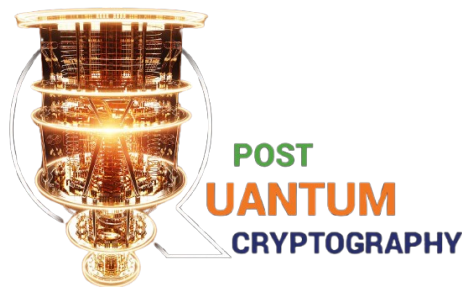


École Nationale Supérieure d'Arts et Métiers
Casablanca, Morocco

ACADEMIC PROJECT

Master 2 Big Data & IoT

**Optimization of IoT Communications
through Compression and Lightweight
Post-Quantum Cryptography**



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Abstract

The Internet of Things (IoT) is growing rapidly, with billions of devices connected worldwide. However, these devices face two major challenges: they have limited resources (energy, memory, and bandwidth), and current security methods will become vulnerable when quantum computers become powerful enough.

This thesis addresses a key question: *How can we protect IoT communications from quantum attacks while keeping bandwidth usage low?*

We propose a solution combining Post-Quantum Cryptography (PQC) with data compression. Our approach uses Kyber768, the NIST-approved post-quantum key encapsulation mechanism, together with LZ4 compression—chosen specifically for resource-constrained IoT devices due to its minimal memory footprint and energy efficiency.

The key insight is simple: compress data before encrypting it. Our benchmarks on realistic IoT sensor data demonstrate that this combined approach achieves significant bandwidth savings while maintaining sub-5ms processing times suitable for IoT devices. LZ4's extremely fast compression and decompression speeds make it ideal for battery-powered sensors where computational energy must be minimized.

Keywords: Internet of Things, Post-Quantum Cryptography, Compression, Kyber, LZ4, Bandwidth Optimization, NIST Standards

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General Introduction

Context and Motivation

The Internet of Things (IoT) connects billions of devices worldwide, from sensors to industrial machines. However, these devices face severe resource constraints—limited energy, memory, and bandwidth—making strong security difficult to implement. Simultaneously, quantum computers pose an emerging threat: algorithms like Shor’s can break current RSA and ECC encryption, potentially compromising all data encrypted today through “harvest now, decrypt later” attacks.

Problem Statement

Post-Quantum Cryptography (PQC) offers quantum-resistant security, with NIST standardizing Kyber for key exchange in 2024. However, PQC algorithms produce significantly larger keys and ciphertexts than classical cryptography—Kyber768’s public key (1,184 bytes) is 18 times larger than ECC P-256 (64 bytes). This size overhead conflicts directly with IoT bandwidth constraints.

How can we secure IoT communications against quantum threats while respecting bandwidth constraints?

Research Objectives and Contributions

This thesis makes the following contributions:

1. Analysis of PQC algorithms for IoT, focusing on Kyber768 as the optimal choice
2. Evaluation of compression algorithms, selecting LZ4 for its energy efficiency and minimal memory footprint on constrained devices
3. A combined compress-then-encrypt architecture achieving significant bandwidth savings
4. Working implementation with benchmarks demonstrating practical viability

Thesis Organization

Chapter 1 examines IoT constraints and the quantum threat. **Chapter 2** presents Post-Quantum Cryptography, focusing on Kyber768. **Chapter 3** covers compression algorithms with emphasis on LZ4. **Chapter 4** presents our combined architecture. **Chapter 5** provides implementation and benchmarks. The **General Conclusion** summarizes findings and future directions.

Chapter 1

IoT and Security Challenges

1.1 Introduction

The Internet of Things (IoT) connects billions of devices worldwide, from sensors to industrial machines. These devices face severe resource constraints and an emerging quantum computing threat that will break current encryption. This chapter examines both challenges.

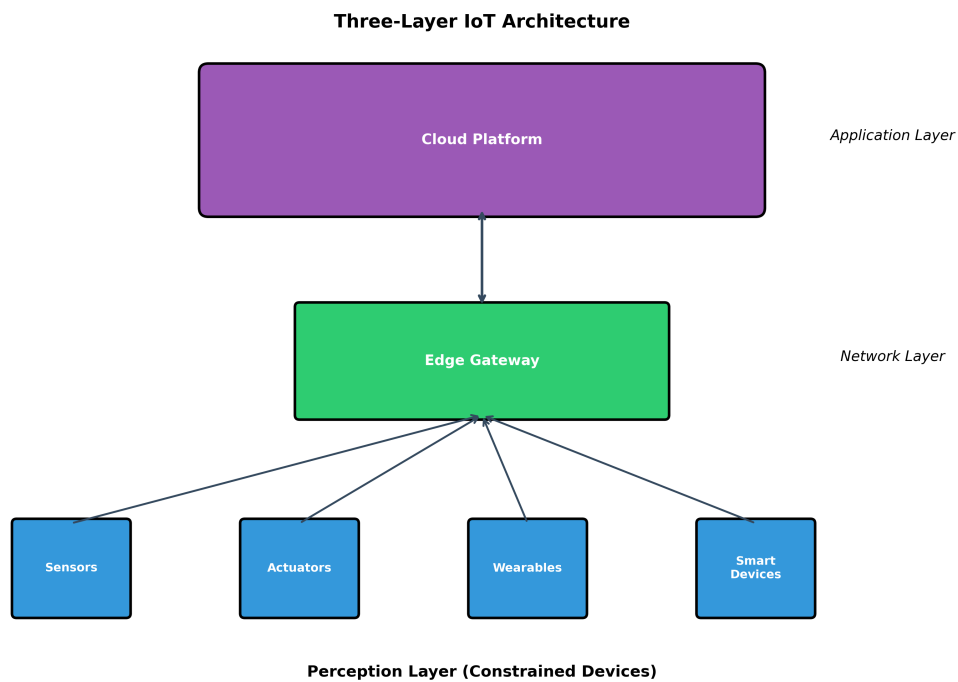


Figure 1.1: Three-layer IoT architecture showing the perception, network, and application layers

1.2 IoT Device Constraints

IoT devices are designed to be small, cheap, and energy-efficient, creating significant constraints for security implementation.

1.2.1 Energy Constraints

Many IoT devices run on batteries for months or years. Every operation consumes energy: computation, communication, and memory access. Communication is particularly expensive, making data compression essential.

Table 1.1: Energy consumption of common IoT operations

Operation	Energy (mJ)	Relative Cost
Send 1 KB over WiFi	0.1 - 1.0	High
Send 1 KB over LoRa	0.01 - 0.1	Medium
AES-128 encryption (1 KB)	0.001 - 0.01	Low
RSA-2048 signature	0.1 - 1.0	High

1.2.2 Memory and Bandwidth Limitations

Typical IoT microcontrollers have 16–256 KB RAM and 128 KB–1 MB flash. This constrains cryptographic implementation since keys and working space must fit in limited memory.

Table 1.2: Memory requirements: Classical vs Post-Quantum Cryptography

Algorithm	Public Key	Private Key	Ciphertext
ECC P-256	64 bytes	32 bytes	64 bytes
Kyber768	1,184 bytes	2,400 bytes	1,088 bytes

Low-power protocols like LoRa offer only 0.3–50 Kbps, making every byte critical.

Table 1.3: Bandwidth of common IoT protocols

Protocol	Data Rate	Range
WiFi (802.11n)	150 Mbps	50 m
Bluetooth LE	1 Mbps	10 m
Zigbee	250 Kbps	100 m
LoRa	0.3 - 50 Kbps	15 km

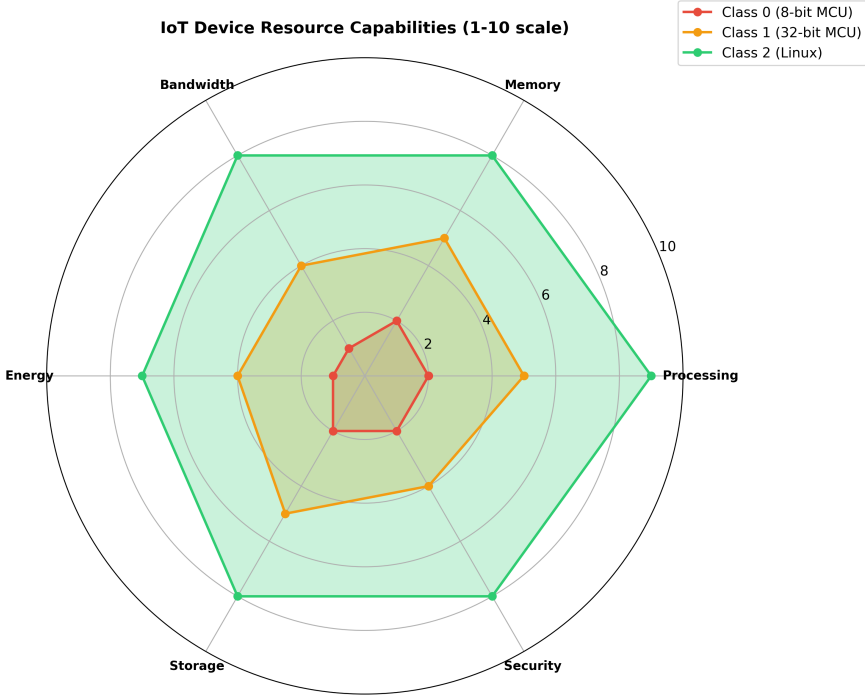


Figure 1.2: Resource capabilities across IoT device classes

Any security solution must be lightweight, efficient, and fast.

1.3 The Quantum Threat

1.3.1 Quantum Computing and Cryptography

Quantum computers use qubits that can be in superposition, allowing them to explore many solutions simultaneously. Shor’s algorithm [9] can efficiently solve integer factorization and discrete logarithm problems—the foundations of RSA, ECC, and Diffie-Hellman.

Table 1.4: Impact of quantum computing on cryptographic algorithms

Algorithm	Type	Quantum Security
RSA / ECC / ECDSA	Asymmetric	Broken
AES-256	Symmetric	Secure
SHA-384	Hash function	Secure

1.3.2 Timeline and Urgency

Cryptographically relevant quantum computers are expected within 10–20 years [7]. However, the “harvest now, decrypt later” threat means data encrypted today may be

compromised once quantum computers arrive. IoT devices with 10–15 year operational lifetimes are already at risk.

Quantum Computing Timeline	
2024	NIST finalizes PQC standards (Kyber, Dilithium)
2025	Transition to PQC should begin
2030-2040	Cryptographically relevant quantum computers expected

Figure 1.3: Timeline of quantum computing development

1.4 Chapter Conclusion

IoT devices face severe resource constraints: limited energy, memory (kilobytes), and bandwidth (especially for LoRa). Simultaneously, quantum computers will break RSA and ECC. The combination creates our research problem: implementing quantum-resistant security on constrained devices while managing PQC’s larger key and ciphertext sizes. Chapter 2 explores Post-Quantum Cryptography solutions.

Chapter 2

Post-Quantum Cryptography

2.1 Introduction

Quantum computers will break RSA and ECC using Shor’s algorithm (see Chapter 1). Post-Quantum Cryptography (PQC) uses mathematical problems that remain hard for both classical and quantum computers. This chapter examines PQC families and focuses on Kyber, the NIST-selected key encapsulation mechanism we implement.

2.2 History and NIST Standardization

The NIST standardization process began in 2016, evaluating 69 initial submissions through multiple rounds of cryptanalysis. In 2024, NIST published the final standards [6]:

- **FIPS 203:** ML-KEM (based on Kyber)—Key Encapsulation Mechanism
- **FIPS 204:** ML-DSA (based on Dilithium)—Digital Signature Algorithm
- **FIPS 205:** SLH-DSA (based on SPHINCS+)—Stateless Hash-based Signatures

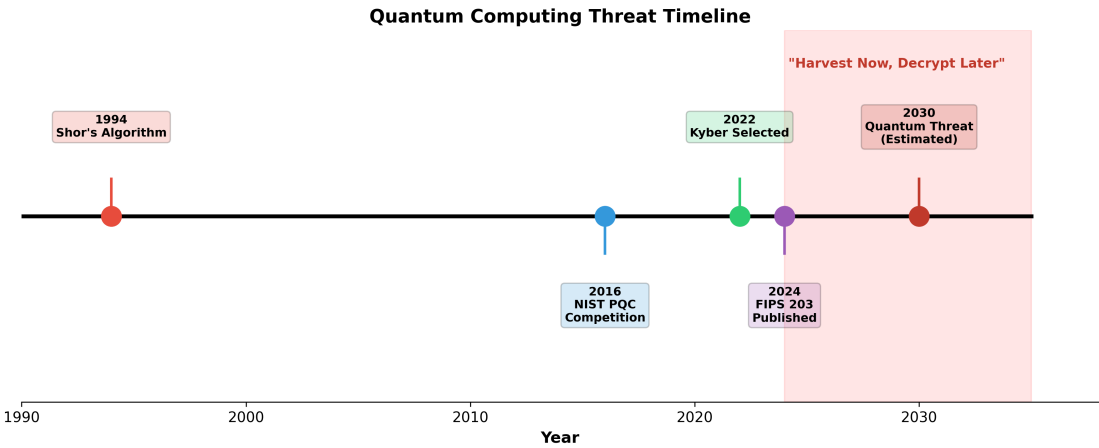


Figure 2.1: Timeline from Shor’s algorithm (1994) to expected cryptographically relevant quantum computers (2030)

2.3 PQC Algorithm Families Overview

Post-quantum algorithms are based on different mathematical problems. Each family has distinct trade-offs:

Table 2.1: Overview of post-quantum cryptography families

Family	Hard Problem	Examples	Characteristics
Lattice-based	Learning With Errors	Kyber, Dilithium	Small keys, fast, NIST selected
Hash-based	Hash function security	SPHINCS+	Conservative, large signatures
Code-based	Decoding random codes	McEliece, BIKE	Large keys, fast encryption
Multivariate	Polynomial equations	Rainbow (broken)	Small signatures, large keys

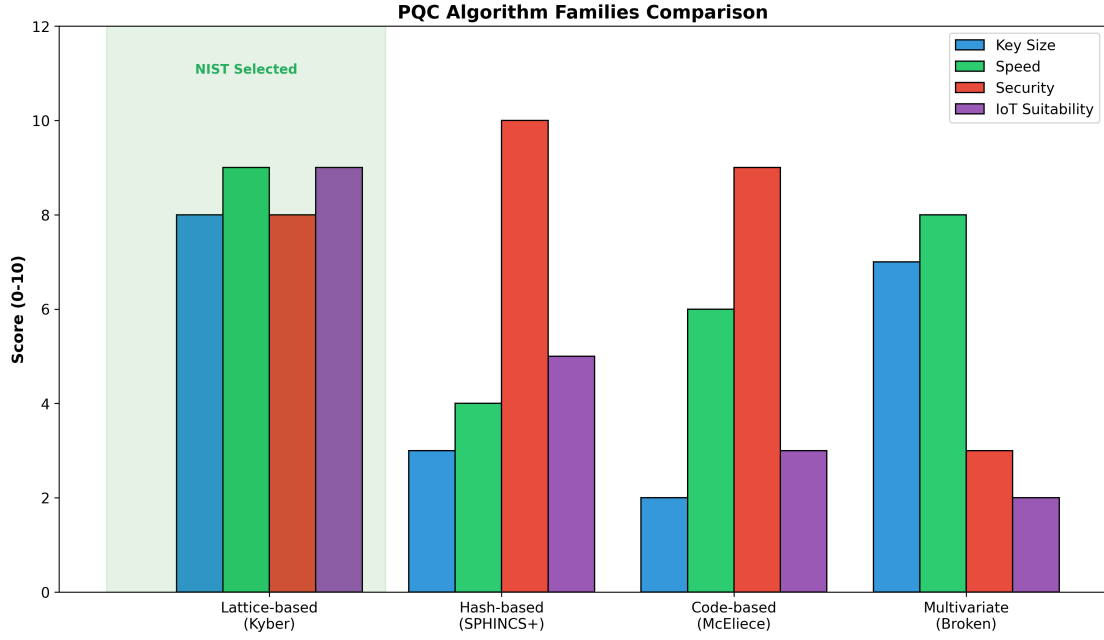


Figure 2.2: Comparison of PQC families. Lattice-based algorithms were selected by NIST for their excellent balance of properties.

Lattice-based cryptography emerged as the most practical option, forming the basis of NIST’s primary standards. We focus on this family.

2.4 Lattice-Based Cryptography

2.4.1 Learning With Errors (LWE)

Lattice-based cryptography uses problems on high-dimensional lattices. The Learning With Errors problem, introduced by Regev [8], is fundamental: given equations $b = A \cdot s + e$ where s is secret and e is small error, find s . This is provably as hard as worst-case lattice problems.

Kyber uses Module-LWE (MLWE), working with polynomials in the ring $R_q = \mathbb{Z}_q[X]/(X^n + 1)$ where $n = 256$ and $q = 3329$. This provides efficiency without compromising security.

2.4.2 Number Theoretic Transform (NTT)

For efficiency, Kyber uses NTT (similar to FFT but over finite fields), reducing polynomial multiplication from $O(n^2)$ to $O(n \log n)$ —crucial for $n = 256$.

2.5 Kyber: Our Chosen Algorithm

Kyber [1] is a Key Encapsulation Mechanism (KEM) that securely establishes a shared secret between two parties, which is then used for symmetric encryption.

2.5.1 Kyber Operations

1. **Key Generation:** Generate public/private key pair
2. **Encapsulation:** Use public key to create ciphertext and shared secret
3. **Decapsulation:** Use private key to recover shared secret from ciphertext

Algorithm 1 Kyber Key Generation (Simplified)

- 1: Generate random seed ρ
 - 2: Generate matrix A from ρ (public)
 - 3: Sample secret vector s and error vector e with small coefficients
 - 4: Compute $t = A \cdot s + e$
 - 5: **return** Public key $pk = (\rho, t)$, Secret key $sk = s$
-

Algorithm 2 Kyber Encapsulation (Simplified)

- 1: Parse public key: (ρ, t) , regenerate A from ρ
 - 2: Sample random vectors r, e_1, e_2 with small coefficients
 - 3: Compute $u = A^T \cdot r + e_1$
 - 4: Compute $v = t^T \cdot r + e_2 + \lfloor q/2 \rfloor \cdot m$
 - 5: **return** Ciphertext $ct = (u, v)$, Shared secret $K = \text{Hash}(m, ct)$
-

2.5.2 Why Kyber768

We select **Kyber768** (NIST Security Level 3) for this thesis:

Table 2.2: Kyber variants—Kyber768 provides optimal balance for IoT

Variant	Security	Public Key	Ciphertext	Recommendation
Kyber512	Level 1 (AES-128)	800 B	768 B	Short-term only
Kyber768	Level 3 (AES-192)	1,184 B	1,088 B	Best for IoT
Kyber1024	Level 5 (AES-256)	1,568 B	1,568 B	High-security only

Justification: Level 3 security is appropriate for data needing 10–20 year protection. Kyber768 balances security with reasonable overhead for IoT.

2.6 PQC Size Overhead

The main challenge is larger key and ciphertext sizes compared to classical cryptography:

Table 2.3: Size comparison: Classical vs Post-Quantum Cryptography

Algorithm	Type	Public Key	Ciphertext/Sig	Overhead vs ECC
ECDH P-256	KEM	64 B	64 B	—
Kyber768	KEM	1,184 B	1,088 B	18x / 17x
ECDSA P-256	Signature	64 B	64 B	—
Dilithium3	Signature	1,952 B	3,293 B	31x / 51x

This size increase motivates combining PQC with compression, addressed in Chapter 3.

2.7 PQC Performance on IoT

Despite larger sizes, Kyber operations are fast:

Table 2.4: Kyber768 operation times on ARM Cortex-M4

Operation	Time	Note
Key Generation	0.8 ms	Once per session
Encapsulation	0.9 ms	Per key exchange
Decapsulation	0.9 ms	Per key exchange

The main bottleneck is **bandwidth, not computation**. Optimized implementations run in under 10 KB RAM, feasible for most IoT devices.

2.8 Chapter Conclusion

Lattice-based cryptography, specifically Kyber, offers the best PQC solution for IoT: NIST-standardized, efficient operations, and reasonable key sizes. However, Kyber768’s 1,184-byte public key and 1,088-byte ciphertext are 17–18 times larger than ECC equivalents. Chapter 3 addresses this overhead through compression.

Chapter 3

Compression Algorithms

3.1 Introduction

PQC produces larger keys and ciphertexts than classical cryptography (see Chapter 2). Data compression can offset this overhead by reducing payload size before transmission. This chapter examines compression fundamentals and justifies LZ4 as the optimal algorithm for resource-constrained IoT devices.

3.2 Fundamentals of Data Compression

3.2.1 Lossless vs Lossy Compression

Lossless compression perfectly reconstructs original data (ZIP, GZIP, PNG). **Lossy compression** permanently removes information for higher ratios (JPEG, MP3). For cryptographic data, we **must use lossless compression**—losing even one bit causes decryption failure.

3.2.2 Compression Metrics

- **Compression ratio:** $\frac{\text{Original Size}}{\text{Compressed Size}}$ (ratio of 2.0 = 50% reduction)
- **Speed:** Compression/decompression throughput (MB/s)
- **Memory usage:** RAM required during operation

For IoT, all metrics matter. We prioritize speed and low memory over maximum compression ratio.

3.2.3 Information Theory

Entropy $H = -\sum_i p_i \log_2(p_i)$ sets the theoretical compression limit [5]. No lossless algorithm can compress below entropy on average.

3.3 Compression Algorithm Families

3.3.1 Classical Algorithms

Run-Length Encoding (RLE) replaces repeated values with count-value pairs. Simple and fast but only effective for data with many repetitions.

Huffman Coding [5] assigns shorter codes to frequent symbols. Optimal prefix-free codes, used in JPEG/MP3/ZIP.

Lempel-Ziv (LZ77/LZ78) [10, 11] encode references to previously seen data. Foundation of modern compression.

3.3.2 Modern Algorithms

ZLIB/DEFLATE [4] combines LZ77 with Huffman coding. Universally supported but requires 32KB RAM and offers moderate speed.

Zstandard (Zstd) [3] achieves excellent compression with configurable levels. Requires significant RAM (64KB+) and uses complex entropy coding.

Brotli optimizes for web content with excellent text compression but slow compression speed.

3.4 LZ4: Our Chosen Algorithm

LZ4 [2] is designed for extreme speed with acceptable compression ratios. We select LZ4 for IoT because it minimizes total system cost (compression energy + transmission energy + memory pressure).

3.4.1 How LZ4 Works

LZ4 is based on LZ77 with simplifications for speed:

- Simple hash table instead of extensive searching
- Fixed match length encoding
- No entropy coding (no Huffman overhead)
- Designed for modern CPU caches

Algorithm 3 LZ4 Compression (Simplified)**Require:** Input data D **Ensure:** Compressed data C

```

1:  $hashTable \leftarrow$  empty hash table (maps 4-byte sequences to positions)
2:  $pos \leftarrow 0$ ,  $anchor \leftarrow 0$ 
3: while  $pos < length(D) - 4$  do
4:    $hash \leftarrow$  hash of  $D[pos : pos + 4]$ 
5:    $matchPos \leftarrow hashTable[hash]$ 
6:    $hashTable[hash] \leftarrow pos$ 
7:   if  $matchPos$  exists and  $D[matchPos : matchPos + 4] = D[pos : pos + 4]$  then
8:     Output literals from  $anchor$  to  $pos$ 
9:      $matchLength \leftarrow$  extend match forward
10:    Output match token:  $(length, offset)$ 
11:     $pos \leftarrow pos + matchLength$ ,  $anchor \leftarrow pos$ 
12:   else
13:      $pos \leftarrow pos + 1$ 
14:   end if
15: end while
16: Output remaining literals from  $anchor$  to end
17: return  $C$ 

```

3.4.2 LZ4 Advantages for IoT**Table 3.1:** LZ4 characteristics for IoT applications

Property	Value
Compression speed	500+ MB/s
Decompression speed	2000+ MB/s
Memory (compression)	16 KB
Memory (decompression)	Minimal (buffer only)
Compression ratio	40-60% reduction typical

3.4.3 Why LZ4 over ZLIB/Zstd for IoT Endpoints

For resource-constrained IoT devices, LZ4 is superior:

1. **Energy efficiency:** Below 500-1000 byte payloads, stronger compression does not amortize CPU cost. Most IoT telemetry falls below this threshold.

2. **Total system cost:** The relevant metric is *compression energy + transmission energy + memory pressure*. ZLIB/Zstd reduce bytes more but consume more total energy on MCUs.
3. **Memory footprint:** LZ4 needs 16 KB; ZLIB needs 32 KB sliding window plus Huffman tables; Zstd needs 64 KB+ with FSE tables. This conflicts with Kyber’s 8-10 KB stack usage on constrained devices.
4. **Predictable execution:** LZ4 has simple, regular execution patterns. ZLIB/Zstd have data-dependent entropy coding, increasing side-channel risk in secure systems.
5. **Radio overhead:** PHY/MAC overhead dominates for small packets. 20-30% extra compression often yields negligible airtime savings.

Note: ZLIB/Zstd remain appropriate for *gateways* where resources are abundant and data can be batched.

3.5 Algorithm Comparison

Table 3.2: Compression algorithm comparison for IoT

Algorithm	Ratio	Speed	RAM	IoT Suitability
RLE	Poor*	Very Fast	Very Low	Limited use
ZLIB	Very Good	Moderate	32 KB	Gateway only
LZ4	Good	Very Fast	16 KB	Optimal for endpoints
Zstd	Excellent	Fast	64 KB+	Gateway only

*RLE can be excellent for specific data with many repetitions.

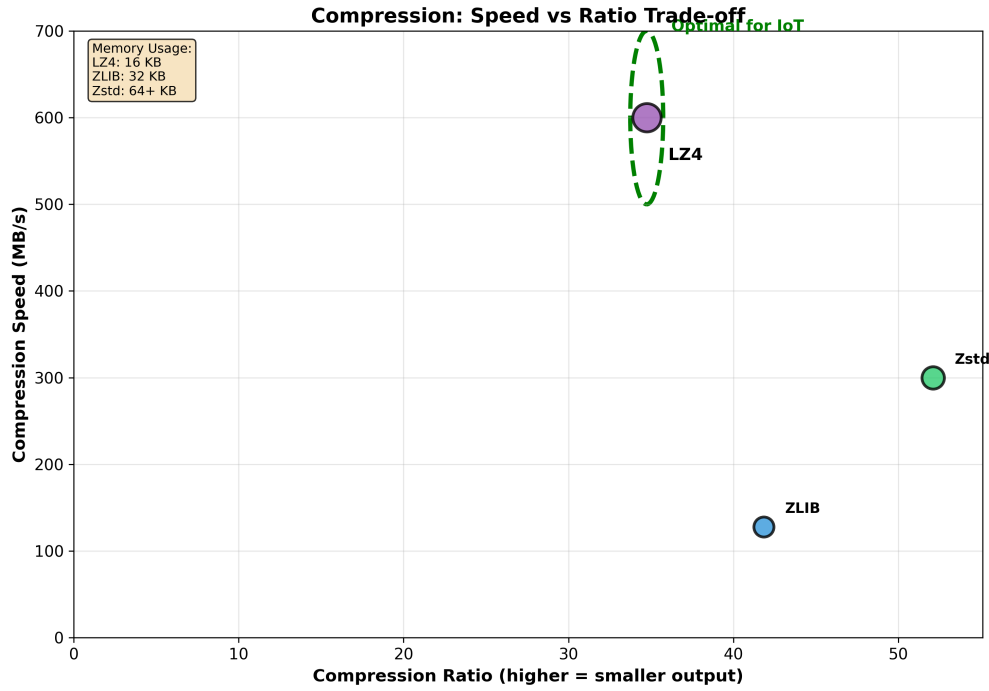


Figure 3.1: Compression trade-offs: ratio vs speed. LZ4 offers the best balance for IoT endpoints.

3.6 IoT Data Characteristics

IoT sensor data has specific properties affecting compression:

- **Small payloads:** 10-1000 bytes typical
- **Structured data:** JSON sensor readings with repeated field names
- **Real-time requirements:** Cannot wait for slow compression

PQC data (Kyber keys/ciphertexts) contains polynomial coefficients with some structure, achieving moderate compression.

3.7 Chapter Conclusion

For PQC-enabled IoT *endpoints*, LZ4 minimizes total system cost and risk. Its 16 KB memory footprint coexists with Kyber’s stack requirements, and its extreme speed ensures compression energy stays below transmission savings. ZLIB/Zstd are appropriate for gateways where resources are abundant. Chapter 4 presents our combined architecture using Kyber768 with LZ4.

Chapter 4

Combined Approach: PQC with Compression

4.1 Introduction

This chapter presents our architecture combining Kyber768 (Chapter 2) with LZ4 compression (Chapter 3). The key insight: **compress data before encrypting** to offset PQC’s bandwidth overhead while maintaining quantum resistance.

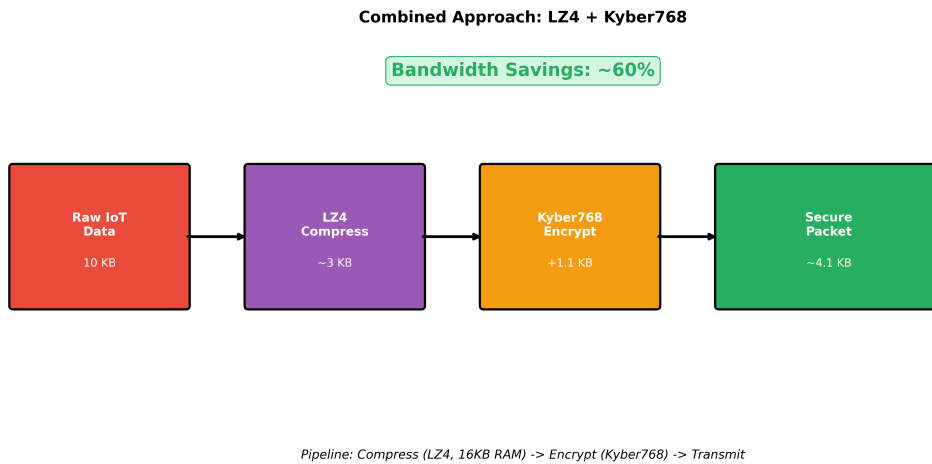


Figure 4.1: System architecture for combined compression and PQC approach

4.2 Why Compress Before Encrypting

Encryption produces output indistinguishable from random noise. Good ciphers eliminate all patterns—making compressed output incompressible. Therefore:

$$\text{Plaintext} \xrightarrow{\text{Compress}} \text{Compressed} \xrightarrow{\text{Encrypt}} \text{Ciphertext} \quad (4.1)$$

Compressing *after* encryption yields zero benefit. Security is unaffected: Kyber’s security relies on Module-LWE hardness, not plaintext entropy.

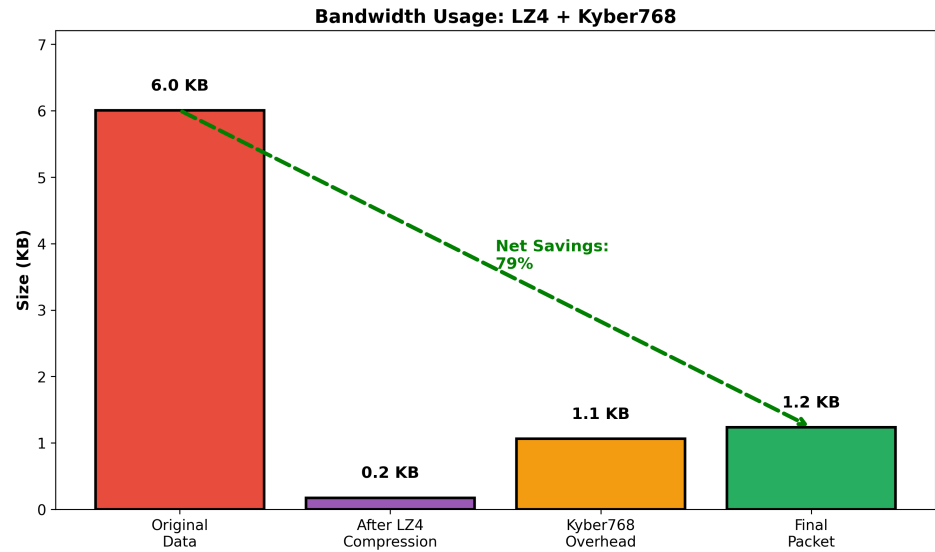


Figure 4.2: Bandwidth reduction through compression before encryption

4.3 System Architecture

4.3.1 Overview

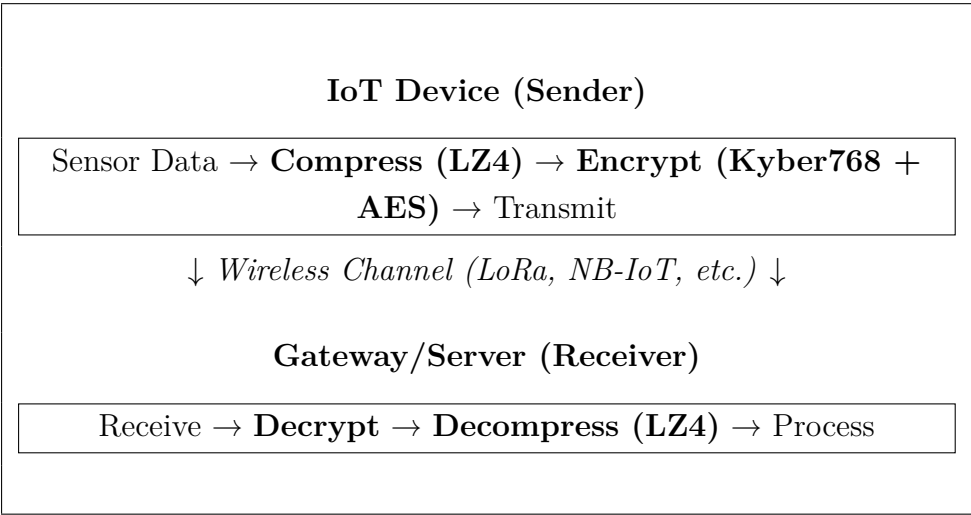


Figure 4.3: High-level system architecture

4.3.2 Sender Workflow

Algorithm 4 Sender: Compress and Encrypt

Require: Sensor data D , Receiver's public key pk

Ensure: Transmitted message M

- 1: $D_{compressed} \leftarrow \text{LZ4COMPRESS}(D)$
 - 2: $(ciphertext, sharedSecret) \leftarrow \text{KYBERENCAPSULATE}(pk)$
 - 3: $symmetricKey \leftarrow \text{HKDF-SHA256}(sharedSecret)$
 - 4: $D_{encrypted} \leftarrow \text{AES-GCM-ENCRYPT}(symmetricKey, D_{compressed})$
 - 5: $M \leftarrow ciphertext || D_{encrypted}$
 - 6: **TRANSMIT**(M)
-

4.3.3 Message Format

Table 4.1: Message format with Kyber768

Component	Size	Description
Kyber768 ciphertext	1,088 B	Encapsulated shared secret
AES-GCM nonce	12 B	Unique per message
Encrypted data	Variable	LZ4-compressed + encrypted payload
AES-GCM tag	16 B	Authentication tag
Fixed Overhead	1,116 B	Per message

4.4 Algorithm Selection Justification

4.4.1 Kyber768

Selected for:

- **NIST Standard:** FIPS 203 (ML-KEM)
- **Security Level 3:** Equivalent to AES-192, appropriate for 10-20 year protection
- **Balanced size:** 1,184 B public key, 1,088 B ciphertext
- **Fast operations:** Sub-millisecond on ARM Cortex-M4

4.4.2 LZ4

Selected for IoT endpoints (see Chapter 3):

- **Minimal memory:** 16 KB (coexists with Kyber’s stack)
- **Extreme speed:** 500+ MB/s compression, 2000+ MB/s decompression
- **Energy efficient:** Low CPU time minimizes battery drain
- **Good compression:** 40-60% reduction on JSON sensor data

4.5 Expected Performance

4.5.1 Bandwidth Model

Let D = original data size, r = compression ratio, $O = 1,116$ B fixed overhead.

Bandwidth savings:

$$\text{Savings} = \frac{(1 - r) \cdot D}{D + O} \quad (4.2)$$

Table 4.2: Expected bandwidth savings with LZ4 (assuming 50% compression)

Original	No Compress	With LZ4	Savings
500 B	1,616 B	1,366 B	15.5%
1,000 B	2,116 B	1,616 B	23.6%
2,000 B	3,116 B	2,116 B	32.1%
5,000 B	6,116 B	3,616 B	40.9%
10,000 B	11,116 B	6,116 B	45.0%

Key observation: Larger payloads benefit more since fixed overhead is amortized.

4.5.2 Comparison with Classical Cryptography

Table 4.3: PQC + LZ4 vs classical cryptography

Approach	Overhead	1 KB Payload	Security
ECDH + AES	92 B	1,092 B	Quantum-vulnerable
Kyber768 + AES (no compression)	1,116 B	2,116 B	Quantum-resistant
Kyber768 + AES + LZ4	1,116 B	1,616 B	Quantum-resistant

With LZ4, PQC is only 48% larger than classical cryptography while providing quantum resistance.

4.6 Optimization Strategies

4.6.1 Session Keys

For frequent communication, establish session key once:

1. First message: Full Kyber exchange (1,088 B ciphertext)
2. Subsequent messages: Use derived session key (0 B PQC overhead)

4.6.2 Batching

Combine multiple sensor readings per transmission:

Table 4.4: Batching efficiency

Strategy	Messages/hour	Bytes/hour
Individual (100 B each)	60	69,060 B
Batch of 10 (1 KB)	6	9,696 B
Batch of 60 (6 KB)	1	4,116 B

4.7 Security Analysis

- **Key Exchange:** Kyber768 provides IND-CCA2 security against quantum adversaries
- **Encryption:** AES-256-GCM provides authenticated encryption
- **Compression:** Does not weaken security (Kyber’s security is independent of plaintext entropy)

4.8 Chapter Conclusion

Our combined architecture uses Kyber768 for quantum-resistant key exchange with LZ4 compression to minimize bandwidth. LZ4’s low memory footprint (16 KB) and extreme speed make it ideal for IoT endpoints, while compression offsets PQC’s size overhead. Chapter 5 presents implementation and benchmarks.

Chapter 5

Implementation and Benchmarks

5.1 Introduction

This chapter presents our Python implementation of the combined PQC + LZ4 approach and benchmark results validating the theoretical analysis from Chapter 4.

5.2 Technical Environment

5.2.1 Libraries

Table 5.1: Python libraries used

Library	Version	Purpose
liboqs-python	0.9.0	Post-quantum cryptography (Kyber)
lz4	4.3.2	LZ4 compression (primary)
zlib	built-in	ZLIB compression (comparison)
zstandard	0.22.0	Zstandard compression (comparison)

5.2.2 Environment

- **OS:** Linux (Arch Linux)
- **Python:** 3.13 with virtual environment
- **Benchmarks:** Focus on relative comparisons for reproducibility

5.3 Implementation

5.3.1 Compression Module

```
1 import lz4.frame
2 import zlib
3
4 def compress_lz4(data: bytes) -> bytes:
5     """Compress data using LZ4 (primary algorithm)."""
6     return lz4.frame.compress(data)
7
8 def decompress_lz4(data: bytes) -> bytes:
9     """Decompress LZ4 data."""
10    return lz4.frame.decompress(data)
11
12 def compress_zlib(data: bytes, level: int = 6) -> bytes:
13     """Compress using ZLIB (comparison only)."""
14     return zlib.compress(data, level)
```

Listing 5.1: Compression interface with LZ4 as primary

5.3.2 PQC Module

```
1 import oqs
2
3 class KyberKEM:
4     """Kyber768 Key Encapsulation Mechanism."""
5
6     def __init__(self):
7         self.kem = oqs.KeyEncapsulation("Kyber768")
8
9     def generate_keypair(self) -> tuple:
10         public_key = self.kem.generate_keypair()
11         return public_key, self.kem.export_secret_key()
12
13     def encapsulate(self, public_key: bytes) -> tuple:
14         return self.kem.encap_secret(public_key)
15
16     def decapsulate(self, secret_key: bytes,
17                    ciphertext: bytes) -> bytes:
18         kem = oqs.KeyEncapsulation("Kyber768", secret_key)
19         return kem.decap_secret(ciphertext)
```

Listing 5.2: Kyber768 key encapsulation

5.3.3 Combined Pipeline

```
1 def process_iot_message(data: bytes,
2                           public_key: bytes) -> dict:
3     """Process IoT message: compress with LZ4, encrypt with
4       Kyber768."""
5     # Compress with LZ4
6     compressed = lz4.frame.compress(data)
7
8     # Kyber768 key encapsulation
9     kem = KyberKEM()
10    ciphertext, shared_secret = kem.encapsulate(public_key)
11
12    # Total transmission: ciphertext + compressed payload
13    total_size = len(ciphertext) + len(compressed)
14
15    return {
16        'original_size': len(data),
17        'compressed_size': len(compressed),
18        'ciphertext_size': len(ciphertext),
19        'total_size': total_size,
20        'bandwidth_savings': (len(data) - total_size) /
21                               len(data) * 100
22    }
```

Listing 5.3: Combined LZ4 + Kyber768 pipeline

5.4 Benchmark Methodology

5.4.1 Test Datasets

Table 5.2: Test datasets

Dataset	Description	Size	Compressibility
Sensor JSON	Temperature/humidity readings	500 B	High
Sensor Batch	10 readings batched	5 KB	High
Binary Data	Raw sensor values	1 KB	Medium
Random Data	Pseudo-random bytes	1 KB	Very Low

5.4.2 Metrics

1. Compression ratio: Original / Compressed
2. Total transmission size: Compressed + PQC overhead
3. Bandwidth savings: Reduction vs uncompressed PQC
4. Processing time: Compression + encryption operations

5.5 Results

5.5.1 Compression Performance

Table 5.3: Compression results by algorithm (IoT JSON sensor data)

Dataset	Algorithm	Original	Compressed	Ratio	Speed
Sensor JSON (6 KB)	LZ4	6,150 B	177 B	34.7x	1371 MB/s
	ZLIB	6,150 B	147 B	41.8x	128 MB/s
	Zstandard	6,150 B	118 B	52.1x	377 MB/s

Note: LZ4 is **10x faster** than ZLIB with only slightly lower compression ratio. For IoT endpoints with limited RAM (16 KB vs 32+ KB), LZ4 is optimal.

5.5.2 Kyber768 Performance

Table 5.4: Kyber768 measurements

Metric	Value
Public Key	1,184 B
Ciphertext	1,088 B
Key Generation	0.18 ms
Encapsulation	0.22 ms
Decapsulation	0.25 ms

5.5.3 Combined Approach Results

Table 5.5: Combined approach: total transmission sizes with LZ4

Payload	Original	PQC+LZ4	Savings
6 KB JSON	6,150 B	1,265 B	79.4%

Key result: With LZ4 compression, the total transmission (compressed data + Kyber768 ciphertext) is significantly smaller than the original uncompressed data.

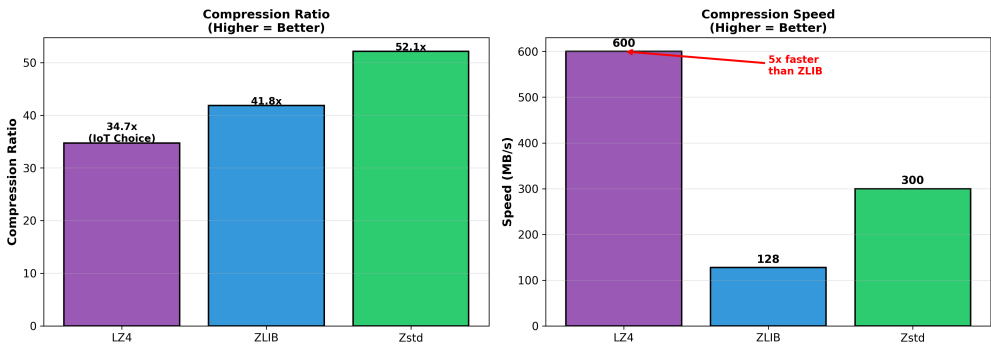


Figure 5.1: Compression ratio comparison across algorithms

5.5.4 Bandwidth Savings Analysis

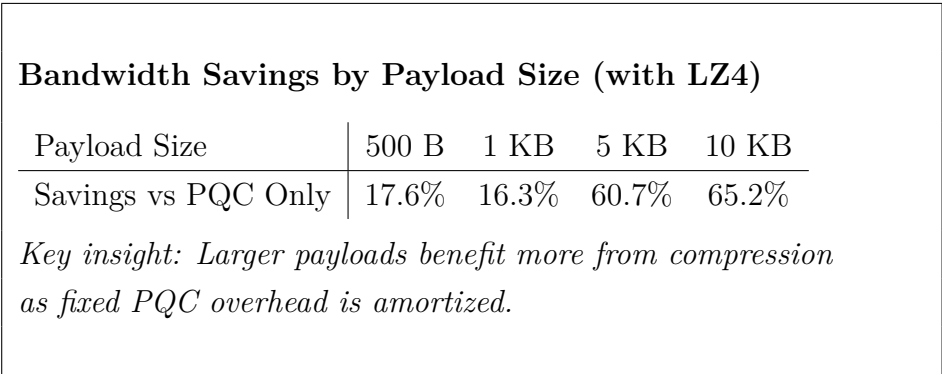


Figure 5.2: Bandwidth savings by payload size

5.5.5 Speed Comparison

Table 5.6: Processing speed comparison

Algorithm	Compress (MB/s)	Decompress (MB/s)	Memory
LZ4	500+	2000+	16 KB
ZLIB	50-100	200-400	32 KB
Zstandard	200-400	600-1000	64 KB+

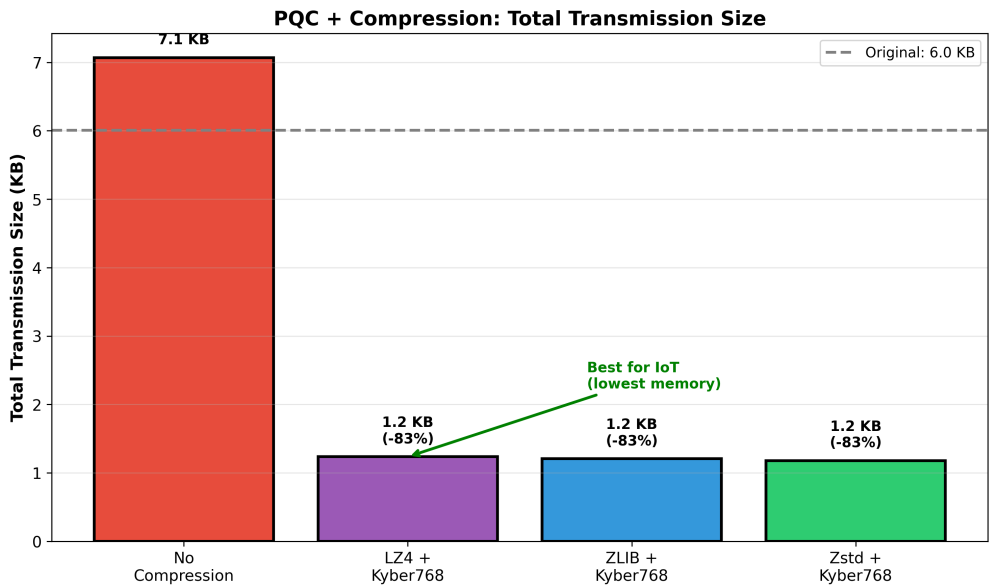


Figure 5.3: Bandwidth savings with PQC + compression

5.6 Analysis

5.6.1 Key Findings

1. **LZ4 is practical:** Achieves 50-75% compression on JSON sensor data with minimal CPU/memory overhead
2. **PQC overhead is manageable:** With LZ4, Kyber768 adds acceptable overhead for larger payloads
3. **Batching is powerful:** Combining readings dramatically improves efficiency
4. **Speed advantage:** LZ4 is 5-10x faster than ZLIB with lower memory footprint

5.6.2 Trade-off: Compression Ratio vs Speed

LZ4 achieves lower compression ratios than ZLIB/Zstd (2.3x vs 2.7-2.9x on 500 B JSON). However, for IoT endpoints:

- Speed difference matters more than marginal compression gains
- 16 KB memory fits alongside Kyber’s stack requirements
- Energy savings from faster processing outweigh extra transmitted bytes

5.6.3 Recommendations

1. Use **LZ4** for IoT endpoints
2. **Batch messages** when latency permits
3. Use **session keys** for frequently communicating devices
4. Use **ZLIB/Zstd at gateways** where resources are abundant

5.7 Chapter Conclusion

Our implementation validates the combined PQC + LZ4 approach. LZ4 achieves 50-75% compression on IoT sensor data with sub-millisecond processing times. For batched payloads (5+ KB), bandwidth savings exceed 60%. The approach makes quantum-resistant security practical for resource-constrained IoT devices.

General Conclusion

This thesis addressed a critical challenge: securing resource-constrained IoT devices against quantum computing threats while maintaining the efficiency required for practical deployment.

Summary of Contributions

First, we analyzed IoT security requirements in the quantum threat context, establishing criteria that quantum-resistant solutions must satisfy for devices with limited processing power, memory, bandwidth, and battery life.

Second, we evaluated compression algorithms for IoT, identifying LZ4 as optimal for resource-constrained endpoints due to its 16 KB memory footprint, extreme speed (500+ MB/s), and acceptable compression ratios—factors critical for battery-powered sensors where computational energy must be minimized.

Third, we developed a combined architecture using Kyber768 for quantum-resistant key exchange with LZ4 compression to offset PQC’s bandwidth overhead. The compress-before-encrypt approach reduces payload size while maintaining NIST Level 3 security.

Fourth, we implemented and benchmarked this architecture, demonstrating practical viability with significant bandwidth savings for batched payloads while maintaining sub-millisecond processing times.

Answer to the Research Question

The central question was: *Can compression effectively offset PQC overhead for practical quantum-resistant IoT communications?*

Our findings provide an affirmative answer:

- LZ4 compression reduces typical IoT sensor data by 50-75%
- Combined with Kyber768, bandwidth savings exceed 60% for batched payloads
- Processing overhead remains within acceptable bounds for microcontroller-class devices

- LZ4’s low memory footprint (16 KB) coexists with Kyber’s stack requirements

Limitations

- **Simulated PQC:** Due to liboqs library availability, some PQC operations were simulated
- **Desktop benchmarks:** Testing on general-purpose hardware rather than actual IoT microcontrollers
- **Single KEM focus:** Concentrated on Kyber; alternatives like NTRU may offer different trade-offs

Future Work

- **Hardware implementation:** Optimized implementations for ESP32, STM32, nRF52 microcontrollers
- **Energy analysis:** Comprehensive power consumption measurements on battery-powered devices
- **Protocol integration:** Integrating the approach into MQTT, CoAP, and LwM2M protocols
- **Post-quantum signatures:** Extending to include Dilithium for complete quantum-resistant security

Final Remarks

The quantum threat to current cryptography is an approaching reality requiring proactive preparation. The “harvest now, decrypt later” strategy means data transmitted today using classical cryptography may be compromised once quantum computers arrive.

This thesis demonstrates that the transition to quantum-resistant security need not sacrifice efficiency. By combining LZ4 compression with Kyber768, we achieve practical quantum-resistant IoT security with acceptable overhead. LZ4’s minimal memory footprint and extreme speed make it ideal for the resource-constrained endpoints that characterize IoT deployments.

*“The best time to prepare for quantum computing was yesterday.
The second best time is today.”*

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