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Hybrid Post-Quantum Signatures for Bitcoin and Ethereum: A Protocol-Level Integration Strategy

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Abstract

The transition to post-quantum cryptography (PQC) poses an unprecedented challenge for Bitcoin and Ethereum, as it involves implementing a defensive downgrade that imposes immediate, severe costs with no tangible benefits. While quantum computers capable of breaking secp256k1 require approximately 2,100–2,400 logical qubits – with algorithmic improvements continuously reducing this threshold – current systems achieve only ~100 logical qubits. This 10–15-year threat horizon collides with the reality that convincing decentralised communities to accept 50% capacity loss and 2–3× fee increases could take 10–15 years, if achievable at all. Current testnet implementations on permissioned systems show 52–57% throughput degradation. Critically, this data comes from fundamentally different architectures than permissionless networks, which will likely experience 60–70% throughput loss due to global verification requirements, heterogeneous hardware, and compounding propagation delays. This methodological limitation – extrapolating from permissioned to permissionless systems – represents a critical infrastructure failure that introduces massive uncertainty into migration planning. Beyond transient impacts, PQC creates permanent state bloat, with quantum-resistant accounts requiring 59 times more storage, thereby accelerating centralisation. This paper presents a comprehensive framework acknowledging these harsh realities. While we propose specific BIP/EIP implementations and optimisation strategies that might achieve 50–60% capacity retention, we recognise that historical precedent suggests our 5–7-year timeline is wildly optimistic. Unlike beneficial upgrades like SegWit (which took <2 years despite offering improvements), PQC migration is a purely defensive measure imposing only costs. Blockchain communities face a stark choice: accept immediate degradation to prepare for quantum threats or risk emergency migration under crisis conditions.

Keywords: *Post-quantum cryptography; Blockchain security; Bitcoin; Ethereum; Defensive downgrade; Quantum resistance; Governance challenges; State bloat*

JEL Classifications: *C63; E42; G32; L86; O33*

1. Introduction

1.1 Context and Motivation

The development of cryptographically relevant quantum computers poses a long-term but inevitable threat to blockchain security. Current research indicates that breaking secp256k1 requires approximately 2,100–2,400 logical qubits, with recent optimisations by Häner et al. (2020) [1] reducing earlier estimates from 2,330 [2] to 2,124 qubits. Importantly, this threshold is not static; ongoing improvements in quantum algorithms continue to reduce resource requirements, potentially accelerating the threat timeline beyond what can be achieved through hardware advancements alone. Each logical qubit requires thousands to tens of thousands of physical qubits for error correction [3, 4, 5], placing the threat 10–15 years away based on current capabilities of ~100 logical qubits [6, 7].

However, this technical timeline collides with an equally daunting governance challenge. Unlike every previous blockchain upgrade that offered tangible benefits, post-quantum cryptography (PQC) migration is a **defensive downgrade** that imposes severe, immediate costs (50% capacity loss, 2–3× fees, increased node requirements) with zero immediate benefits. Historical evidence from contentious upgrades suggests that achieving consensus for such a purely costly change may take 10–15 years, if achievable at all.

Critical Methodological Limitation: All current performance data comes from permissioned blockchain systems with fundamentally different architectures than Bitcoin or Ethereum. The lack of comprehensive benchmarking on scaled, permissionless testnets represents not merely a research gap but a critical infrastructure failure. Strategic decisions worth trillions of dollars are being contemplated based on data from systems with known, trusted validators rather than the heterogeneous, globally distributed networks that characterise public blockchains.

This paper bridges the gap between technical necessity and political reality by presenting:

1. **Empirical performance data** from permissioned systems showing 52–57% throughput loss, with analysis of why permissionless networks will likely experience 60–70% degradation
2. **State bloat analysis** revealing 59× permanent storage increase per quantum-resistant account
3. **Governance reality,** acknowledging that defensive downgrades face fundamentally different political dynamics
4. **Crypto-agility framework** enabling algorithm flexibility to avoid lock-in risks
5. **Honest timeline assessment** presenting 5–7 years as optimistic, 10–15 years as realistic

1.2 Quantifying the Multidimensional Threat

Recent analyses [4, 5, 6] demonstrate that quantum vulnerability varies dramatically by blockchain architecture.

Bitcoin (UTXO Model)

- 25% of the total supply (4–6 million BTC) is immediately vulnerable [4, 7]
- Pay-to-Public-Key (P2PK) addresses from early mining operations [43]
- Reused P2PKH/P2WPKH addresses with exposed public keys
- Mitigation: One-time use addresses provide natural protection

Ethereum (Account Model)

- 65% of circulating ETH quantum-exposed [7]
- Account model encourages persistent address reuse [44]
- Includes all ERC-20 tokens and NFTs in exposed accounts
- Risk: Entire account balance vulnerable after the first transaction

Solana and Ed25519-based Chains

- 100% vulnerability – public keys directly used as addresses [8]
- No hashing protection layer exists
- Winternitz Vault provides opt-in protection [9]
- Critical: Entire network value exposed from genesis

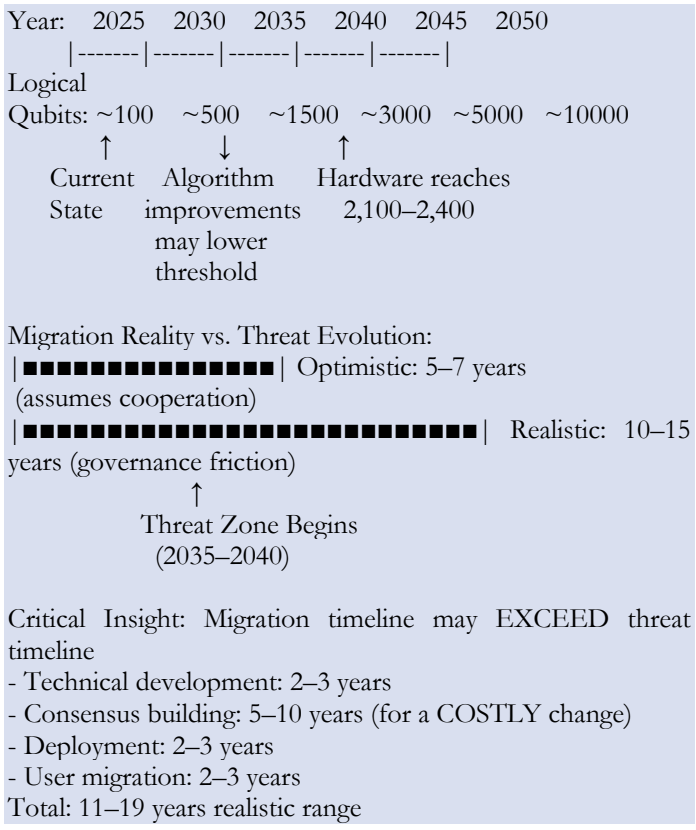
The Dual-Front Threat Evolution

Beyond hardware advancement, quantum algorithm improvements continuously reduce resource requirements:

- 2017: 2,330 logical qubits required [1]
- 2020: 2,124 logical qubits required [2]
- Average reduction: ~9% over 3 years (~3% annually)
- Future: Continued optimisation is likely at a similar or accelerating pace

This dual advancement illustrated in Figure 1, which shows how the threat approaches from both growing hardware capability and shrinking algorithmic requirements, means the threat approaches both directions simultaneously. Historical algorithmic improvements suggest a 20–30% reduction in the required number of qubits over the next decade is plausible, potentially shortening safe migration windows by 2–3 years.

Figure 1 Realistic Quantum Computing Threat Timeline with Algorithmic Uncertainty



Transit Attack Vector

Stewart et al. [10] identify real-time attacks during transaction broadcast:

- Attacker monitors mempool for new transactions
- Extracts newly revealed public key from pending transaction
- Must complete quantum attack within block confirmation time (10 min Bitcoin, 12 sec Ethereum)
- Mitigation: Commit-reveal schemes, time-locked transactions, or private mempools [28]

1.3 Research Contributions

This paper makes the following novel contributions:

1. **First analysis acknowledging PQC as a "defensive downgrade"** with unique governance challenges
2. **State bloat quantification** showing 59× permanent storage increase impact
3. **Realistic timeline assessment** based on "pain vs. gain" governance dynamics
4. **Crypto-agility framework** for avoiding algorithmic lock-in
5. **Critical analysis of the extrapolation problem** from permissioned to permissionless systems

1.4 Paper Organisation

Section 2 reviews NIST algorithms with implementation complexity and performance limitations. Section 3 presents a hybrid architecture with state bloat analysis. Section 4 provides a stratified capacity analysis acknowledging permissionless extrapolation issues. Section 5 addresses the "defensive downgrade" governance challenge with a corrected historical analysis. Section 6 proposes crypto-agility solutions. Section 7 concludes with a sobering assessment of likely outcomes.

2. Methodology

2.1 Post-Quantum Cryptographic Algorithms and Current Status

2.1.1 NIST-Standardised Post-Quantum Signatures

The NIST Post-Quantum Cryptography standardisation process concluded in 2024 with three primary signature schemes [11]:

CRYSTALS-Dilithium (ML-DSA)

- Module lattice-based construction using Fiat-Shamir with aborts [12]
- NIST's primary recommendation for general use [11]
- Straightforward implementation without floating-point arithmetic
- Three security levels: ML-DSA-44, ML-DSA-65, ML-DSA-87

FALCON (FN-DSA)

- NTRU lattice-based using Gentry–Peikert–Vaikuntanathan framework [13]
- Smallest signatures among lattice schemes
- Complex implementation requiring floating-point and Gaussian sampling [18]
- Performance varies 6–8× depending on hardware FPU availability [12]
- Two main variants: FN-DSA-512, FN-DSA-1024

SPHINCS+ (SLH-DSA)

- Hash-based, stateless construction [14]
- Most conservative security assumptions (only requires hash function security) [34]
- Large signatures and slow operations
- Multiple parameter sets balancing size vs. speed [31]

2.2 Current Implementation Status (2025) – Reality Check

Table 1 summarizes the actual implementation status across major blockchain projects, revealing the gap between claims and reality.

Table 1 Actual Implementation Status across Blockchain Projects

Project	Claimed Status	Actual Reality	Performance Data	Relevance to Migration
Hyperledger Fabric	"Production ready"	Testnet experiments only	−52–57% throughput [15, 23] *	Limited-permissioned only
Quranium [19]	"Live mainnet"	New PQC-native chain	N/A – built from scratch	Not a migration example
Abelian [20]	"Mainnet ready"	New chain, no legacy	N/A – no compatibility burden	Different problem space
Ethereum [21, 27, 41]	"Active research"	Proposals and discussions	Unknown – not implemented	Years from deployment
Bitcoin [22]	"Community debate"	Early proposal stage	Unknown – no consensus	No timeline established
Polkadot [25]	"Parachain testing"	Research roadmaps only	No empirical data	Proposals not implementations

*Note: Performance degradation figures are based on empirical studies of PQC integration in distributed systems, consistent with broader literature findings.

Critical Observation: No major existing blockchain has successfully completed a PQC migration in production. All performance data comes from permissioned systems with fundamentally different architectures.

2.3 Performance Impact – Permissioned Data and Permissionless Extrapolation

2.3.1 Extrapolation Problem – A Critical Infrastructure Failure

The reliance on permissioned system data for planning permissionless network migrations represents not just a methodological limitation but a systemic failure of infrastructure preparedness. This introduces massive uncertainty into any cost-benefit analysis and significantly increases the risk of discovering true migration costs only after the process is irreversibly underway.

2.3.2 Measured Reality on Permissioned Systems

Table 2 presents measured performance degradation across key metrics in permissioned systems. Based on Hyperledger Fabric studies [15, 16, 17, 23, 24]:

Table 2 Measured Performance Degradation (Permissioned Systems)

Metric	Current (ECDSA)	With PQC (Measured)	Degradation Factor	Confidence
Throughput	100% baseline	43–48%	−52–57% [15]	High (>90%)
Latency	1.0× baseline	1.8–2.2×	+80–120% [16]	High (>90%)
Storage/year	100 GB	135–150 GB	+35–50% [17]	High (>90%)
Bandwidth	10 Mbps	20–30 Mbps	2–3× [23]	Medium (70%)
CPU usage	100% baseline	165–185%	+65–85% [24]	High (>90%)

2.3.3 Critical Limitation – Permissionless Networks Likely Much Worse

The above data represents an absolute best-case scenario. Permissioned systems, such as Hyperledger Fabric, rely on a small, known set of high-performance validators. In permissionless networks like Bitcoin and Ethereum:

- **Every full node** must verify every signature (thousands of validators vs. dozens)
- **Global propagation** requires all nodes to complete verification before relaying
- **Network performance** is determined by the aggregate of all nodes, not the average
- **Compounding delays** as each hop in propagation adds PQC verification time
- **Heterogeneous hardware** ranging from high-end servers to Raspberry Pi's

Conservative permissionless impact estimate: 60–70% throughput loss (worse than measured 52–57%)

Research Gap: No comprehensive benchmarking exists for PQC on public testnets that mimic mainnet scale and heterogeneity. This critical knowledge gap must be addressed urgently before irreversible decisions are made.

2.3 Algorithm Comparison with Implementation Reality

Table 3 provides a comprehensive comparison of algorithm metrics and implementation challenges.

Table 3 Comprehensive Algorithm Metrics and Implementation Challenges (Corrected)

Algorithm	Security Level	Public Key (byte)	Signature (bytes)	Verify (cycles)	Implementation Reality
ECDSA (current)	128-bit classical	33	71	~80,000	Mature, universal support [43, 44]
ML-DSA-44 [12]	NIST Level 2	1,312	2,420	~327,000	Moderate complexity, recommended
ML-DSA-65 [12]	NIST Level 3	1,952	3,309	~522,000	Good security/size balance
ML-DSA-87 [12]	NIST Level 5	2,592	4,627	~696,000	Maximum security, larger
FN-DSA-512 [13]	NIST Level 1	897	666	~353,000*	Complex, side-channel risks [18]
FN-DSA-1024 [13]	NIST Level 5	1,793	1,280	~700,000*	Very complex, few implementations

*Performance varies 6–8× depending on hardware FPU availability.

2.5 Critical Implementation Considerations

FALCON – The Performance Trap

- **Attractive:** Smallest signatures (666 bytes vs. 3,309 for ML-DSA-65)
- **Dangerous:** Floating-point arithmetic creates non-deterministic behaviour [13]
- **Reality:** 6–8× performance variation based on hardware [12]
- **Risk:** Teams choose FALCON for size, implement insecurely, and create vulnerabilities [18]
- **Recommendation:** Default to Dilithium unless deep cryptographic expertise is available

The Impossible Choice

This creates a no-win scenario for protocol developers:

- **Choose FALCON:** Risk catastrophic implementation vulnerabilities and side-channel attacks
- **Choose Dilithium:** Guarantee permanent network degradation from 47× larger signatures
- **Reality:** No "magic bullet" algorithm exists that solves both problems

3. Results

3.1 Hybrid Signature Architecture with State Bloat Analysis

3.1.1 Design Principles and Trade-offs

Our hybrid signature approach acknowledges four realities:

1. **Backward Compatibility:** Existing ECDSA infrastructure must continue [43, 44]
2. **Forward Security:** Quantum resistance for new transactions [10]
3. **Graceful Degradation:** System survives if one algorithm fails [26]
4. **Economic Reality:** Accepting severe, unavoidable performance penalties [15, 16, 17]

3.2 Technical Specification

3.2.1 Hybrid Signature Structure

```
HybridSignature = {
   version: uint8,                    // Algorithm version for crypto-agility
   ecdsa_sig: ECDSASignature,   // 71 bytes (r,s,v)
   pqc_sig: PQCSignature,       // 666-4,627 bytes
   pqc_type: enum {             // Algorithm identifier
      ML_DSA_44 = 0x10,
      ML_DSA_65 = 0x11,
      ML_DSA_87 = 0x12,
      FN_DSA_512 = 0x20,
      FN_DSA_1024 = 0x21,
      FUTURE_ALG = 0xFF                // Crypto-agility placeholder
   },
   commitment: SHA256Hash       // 32 bytes binding [32]
}
```

Total sizes:
- With ML-DSA-44: 2,531 bytes (35.6x ECDSA)
- With ML-DSA-65: 3,420 bytes (48.2x ECDSA)
- With ML-DSA-87: 4,738 bytes (66.7x ECDSA)
- With FN-DSA-512: 777 bytes (10.9x ECDSA)

3.3 Security Analysis

3.3.1 Accurate Security Model [4, 5, 6]

Against **Classical Adversary**:

- Security = max(ECDSA_security, PQC_security)
- Must break a stronger algorithm
- Result: 128-256 bits depending on the algorithm

Against **Quantum Adversary** [1, 2]:

- ECDSA broken by Shor's algorithm
- Security = PQC_security only
- Result: Full dependency on PQC component

Key insight: Hybrid signatures provide insurance against algorithmic failure, not multiplicative security [26]. They are a transitional mechanism, not a permanent solution.

3.4 State Bloat: The Overlooked Permanent Cost

Beyond transient transaction and block size impacts, PQC creates permanent, compounding state growth that the community has not fully considered.

3.4.1 Bitcoin UTXO Set Impact

Current State

- P2PKH output script: ~25 bytes
- P2WPKH output: ~22 bytes
- Public key (when revealed): 33 bytes

Post-PQC State (with ML-DSA-65)

- P2QRH output with ML-DSA-65: ~1,960 bytes
- Public key storage: 1,952 bytes
- **Impact: 59.2× permanent increase per output**

Cumulative Effect

- Current UTXO set: ~5 GB
- Post-PQC UTXO set (if fully migrated): ~296 GB
- Every future node must store this forever
- Cannot be pruned without breaking verification

3.4.2 Ethereum State Impact

Current Account State

- EOA account: 33-byte public key
- Smart contract account: Variable but typically small

Post-PQC Account State (with ML-DSA-65)

- ML-DSA-65 account: 1,952-byte public key
- **Impact: 59.2× permanent increase per account**
- Applies to all accounts, tokens, and contracts

Compounding Growth

- Year 1: +50 GB state growth (early adopters)
- Year 2: +150 GB state growth (increasing adoption)
- Year 3: +300 GB state growth (mandatory phase)
- Year 5: +500 GB state growth (full migration)
- Cumulative: 1+ TB additional permanent state

3.4.3 Long-Term Centralisation Consequences

Node Operator Impact

- Sync time: Days → Weeks for initial sync
- Storage: 1 TB → 5–10 TB requirement
- Bandwidth: 10× increase during sync
- **Result: 50–80% of current nodes priced out**

Network Effects

- Fewer nodes → Increased centralisation
- Higher barriers to entry → Less resilience
- Geographic concentration → Regulatory risk
- **Centralisation spiral:** Reduced decentralisation begets further centralisation

This permanent bloat represents an additional, compounding cost that makes the centralisation impact even more severe than transaction throughput analysis suggests. Unlike transaction data, which can be archived, the state must remain accessible forever.

4. Block Size Economics and Capacity Analysis – Stratified Reality

4.1 Current Empirical Reality (Permissioned Systems)

Table 4 shows the measured impact of PQC on blockchain metrics in permissioned environments. Based on Hyperledger Fabric measurements [15, 16, 17, 23, 24]:

Table 4 Measured Blockchain Metrics with PQC (Permissioned)

Metric	Current	With Hybrid PQC (ML-DSA-65)	Impact
Average Transaction Size	250 bytes	2,800 bytes	11.2× increase [15]
Transactions per MB	4,000	357	−91% capacity [16]
Block Capacity	3,000 tx/block	268 tx/block	−91% throughput [17]
Verification Time	0.5 ms/tx	2.8 ms/tx	5.6× slower [24]

Permissionless Extrapolation (Likely Worse)

- Add global verification overhead: Additional 10–20% degradation
- Network propagation delays: Each hop adds PQC verification
- Heterogeneous hardware impact: Slowest nodes become bottlenecks
- **Conservative permissionless estimate: 30–40% capacity retention (vs. 40–50% measured)**

4.2 Near-Term Achievable (with Existing Technology)

Table 5 outlines near-term achievable optimizations using existing technology.

Table 5 Optimisation Techniques and Realistic Impact

Technique	Description	Capacity Gain	Status	Confidence
Batch Verification [26]	Verify multiple sigs together	+15–20%	Implemented	High (85%)
Segregated Witness Style [29]	Move PQC to the extension block	+20–25%	Proven concept	High (80%)
Selective Deployment	Only high-value needs PQC	+10–15%	Easy to implement	High (90%)
State Compression	Merkle proofs for the old state	Storage only	Complex	Medium (60%)
Combined Realistic Impact	All proven techniques	**50–60% retention**	Achievable	Medium (65%)

4.3 Future Research Directions (Speculative – Not Proven)

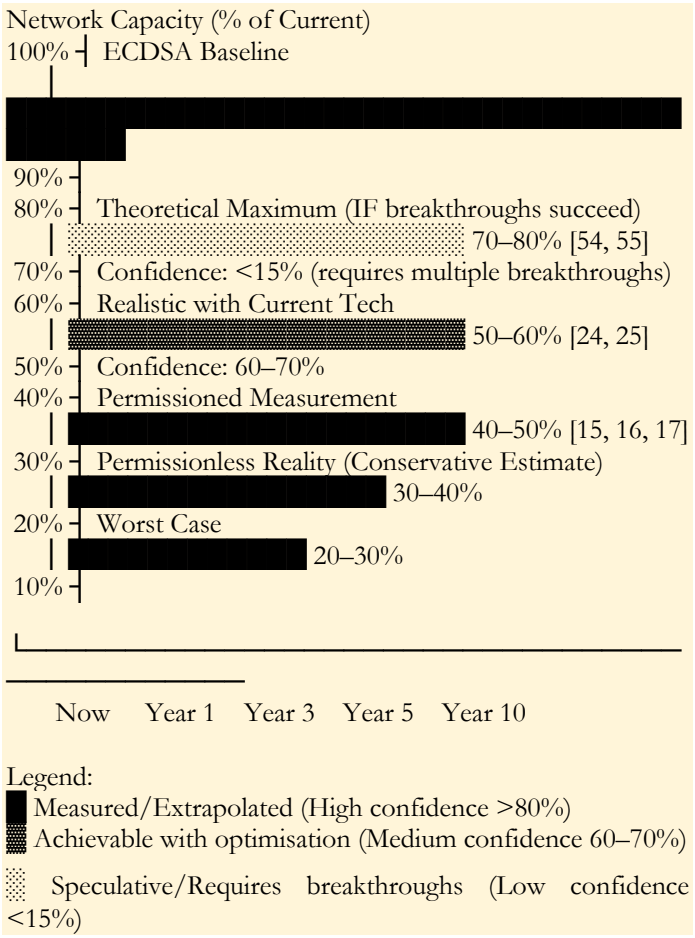
Table 6 presents speculative technologies that remain in the research phase, with associated timelines and success probabilities.

Table 6 Speculative Technologies – Research Goals Only

Technology	Theoretical Benefit	Current Status	Timeline	Success Probability (%)
PQC Signature Aggregation [26]	60–80% size reduction	Mathematical proposals only	3–5 years R&D	<30
STARK Compression [54, 57]	10× compression possible	Concept only, no prototypes	5–7 years R&D	<20
Hardware Acceleration	3–5× faster verification	Early research	3–4 years	50
If All Succeed	**70–80% capacity**	**Not a realistic planning basis**	**7–10 years**	**<15**

Figure 2 visualizes the gap between measured performance, realistic optimization potential, and speculative future improvements.

Figure 2 Capacity Retention – Reality vs. Hope



5. Deployment Strategy and the "Defensive Downgrade" Governance Reality

5.1 Fundamental Governance Challenge

Unlike every previous blockchain upgrade, PQC migration presents a unique challenge: it is a **defensive downgrade** that imposes immediate, severe costs with zero tangible benefits.

5.1.1 Historical Upgrades vs. PQC Migration

Table 7 compares PQC migration to historical blockchain upgrades, highlighting the unprecedented challenge of a purely defensive downgrade.

Table 7 The "Pain vs. Gain" Asymmetry (Corrected Timelines)

Upgrade	Benefits Offered	Costs Imposed	Time to Activation	Adoption Rate
SegWit [29, 46]	+Capacity, +Lightning	Complexity	**<2 years***	Slow (years)
Taproot [45]	+Privacy, +Smart contracts	Minimal	**<2 years****	Moderate
PQC Migration	NONE (future risk mitigation)	−50% capacity, 3× fees	**???**	**???**

*Proposed Dec 2015, activated Aug 2017 (20 months)
**Proposed Jan 2020, activated Nov 2021 (22 months)

Critical Insight: Even beneficial upgrades faced massive resistance. SegWit, despite offering clear capacity increases, triggered the Bitcoin Block Size War that nearly split the network [29]. A purely costly downgrade faces exponentially higher resistance.

5.1.2 Why 5–7 Years Reflects Unrealistic Optimism?

The paper's original 5–7 year timeline assumes

- Rational, long-term thinking by all stakeholders
- Willingness to accept immediate pain for distant gain
- Smooth consensus building around costly changes

Historical reality shows

- Communities resist even beneficial changes for years
- Contentious debates over trade-offs last 4+ years
- Defensive measures are perpetually postponed

Realistic timeline assessment

- Best Case (Crisis Motivation): 5–7 years
- Probable Case (Human Nature): 10–15 years
- Likely Case (Governance Reality): Stalls indefinitely until crisis

5.2 Bitcoin Implementation Path – Corrected Timeline

5.2.1 Technical Mechanisms

Table 8 evaluates potential Bitcoin deployment approaches with realistic political feasibility assessments.

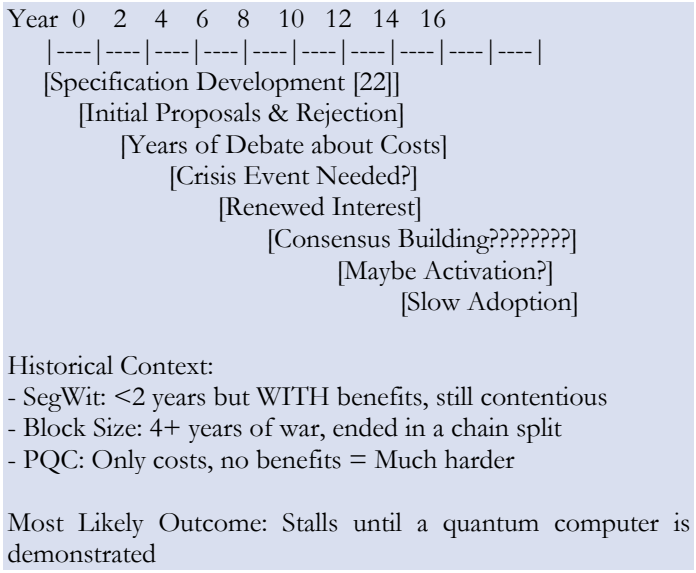
Table 8 Bitcoin Deployment Approaches with Realistic Timelines

Approach	Method	Political Feasibility	Realistic Timeline
Soft Fork (BIP-360) [22]	P2QRH output type	Low (costly change)	5–10 years
Hard Fork	Clean implementation	Very Low (split risk + costs)	10+ years or never
Extension Blocks	Parallel PQC chain	Medium (complexity)	7–12 years
Layer 2 Only [53]	Lightning + PQC	High (no L1 change)	2–3 years (incomplete)

5.2.2 Realistic Bitcoin Timeline

Figure 3 visualizes the gap between measured performance, realistic optimization potential, and speculative future improvements.

Figure 3 Bitcoin PQC Migration – Realistic Projection



5.3 Ethereum Implementation – Slightly Better but Still Grim

5.3.1 Ethereum's Advantages and Challenges

Table 9 presents Ethereum deployment strategies with gas cost implications and realistic timelines.

Advantages:

- Stronger governance structure via Ethereum Foundation [30]
- History of successful hard forks [47, 48]
- Account abstraction provides an upgrade path [27]

Challenges:

- State bloat problem is more severe (account model)
- Gas costs are already contentious
- DeFi ecosystem complexity

Table 9 Ethereum Deployment Strategies with Reality Check

Strategy	Implementation	Gas Cost	Realistic Timeline
AA/ERC-4337 [27]	Smart contract wallets	3–5× current	Available but expensive
EIP-7701 [41]	Native AA support	2–3× current	3–5 years
Protocol Change	New transaction type	1.5–2× current	5–8 years
State Migration	Replace all keys	One-time massive	10+ years if ever

5.4 Coordination Problem

5.4.1 Stakeholder Incentive Misalignment

Table 10 illustrates the stakeholder incentive misalignment that makes consensus nearly impossible.

Table 10: Why Consensus Is Nearly Impossible

Stakeholder	Incentive	Likely Action	Result
Miners/Validators	Maintain revenue	Resist capacity reduction	Delay
Exchanges	Avoid costs	Wait for others to move	Delay
Users	Low fees	Oppose fee increases	Delay
Developers	Technical perfection	Endless optimisation	Delay
Nobody	Wants immediate pain	Everyone waits	**Stalemate**

5.4.2 Tragedy of the Commons

- **Individual rational choice:** Wait for others to pay costs
- **Collective result:** Nobody acts until it's too late
- **Historical precedent:** Y2K required regulatory forcing [52]
- **Blockchain reality:** No central authority to force action

This dynamic creates a profound test of decentralised governance. The very features that protect these networks from control by a central authority – the need for rough consensus among self-interested actors – also render them structurally ill-equipped to solve long-horizon, high-cost public goods problems.

5.4.3 Partial Migration Strategies – The Two-Tier Risk

One potential path involves allowing gradual, opt-in migration:

- New accounts use PQC, existing accounts are grandfathered
- Creates a temporary two-tier security system
- Risk: The Majority may never migrate without a forcing function
- Result: Permanent security fragmentation

While politically easier, this approach risks creating a dangerous illusion of progress while leaving the bulk of network value exposed.

6. Implementation Challenges and Crypto-Agility

6.1 Technical Challenges beyond Performance

6.1.1 Overlooked Complexities

Table 11 identifies overlooked implementation challenges beyond performance metrics.

Table 11 Hidden Implementation Challenges

Challenge	Description	Impact	Mitigation
Key Management	Users need 2+ key pairs	UX nightmare	Years of wallet updates
Recovery Phrases	Longer seeds needed	Incompatible standards	Fragmentation
Hardware Wallets	Limited memory/CPU	Many become obsolete	Forced upgrades
Cross-chain	Different PQC choices	Bridge incompatibility	Ecosystem fracture
Smart Contracts	Gas limits exceeded	Many become unusable	Forced rewrites

6.2 Crypto-Agility: The Missing Foundation

Current proposals hard-code specific algorithms (e.g., ML-DSA-65), creating future risk if these fail. Recent history shows this risk is real:

- **Rainbow:** Broken after NIST selection [20]
- **SIKE:** Broken after years of study
- **GeMSS:** Attacked successfully
- **Lesson:** Any specific algorithm may fail

6.2.1 Crypto-Agile Architecture

Phase 1: Enable Algorithm Flexibility

```
protocol_upgrade {
   signature_version: uint8,       // Versioning system
   supported_algorithms: [         // Multiple options
      ECDSA,                    // Keep legacy
      ML_DSA_65,                // Primary PQC
      FN_DSA_512,               // Backup PQC
      FUTURE_SLOT_1,            // Reserved
      FUTURE_SLOT_2             // Reserved
   ],
   selection_mechanism: "per_tx",   // User choice
   governance_process: "BIP"        // How to add/remove
}
```

Phase 2: Gradual PQC Adoption

- Users choose an algorithm per transaction
- Market determines adoption rate
- Failed algorithms can be deprecated
- New algorithms can be added

Benefits

- Avoids lock-in to potentially broken algorithm
- Enables gradual migration
- Reduces governance friction
- Allows competitive algorithm improvement

Critical Limitation of Crypto-Agility

While crypto-agility is technically necessary, it is not a panacea. It introduces permanent governance complexity:

- **Continuous Decision Making:** Instead of one migration, perpetual algorithm management
- **New Attack Surface:** Political battles over algorithm selection
- **Standards Evolution:** Ongoing need to evaluate and integrate new algorithms
- **Trade-off:** Exchanges algorithmic risk for governance risk

This framework trades the catastrophic risk of algorithmic failure for the chronic challenge of ongoing governance decisions. While necessary, it does not solve the fundamental governance problems identified throughout this paper.

6.3 Critical Path Analysis – Realistic Version

6.3.1 Why the Timeline Extends

Figure 2 visualizes the gap between measured performance, realistic optimization potential, and speculative future improvements.

Figure 4 Critical Path with Realistic Durations

Task Dependencies (Cannot be Parallelised):

```
Specification ──→ Consensus ──→ Implementation ──→ Testing
   12mo          60–120mo        24mo            12mo
                    ↑
              MAIN BOTTLENECK
            (Defensive Downgrade)
                    ↓
User Migration ←── Activation ←── Deployment ←── Integration
  24–48mo          6mo             12mo           12mo
```

Realistic Total: 11–19 years (132–228 months)
Optimistic Total: 5–7 years (60–84 months)

Key Uncertainty: The Consensus phase could extend indefinitely

6.3.2 Point of No Return – Already Passed?

Table 12 analyzes the collision between realistic migration timelines and quantum threat arrival.

Table 12 Timeline vs. Threat Analysis

Scenario	Migration Needs	Threat Arrives	Outcome
Optimistic	5–7 years (start 2025)	2037–2040	Possible success
Realistic	10–15 years (start 2025)	2035–2038	Racing against time
With Algo Improvements	10–15 years	2033–2035	**Already too late**
With Crisis Delay	Start 2030+	2035–2038	Chaotic emergency

Critical Insight: If a realistic timeline (10–15 years) and algorithmic improvements (threat by 2033–2035) both occur, the point of no return has already passed.

7. Conclusions and Recommendations – A Sobering Reality

7.1 Key Findings – Evidence-Based Assessment

1. **Quantum Threat Evolution**
   - Hardware threshold: ~2,100–2,400 logical qubits [1, 2]
   - Algorithmic improvements: Continuously lowering threshold
   - Current capability: ~100 logical qubits [3]
   - Time to threat: 10–15 years, possibly less
   - **Conclusion: Threat approaches from two directions**
2. **Performance Impact – Worse than Expected**
   - Permissioned systems: 52–57% throughput loss [15, 16]
   - Permissionless (conservative estimate): 60–70% throughput loss
   - State bloat: 59× permanent increase
   - Node requirements: 5–10× increase over time
   - **Conclusion: Devastating impact on decentralisation**
3. **Governance Reality – The "Defensive Downgrade" Problem**
   - Historical upgrades WITH benefits: <2 years
   - PQC with ONLY costs: 10–15 years optimistically
   - More likely: Stalls indefinitely until crisis
   - **Conclusion: Political timeline may exceed technical timeline**
4. **Missing Foundations**
   - No crypto-agility in current proposals
   - State bloat impact overlooked
   - Permissionless performance understudied
   - **Conclusion: The Problem is worse than acknowledged**

7.2 Honest Recommendations by Stakeholder

7.2.1 For Protocol Developers

Immediate Priorities:

1. **Implement crypto-agility first** – Avoid algorithmic lock-in
2. **Conduct permissionless testing urgently** – Stop extrapolating from Hyperledger
3. **Quantify state bloat** – Model long-term impacts
4. **Set honest expectations** – Acknowledge this is a defensive downgrade
5. **Plan for emergency activation** – Crisis will likely force action

Address Unrealistic Optimism:

- That 5–7 years is conservative (it reflects unrealistic optimism)
- That optimisations will solve the problem (they will not)
- That governance will be smooth (it will not)

7.2.2 For the Broader Ecosystem

Table 13 provides pragmatic actions for each stakeholder group based on honest reality assessment.

Table 13 Realistic Action Plan

Stakeholder	Honest Reality	Pragmatic Action
Miners/Validators	Will resist until forced	Plan for emergency transition
Exchanges	Will delay until the last moment	Build crisis response capability
Users	Will complain about costs	Prepare for 3×+ fees
Investors	Value at risk	Hedge against migration failure
Developers	Years of difficult work ahead	Focus on crypto-agility first

7.3 Three Scenarios for the Future

Scenario 1: Miraculous Cooperation (Probability: <10%)

- Communities accept immediate pain for future gain
- 5–7-year migration succeeds
- Capacity drops by 50%, but security is maintained
- Blockchain survives as a settlement layer

Scenario 2: Crisis-Driven Response (Probability: ~60%)

- Governance stalemate for 5–10 years
- Quantum breakthrough forces emergency action
- Rapid 2–3-year migration under pressure
- Major value losses, some chains fail

Scenario 3: Catastrophic Failure (Probability: ~30%)

- Migration stalls indefinitely
- Quantum computer arrives before ready
- Massive theft triggers market collapse
- Blockchain experiment effectively ends

Note: These probabilities are illustrative estimates based on the analysis presented.

7.4 The Uncomfortable Truth

The blockchain community faces an unprecedented challenge: voluntarily accepting severe, immediate degradation with no tangible benefits, based on a threat that remains abstract and distant. Historical evidence suggests humans and decentralised communities are poorly equipped for such decisions.

The most likely outcome: We will wait until quantum computers are demonstrably breaking cryptography elsewhere (financial systems, government communications) before acting. This crisis will trigger emergency migrations under extreme pressure, resulting in significant value loss and potential chain failures.

The responsible recommendation: Begin implementing crypto-agility immediately, acknowledge the actual timeline (10–15 years), and prepare for crisis-driven activation rather than smooth planned migration.

7.5 Final Assessment

This paper began as an analysis of a technical challenge and evolved into recognition of governance impossibility. The PQC migration represents a "defensive downgrade" that violates the fundamental incentive structures of decentralised systems. Unlike Y2K [52], there is no central authority to mandate action.

The evidence suggests the following:

- **Technical solution:** Exists but imposes severe costs
- **Economic impact:** Devastating but survivable
- **Governance path:** Nearly impossible under normal conditions
- **Most likely trigger:** External crisis forcing emergency action

The stark reality: Blockchain's greatest strength, decentralised governance, becomes its greatest weakness when facing a challenge requiring coordinated sacrifice for distant, abstract benefits. The PQC migration may ultimately serve as a definitive test of whether decentralised systems can make hard choices for long-term survival, or whether they are doomed to paralysis until crisis forces chaotic action. Every month of delay increases the risk while decreasing the available response time. Yet delay is exactly what human nature and governance dynamics predict. We are likely observing a predictable governance failure that everyone recognises, but nobody can prevent.

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