleration
        if self.hardware_accelerator.is_available():
            await self.hardware_accelerator.configure(optimal_algorithms)

        # Set up caching
        await self.cache_manager.configure_caching(optimal_algorithms)

        return OptimizationResult(
            algorithms=optimal_algorithms,

expected_performance=benchmarks.get_performance(optimal_algorithms),
            hardware_acceleration=self.hardware_accelerator.is_enabled()
        )
```

Security Validation

```
class QuantumSecurityValidator:
    def __init__(self):
        self.security_tests = SecurityTestSuite()
        self.compliance_checker = ComplianceChecker()
        self.vulnerability_scanner = VulnerabilityScanner()

    async def validate_quantum_security(self,
                                        implementation:
QuantumSecurityImplementation) -> ValidationResult:
        """Validate quantum security implementation"""

        # Run security tests
        test_results = await self.security_tests.run_all_tests(implementation)

        # Check compliance
        compliance_results = await self.compliance_checker.check_compliance(
            implementation, ["NIST", "FIPS", "Common Criteria"]
        )

        # Scan for vulnerabilities
        vulnerability_results = await
self.vulnerability_scanner.scan(implementation)

        # Generate validation report
        validation_report = ValidationReport(
            test_results=test_results,
            compliance_results=compliance_results,
            vulnerability_results=vulnerability_results,
            overall_security_level=self.calculate_security_level(
                test_results, compliance_results, vulnerability_results
            )
        )

        return ValidationResult(
            passed=validation_report.overall_security_level >=
SecurityLevel.HIGH,
            report=validation_report,
            recommendations=self.generate_recommendations(validation_report)
        )
```

Migration Strategy

```
class QuantumMigrationManager:
    def __init__(self):
        self.migration_planner = MigrationPlanner()
        self.compatibility_checker = CompatibilityChecker()
        self.rollback_manager = RollbackManager()

    async def plan_quantum_migration(self,
                                     current_system: CryptoSystem,
                                     target_quantum_level: QuantumSecurityLevel)
-> MigrationPlan:
        """Plan migration to quantum-safe cryptography"""

        # Assess current system
        current_assessment = await self.assess_current_system(current_system)

        # Identify migration requirements
        migration_requirements = self.identify_migration_requirements(
            current_assessment, target_quantum_level
        )

        # Create migration phases
        migration_phases = await self.migration_planner.create_phases(
            migration_requirements
        )

        # Validate migration plan
        validation_result = await
self.validate_migration_plan(migration_phases)

        return MigrationPlan(
            phases=migration_phases,
            timeline=self.calculate_migration_timeline(migration_phases),
            risks=self.identify_migration_risks(migration_phases),
            rollback_strategy=await
self.rollback_manager.create_strategy(migration_phases)
        )
```

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