

Quantum Disruption: An SOK of How Post-Quantum Attackers Reshape Blockchain Security and Performance

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Abstract—As quantum computing advances toward real-world applicability, it poses a significant threat to classical cryptographic systems, including not only digital signature schemes but also key exchange protocols, public-key encryption algorithms, and certain hash-based constructions that secure network infrastructures. These schemes are foundational to most blockchain platforms, raising serious concerns about the long-term security and integrity of blockchain applications. While transitioning to post-quantum solution might look straightforward, larger sizes and larger computation demand for post-quantum building blocks can have unintended consequences for the blockchain applications and in some cases might make such transition impractical.

In this paper, we examine the impact of transitioning blockchain systems to post-quantum cryptography across four dimensions. Our analysis begins by dissecting the specific cryptographic primitives most vulnerable to quantum attacks—particularly those embedded in consensus protocols, identity management, and transaction validation layers. We then explore the emerging spectrum of post-quantum adaptations proposed across blockchain implementations, focusing on their practical feasibility and the implications of integrating them into the decentralized environment of distributed ledgers. Through this lens, we assess how the substitution of classical primitives with post-quantum alternatives impacts system performance, alters protocol behavior, and reshapes the underlying incentive and trust structures that sustain blockchain ecosystems. Our findings reveal that integrating post-quantum signature schemes into blockchain frameworks is far from a drop-in replacement; rather, it demands careful architectural reconsideration, as naive substitution risks destabilizing core protocol operations and weakening the security and efficiency guarantees that blockchains fundamentally rely upon.

1. Introduction

The emergence of quantum computing poses a critical challenge to classical cryptographic systems. Recent milestones – such as Microsoft’s quantum processing unit [1] and Google’s Willow chip [2] – suggest that practical quantum computation may soon be achievable. As these technologies advance, the cryptographic foundations of modern digital infrastructure face increasing exposure to quantum vulnerabilities. This risk is especially pronounced in blockchain systems, which depend on cryp-

tographic primitives inherently susceptible to quantum attacks.

Blockchains support decentralized finance (DeFi) and many distributed applications, relying on public-key cryptography for transaction security, consensus, and identity verification. These systems now secure hundreds of billions of dollars; as of September 2025, DeFi platforms held roughly USD 160 billion in total value locked [3], and the Ethereum ecosystem alone had a market capitalization between USD 480-700 billion [4]. This concentration of digital value emphasizes the importance of ensuring blockchain resilience against emerging quantum threats.

Quantum algorithms such as Shor’s algorithm [5] threaten conventional blockchain signature schemes (RSA, DSA, ECDSA), compromising integrity and authenticity guarantees. In response, major blockchains are shifting to quantum-resilient cryptography while simultaneously advancing privacy mechanisms. Algorand is adopting the lattice-based FALCON signature scheme for generating its State Proofs, providing quantum-safe authentication for cross-chain verification [6]. Similarly, Solana introduces a quantum-resistant Winternitz Vault mechanism based on the Winternitz One-Time Signature (W-OTS) scheme, ensuring that account recovery and key-rotation operations remain secure even in the presence of quantum-capable adversaries [7]. Together, these initiatives signal a growing shift toward quantum-safe and privacy-oriented blockchain architectures.

The transition to post-quantum cryptography (PQC) in blockchain systems is non-trivial because cryptographic primitives are tightly integrated into identity management, transaction validation, and consensus. Replacing them with PQ counterparts can create cascading effects on interoperability, performance, and system stability. PQ algorithms also vary significantly in size, efficiency, and implementation feasibility, complicating deployment across diverse hardware. These factors raise key questions about which components are most vulnerable, how prepared current systems are, and what systemic impacts PQ adoption may introduce. Addressing these issues is essential for evaluating the feasibility and long-term resilience of quantum-secure blockchain infrastructures.

In this work, we present a comprehensive survey of the PQ preparedness of seven of the most widely used blockchain platforms: Bitcoin [8], Ethereum [9], Algorand [10], Monero [11], Avalanche [12], Solana [13], and XRP Ledger (XRPL) [14]. These platforms were selected based on their prominence within the contemporary blockchain ecosystem, as reflected by market capitalization, transac-

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tion volume, and active developer communities. Collectively, they represent the principal architectural paradigms of distributed ledger technology-encompassing proof-of-work (Bitcoin, Monero), proof-of-stake (Ethereum, Algorand), byzantine fault tolerance (Avalanche, XRPL), and proof-of-history (Solana). This diversity ensures that the study captures the spectrum of cryptographic and consensus models used across leading blockchain systems, thereby providing a representative assessment of the broader ecosystem’s resilience and readiness in the PQ context.

Our study is structured around research questions that examine the cryptographic, architectural, and behavioral implications of transitioning to quantum-safe blockchain infrastructures. We first identify which cryptographic components in current designs are most vulnerable to quantum attacks. We then assess the countermeasures proposed by blockchains and evaluate the feasibility of emerging PQ solutions. Next, we analyze the performance impact of adopting PQ signature schemes-focusing on throughput, latency, and block interval-to understand the trade-offs between security and usability. Finally, we explore broader systemic effects, including how PQ adoption may influence fork and stale block rates, consensus convergence, and the economic incentives that shape network behavior.

Our findings indicate that adopting PQ signature schemes such as ML-DSA-44 would substantially affect blockchain system design. Larger signatures and public keys increase per-transaction data size, raising on-chain and archival storage demands, slowing network propagation, and accelerating ledger growth. Under fixed block or gas limits, this expanded payload reduces the number of transactions per block, lowering effective throughput even when consensus parameters remain unchanged. Thus, while the block interval remains constant, overall system efficiency and scalability may degrade unless corresponding protocol or infrastructural optimizations are implemented to accommodate the computational and communication costs associated with PQ primitives.

Outline. Our paper is organized as follows. Section 2 provides background on quantum-resilient blockchain infrastructures. Section 3 surveys representative blockchain applications and their consensus and cryptographic foundations. Section 4 reviews components vulnerable to quantum attacks, and Section 5 outlines emerging PQ defense strategies. Section 6 analyzes performance challenges in adopting PQ schemes, while Section 7 discusses expected systemic impacts. Section 8 concludes with open problems and future research directions.

2. Background

In this section, we provide the essential background necessary to contextualize the subsequent discussion on quantum-resilient blockchain infrastructures. We first outline NIST-standardized PQ cryptographic algorithms that support secure communication in a PQ era. We then examine SNARKs, a key primitive for scalable and privacy-preserving blockchain verification, whose constructions remain largely non-standardized and potentially quantum-vulnerable. Finally, we review consensus protocols, which define trust, security, and performance in blockchains.

2.1. NIST Standardization of PQ Algorithms

Given the significant threat quantum computing poses to foundational cryptographic building blocks, the National Institute of Standards and Technology (NIST) launched a multi-year standardization initiative to evaluate and formalize cryptographic algorithms resilient to quantum attacks [15]. The effort focuses on two essential categories of cryptographic primitives: key encapsulation mechanisms (KEMs) for secure key exchange and digital signature schemes for authentication and data integrity. Initiated in 2016, the process involved extensive analysis of candidate families, including lattice-based, code-based, hash-based, multivariate, isogeny-based, and hybrid schemes-grounded in assumptions believed to quantum adversaries. Lattice-based constructions emerged as the most promising, offering a practical balance between security, efficiency, and implementation feasibility.

The standardization effort culminated in 2024 with the release of the first Federal Information Processing Standards (FIPS) for post-quantum cryptography [16]. FIPS 203 [17] defines ML-KEM, a lattice-based key encapsulation mechanism derived from CRYSTALS-Kyber, while FIPS 204 [18] specifies ML-DSA, a lattice-based digital signature algorithm derived from CRYSTALS-Dilithium. FIPS 205 [19] introduces SLH-DSA, a stateless hash-based digital signature algorithm derived from SPHINCS+. In March 2025, NIST announced the selection of Hamming Quasi-Cyclic (HQC) as a fifth key encapsulation mechanism, providing a non-lattice alternative to ML-KEM, with draft publication expected in 2026 and full standardization by 2027 [20].

In parallel, NIST’s draft guidance in IR 8547 [21] provides migration strategies, risk assessments, and recommendations for cryptographic agility in the shift to post-quantum security. It calls for deprecating quantum-vulnerable algorithms-RSA, ECDSA, EdDSA, DH, and ECDH-by 2030 and fully retiring them by 2035. This marks a key milestone in the global move toward quantum-secure cryptographic infrastructures.

2.2. SNARK

Succinct Non-Interactive Arguments of Knowledge (SNARK)-s are cryptographic proofs that allow a prover to demonstrate the validity of a statement without revealing the underlying data and without requiring interaction with the verifier. In blockchain systems, they provide ZKPs to preserve privacy while ensuring public verifiability of transactions. SNARKs are characterized by three core properties: succinctness (short proofs and fast verification), non-interactivity, achieved through a Common Reference String; and knowledge soundness (only a true witness holder can produce a valid proof). These properties make SNARKs highly efficient for blockchain use, allowing verification of complex computations with minimal on-chain overhead. Practical implementations, such as zk-SNARKs in Zcash [22], provide confidential transactions that still comply with network rules, balancing transparency and privacy.

Conventional SNARKs rely on assumptions such as the discrete logarithm and elliptic curve pairings, which are vulnerable to quantum attacks. This has motivated the

development of PQ alternatives that preserve succinctness and efficiency, including lattice-based SNARKs built on Learning With Errors, hash-based schemes relying on collision-resistant hashes, and toolchains such as zkLLVM that support quantum-resistant backends. STARKs further advance this direction by using hash-based constructions that avoid trusted setup and provide inherent post-quantum security. Together, these approaches mark important progress toward privacy-preserving and quantum-resilient blockchain protocols.

2.3. Consensus Protocols

Consensus protocols serve as the foundation for blockchain systems by ensuring agreement on a shared ledger state among distributed nodes without central oversight. In adversarial and distributed environments, these protocols ensure safety, liveness, and fault tolerance through combinations of cryptographic proofs, economic incentives, and voting mechanisms. Their design dictates the trade-offs among decentralization, security, and scalability—collectively known as the blockchain trilemma. In this section we provide an overview of the principal consensus mechanisms used in contemporary blockchain networks.

Proof of Work (PoW). PoW is based on solving computationally expensive puzzles to determine which node can propose the next block. Miners repeatedly compute SHA-256 hashes until they find a nonce producing a hash value below a target difficulty. This mechanism ensures probabilistic leader election and deters Sybil attacks by tying influence to computational power. PoW achieves consensus through the longest-chain rule, where the chain with the greatest cumulative work is considered canonical. While this approach provides strong security and immutability, it requires significant energy expenditure and offers low transaction throughput (typically 5-10 TPS). PoW remains the foundation of networks such as Bitcoin, Litecoin, Dogecoin, and was used by Ethereum [23] until its shift to PoS.

Proof of Stake (PoS). PoS-based consensus protocols replace computational effort with financial commitment as the basis for block production and validation. Validators lock native tokens as collateral, and their selection probability is proportional to the amount staked. Network security is maintained through economic incentives—rewarding honest behavior and penalizing misconduct via slashing. By substituting energy-intensive computation with staking, PoS achieves substantially lower energy consumption while enhancing scalability and throughput. Various PoS variants have since emerged, each optimizing trade-offs among decentralization, governance, and performance.

Classical Proof of Stake systems use pseudo-random validator selection weighted by stake size to determine block proposers. Finality is typically achieved through hybrid overlay protocols that combine probabilistic and deterministic components to prevent chain forks. Ethereum 2.0, for instance, uses Casper FFG (Friendly Finality Gadget) [24] and LMD-GHOST [25] to finalize blocks within a bounded number of epochs. Cardano uses Ouroboros [26], a provably secure PoS protocol based on verifiable randomness and time-slot leadership, while Polkadot’s

Nominated PoS model [27] combines validator election with reputation-weighted staking.

Delegated Proof of Stake (DPoS) modifies the PoS framework by introducing a governance layer in which token holders delegate their voting power to a limited number of representatives, called delegates or witnesses, who are responsible for block production and validation. The delegate set is periodically re-elected, allowing stakeholders to replace underperforming or malicious actors. Consensus proceeds through a deterministic, round-robin block production schedule, enabling fast confirmation times and high throughput. However, because validation power is concentrated among a small subset of nodes, DPoS introduces partial centralization. This model supports high-performance networks such as EOS [28], TRON [29], Steem [30], and Lisk [31], which prioritize governance efficiency and scalability over complete decentralization.

Pure Proof of Stake (PPoS) aims to enhance decentralization by assigning validator roles through cryptographic randomness rather than explicit voting or delegation. Algorand exemplifies this approach by using Verifiable Random Functions (VRFs) [32] to privately and securely select block proposers and committee members for each round. This eliminates the need for persistent validator identities and minimizes coordination overhead while preserving BFT. PPoS achieves strong security guarantees and rapid finality, making it particularly suitable for open, permissionless networks with large validator populations.

Byzantine Fault Tolerance (BFT). BFT-based consensus protocols help distributed systems maintain safety and liveness despite arbitrary or malicious node behavior, tolerating up to one-third faulty participants under partial synchrony. These protocols achieve agreement without probabilistic mechanisms or resource-intensive computation, with several variants emerging to balance scalability, communication complexity, and trust assumptions.

Practical Byzantine Fault Tolerance (PBFT) is a message-passing protocol for authenticated, semi-trusted networks. Originating from Castro and Liskov’s work [33], PBFT tolerates f Byzantine faults among $3f+1$ nodes through a three-phase commit process—pre-prepare, prepare, and commit—ensuring that all honest replicas agree on transaction order. It provides deterministic finality once a block is committed but incurs $O(n^2)$ communication overhead, limiting scalability. PBFT and its variants are used in permissioned systems such as Hyperledger Fabric [34], Tendermint (Cosmos) [35], Zilliqa [36], and Quorum’s Istanbul BFT [37], where low latency and consistency are prioritized.

Federated Byzantine Fault Tolerance (FBA) generalizes the BFT model by decentralizing trust through overlapping quorum slices instead of fixed validator sets. Each node maintains a Unique Node List (UNL) of trusted peers, and consensus emerges when supermajorities of these lists intersect. This approach supports open membership and energy efficiency while maintaining deterministic finality, provided quorum overlap is sufficient. The Ripple Protocol Consensus Algorithm (RPCA) [38] introduced this design, later formalized in the Stellar Consensus Protocol (SCP) [39], which offers provable safety under federated trust assumptions. FBA is particularly suited for high-throughput, payment-oriented blockchains requiring

predictable finality without reliance on mining or staking.

Probabilistic Byzantine Fault Tolerance uses randomized sampling and iterative voting to achieve consensus probabilistically in open, decentralized networks. Rather than deterministic agreement, repeated subsampling drives the network toward metastable convergence, reducing the likelihood of divergence exponentially. The Avalanche family-Snowflake, Snowball, Avalanche, and Snowman-[40] exemplifies this approach, using lightweight peer polling to achieve consensus without leader election. This design offers near-constant communication complexity and high scalability, trading deterministic finality for rapid, probabilistic agreement suitable for large, permissionless environments.

Proof of Authority (PoA). This protocol achieves agreement through a predetermined and trusted set of validators rather than open competition among anonymous participants. It assigns validation and block production rights to approved nodes—typically verified organizations or individuals whose identities are known to the network. Instead of relying on probabilistic leader election or stake-weighted selection, PoA follows a deterministic validation schedule, which minimizes communication delays and computational overhead. This design provides near-instant block confirmations and high throughput, making PoA well suited for private or consortium blockchains. However, because the protocol depends on a limited number of trusted validators, it introduces centralization risks and relies on the honesty and reputation of those authorities. PoA is implemented in blockchains such as VeChain [41], Energy Web Chain [42], and POA Network [43], as well as in Ethereum testnets like Goerli [44] and Kovan [45], where validator credibility is an acceptable replacement for full decentralization.

Proof of History (PoH). This protocol represents a newer class of consensus innovation, primarily developed for Solana. PoH introduces a verifiable delay function (VDF) [46] to create cryptographic proofs of time passage between events. Each event or transaction is hashed sequentially with the output of the previous one, generating a historical record that acts as a cryptographic timestamp. This allows validators to agree on the chronological order of transactions before running consensus, drastically reducing message overhead. When combined with PoS in Solana’s hybrid model, PoH allows the network to achieve sub-second block times and high throughput [47]. This design addresses synchronization delays inherent in traditional consensus models and demonstrates a viable path toward high-performance decentralized systems.

3. Blockchain Applications

In this section, we provide a brief overview of the seven prominent blockchain applications that we focus on, emphasizing their underlying consensus protocols and the cryptographic primitives that enable secure, decentralized operation. We summarize the results in Table 1.

3.1. Bitcoin

Bitcoin, the most prominent blockchain network, uses PoW consensus protocol, where miners compete to solve cryptographic hash puzzles by discovering a valid nonce.

Due to the computational intensity of this process, specialized hardware such as ASICs and GPUs is required to perform these operations efficiently and profitably.

Transactions in Bitcoin are initiated when a user, through their wallet, creates and signs a transaction specifying the recipient’s address and the transfer amount. The digital signature generated with the user’s private key ensures authenticity and ownership. Once signed, the transaction is broadcast to the network, where nodes validate it by verifying the signature, confirming sufficient balance, and ensuring that the inputs have not been previously spent. Valid transactions are then placed in the mempool, awaiting inclusion in a new block.

Miners select transactions from the mempool and compete to solve the PoW puzzle. The first miner to find a valid solution adds their block to the blockchain, granting the included transactions their first confirmation. Each subsequent block provides additional confirmations, strengthening the transaction’s finality. Typically, six confirmations are considered sufficient to ensure irreversibility, as for an adversary controlling 10% of the network’s hashrate, the probability of successfully reversing the transaction after six blocks is less than 0.03%. [48]

Bitcoin supports two primary transaction types: Pay to Public Key (P2PK) and Pay to Public Key Hash (P2PKH). P2PK was the original transaction format but posed a security risk by exposing users’ public keys directly. To address this, the P2PKH format was introduced, which uses a hashed version of the public key as the address. This ensures that the actual public key remains hidden until the funds are spent, thereby improving privacy and reducing the potential attack surface.

Cryptographic Primitives. Bitcoin relies on several cryptographic primitives to ensure secure and verifiable operations. Transaction authentication is achieved through ECDSA, which verifies ownership and validity of transactions. More recently, Schnorr signatures have been proposed as a compact and efficient alternative, particularly advantageous for multi-signature transactions.

In PoW, Bitcoin utilizes the SHA-256 hashing algorithm for its cryptographic puzzle, requiring miners to find an input that produces a hash below a certain target value. Additionally, Merkle trees facilitate efficient transaction verification within blocks, while Bloom filters support lightweight clients in locating relevant transactions without disclosing their full set of addresses.

3.2. Ethereum

Ethereum is a decentralized blockchain platform distinguished by its smart contract functionality, enabling programmable and trustless applications. Architecturally, it comprises three primary layers: the blockchain layer, the consensus layer, and the application layer.

The *blockchain layer* maintains a distributed ledger replicated across a global network of nodes, recording all transactions and smart contract interactions to ensure transparency and immutability. The *consensus layer* uses PoS protocol, which replaced the original PoW mechanism following “The Merge” in September 2022. As discussed in Section 2.3, PoS defines validator selection, block proposal, and finalization processes that support Ethereum’s security and energy efficiency. The *application*

Blockchain	Signature	Hash	Consensus	VDF/VRF	Contracts	SNARK
Bitcoin	ECDSA(secp256k1)	SHA-256	Proof of Work	No	No	No
Ethereum	ECDSA(secp256k1), BLS, KZG	Keccak-256	Proof of Stake	Yes	Yes	Yes
Algorand	FALCON	SHA-256	Pure Proof of Stake	Yes	Yes	Yes
Solana	EdDSA(ed25519), W-OTS	Keccak-256	Proof of History	No	Yes	No
Avalanche	ECDSA(secp256k1)	SHA-256, Ripemd160	Snowman Consensus	No	Yes	No
Monero	EdDSA(ed25519)	Keccak-256	Proof of Work	No	No	Yes
XRPL	EdDSA(ed25519), ECDSA(secp256k1)	SHA-256	RPCA	No	No	No

TABLE I. CRYPTOGRAPHIC PRIMITIVES USED IN BLOCKCHAINS

layer hosts decentralized applications (dApps) powered by smart contracts executed on the Ethereum Virtual Machine (EVM), a globally shared and deterministic computational environment ensuring consensus on state transitions across all nodes.

A typical transaction begins when a user signs it with a private key and broadcasts it through the gossip network. Validators aggregate pending transactions from the mempool, execute them, and encapsulate the results into beacon blocks. Once two-thirds of validators attest to a block’s correctness, it is finalized—typically every epoch (~6.4 minutes) [49], [50].

Ethereum supports two account types: Externally Owned Accounts (EOAs), controlled via cryptographic key pairs derived from ECDSA; and Contract Accounts (CAs), governed by smart contract code without private keys. EOAs initiate transactions and interact with contracts, while CAs execute predefined logic in response to external calls. This architecture provides the foundation for Ethereum’s programmable, autonomous applications and supports its role as a core layer of decentralized systems.

Cryptographic Primitives. Ethereum uses a diverse set of cryptographic primitives to ensure network integrity and security. For digital signatures, Ethereum uses ECDSA(secp256k1) for transaction signing and Boneh-Lynn-Shacham (BLS) signature scheme within its PoS consensus. The Keccak-256 hash function secures transaction, block, contract, and address data, while KZG (Kate-Zaverucha-Goldberg) commitments support secret sharing and polynomial commitments. Random validator selection is achieved through the VDF.

Ethereum also supports zk-SNARKs to improve privacy and scalability through ZK transaction proofs. Account abstraction further enhances flexibility by allowing custom verification logic, enabling features such as Paymasters for gas sponsorship and Aggregators that compress multiple signatures using BLS or SNARKs. Integration with the Ethereum Object Format adds modularity and execution efficiency, allowing dynamic account code execution and more programmable security mechanisms.

3.3. Algorand

Algorand is a blockchain platform designed for scalability, efficiency, and post-quantum readiness, using its PPoS consensus to achieve secure and decentralized block validation. It supports two categories of smart contracts: stateful and stateless. Stateful contracts (ASC1) maintain on-chain state and enable dApps requiring persistent storage, asset management, or complex coordination. Stateless contracts, or smart signatures, are lightweight scripts without on-chain state, used for logic-based account control

and delegated transaction authorization without disclosing private keys. Together, these models provide a flexible and secure foundation for building scalable, deterministic, and trust-minimized decentralized applications on the Algorand network.

Cryptographic Primitives. Algorand uses several cryptographic mechanisms to ensure integrity, and resilience in the system. Consensus participant selection is achieved through a Verifiable Random Function (VRF), implemented using the Elliptic Curve Verifiable Random Function (ECVRF) signature scheme, which guarantees unpredictability and verifiability of leader election. The SHA-256 hash function is used for data hashing, ensuring robustness and consistency across the network. To strengthen post-quantum security, lattice-based signature scheme FALCON is used for generating state proofs.

State proofs are compact, immutable attestations that summarize the blockchains state over 256 transaction rounds, typically sized between 600 and 900 KB. Their generation involves two stages: first, participating nodes produce commitments by combining public state proof keys with online stake; then, after 256 rounds, these commitments are aggregated into Block Interval Commitment Trees and signed by top online accounts. Once a weighted signature threshold—representing at least one-third of total online stake—is reached, the aggregated proof is verified and recorded on-chain, providing a cryptographically secure and efficient summary of the ledger state.

3.4. Solana

Solana is a high-performance blockchain platform that mirrors Ethereum’s smart contract functionality while using a distinct consensus architecture designed to enhance scalability and efficiency. As outlined in Section 2.3, Solana utilizes a hybrid PoH and DPoS consensus mechanism.

Solana’s data storage architecture leverages archivers and replicators to distribute and preserve blockchain history. Archivers store partitioned ledger segments and periodically verify data integrity via Proof of Replication, while replicators maintain redundant copies to enhance availability and fault tolerance. This offloading of historical data allows validators to focus on real-time transaction processing and throughput optimization.

Cryptographic Primitives. Solana uses EdDSA for digital signatures and SHA-256 for its PoH mechanism. It also integrates a Verifiable Delay Function within the consensus process. Additionally, Solana introduces a quantum-resistant Winternitz Vault mechanism based on the Winternitz One-Time Signature (W-OTS) scheme. Each vault transaction generates a one-time Winternitz keypair, with the public key hashed via Keccak-256 to

derive a Program-Derived Address (PDA). The vault structure includes a split account for outgoing funds and a refund account for residual balances. Transactions are authorized using Winternitz signatures that verify ownership through PDA-derived hashes. Upon closure, a second truncated signature (2240 bits) confirms ownership, and all hashes are aggregated into a final Merkle root, securely finalizing the transfer and vault termination.

3.5. Avalanche

Avalanche is a high-performance blockchain platform distinguished by its customizable Layer 1 networks, known as subnets, and its tri-chain architecture, which comprises the Contract Chain (C-Chain), Platform Chain (P-Chain), and Exchange Chain (X-Chain). The C-Chain implements the Ethereum Virtual Machine (EVM), ensuring compatibility with Ethereum-based decentralized applications (dApps) and smart contracts. The P-Chain functions as the coordination layer, managing subnet creation, validator registration, and staking operations, while the X-Chain facilitates the issuance and exchange of digital assets. As mentioned in the background, consensus across these chains is achieved through the Snowman protocol—a linear, probabilistic BFT mechanism.

Avalanche's subnets operate as independent, application-specific blockchains secured by distinct validator sets and configurable with their own virtual machines, fee structures, and governance models. They communicate via Warp Messaging, enabling cross-subnet data exchange without sacrificing isolation. This modular design supports parallel execution and scalability, but also introduces challenges such as network complexity, liquidity fragmentation, and inconsistent user experiences across independently operated ecosystems.

Cryptographic Primitives. Avalanche relies on widely adopted cryptographic standards to ensure security and interoperability. It uses ECDSA(secp256k1) for digital signatures, offering efficient and secure public key operations. For hashing, it combines SHA-256 and RIPEMD-160 in a two-step process to enhance collision resistance and address obfuscation, providing additional security for transaction validation and key management.

3.6. Monero

Monero is a privacy-focused blockchain designed to preserve user anonymity by concealing transaction details such as the sender, receiver, and amount. It operates on PoW consensus like Bitcoin but uses a one-time ring signature architecture that enhances transaction privacy. This structure blends a user's digital signature with those of other participants, making it computationally infeasible to determine which signer initiated a given transaction.

Block sizes in Monero are dynamically adjusted to maintain network efficiency, with a maximum size equal to twice the median of the last 100 blocks and a minimum of 300 KB. Miners incur penalties if block sizes fall outside this range, ensuring consistent throughput and stability.

Monero's mining process is optimized for CPU participation through the use of P2Pool and RandomX. P2Pool promotes decentralization by distributing mining rewards

across a cooperative network of miners, while RandomX eliminates the advantages of ASIC and GPU hardware by using a memory-hard algorithm that favors general-purpose CPUs. This design mitigates centralization risks and fosters broader participation in the mining process.

Cryptographic Primitives. Monero's privacy framework relies on cryptographic mechanisms that provide confidentiality, unlinkability, and untraceability. Each account derives a spend key and a view key from the Ed25519 elliptic curve, and these are combined via a Keccak-256 hash to produce one-time stealth addresses that prevent linking transactions to a recipient's wallet.

Transaction privacy is further reinforced through ring signatures, which mix the sender's key with decoys to hide the true signer. The security of this mechanism rests on the hardness of the discrete logarithm and elliptic curve discrete logarithm problems.

Monero also uses Ring Confidential Transactions (RingCT) to conceal the transaction amount using Pedersen Commitments. These commitments help validate a value without revealing it, ensuring that only the sender and recipient know the exact amount while preserving the verifiability of the transaction to the broader network.

To enhance efficiency and scalability, Monero integrates Bulletproofs, a ZK proof system that significantly reduces the size of confidential transactions while maintaining security and privacy. Finally, Monero's PoW algorithm utilizes the CryptoNight hash function, a memory-intensive cryptographic hash designed to maximize CPU efficiency while resisting optimization by specialized hardware such as ASICs and GPUs.

3.7. XRP Ledger

XRPL operates as a replicated state machine, where the ledger represents the current state and transactions serve as state transitions. Both successful and failed transactions are recorded to enforce anti-spam fees, ensuring that users incur a cost for submitting invalid or unnecessary transactions. This mechanism maintains the network's efficiency and mitigates spam activity. As described in Section 2.3, consensus in XRPL is achieved through the Ripple Protocol Consensus Algorithm (RPCA), an FBA mechanism.

Each account is responsible for sending transactions and holding XRP. Account structure includes an address, a reserve requirement, a sequence number, and a transaction history. The sequence number enforces strict ordering, allowing a transaction to be added only if its sequence matches the sender's next expected value. This design prevents double-spending and maintains the integrity of the transaction timeline.

Cryptographic Primitives. XRPL uses multiple cryptographic primitives to safeguard network integrity and transaction security. Digital signatures are implemented using ed25519 as the default signing algorithm, while secp256k1 is also supported and used by the Wallet Propose Admin RPC command. The ledger uses the SHA-256 hash function to ensure data integrity through cryptographic hashing of transactions and ledger contents.

Each account is uniquely identified by an address encoded in Base58, derived from the account's master public

key. This addressing scheme provides efficient identification while maintaining cryptographic security within the network's trust model.

4. Vulnerability to Quantum Adversaries

Blockchains rely on cryptographic primitives to ensure security, integrity, and trust, yet the emergence of quantum computing threatens many of these foundations due to algorithms capable of efficiently breaking widely used schemes. Understanding which components are most vulnerable is essential for assessing blockchain resilience. In this section, we address *RQ1: What cryptographic building blocks of current blockchain designs make them a target in the presence of a quantum adversary?* We examine the seven systems introduced earlier, identify their quantum-exposed components, and summarize the results in Table 2.

4.1. Bitcoin

Bitcoin faces significant security challenges in the advent of quantum computing, primarily due to its reliance on discrete logarithm-based digital signature schemes such as Schnorr and ECDSA for transaction authentication. These vulnerabilities stem from Shor's algorithm, which can efficiently solve discrete logarithms, thereby weakening the cryptographic assumptions upon which Bitcoin's security depends. Quantum threats to Bitcoin primarily target two fundamental aspects of its cryptographic framework: the execution of transactions, where public keys are temporarily exposed and vulnerable to quantum attacks, and the addressing mechanism, where certain address types permanently reveal public keys that could be exploited by quantum adversaries.

The first vulnerability arises from Bitcoin's P2PK address scheme. In this structure, the public key is visible on the blockchain, enabling a sufficiently powerful quantum computer to derive the corresponding private key. Consequently, funds held in P2PK addresses are inherently insecure in a post-quantum context. To mitigate this risk, all coins stored in P2PK addresses must be migrated to P2PKH addresses, where only the hash of the public key is exposed. However, the large-scale migration of all unspent bitcoins to quantum-safe addresses is computationally intensive. Estimates suggest that such a migration would require approximately 76 days of cumulative network downtime, or 152 days if only half of the available network bandwidth were utilized.

A second vulnerability arises during transaction initiation: when a transaction is broadcast, the sender's public key is exposed until the block is mined, making P2PKH addresses only conditionally secure. Users are advised to use fresh addresses per transaction, assuming quantum computers cannot run Shor's algorithm within this confirmation window. However, estimates suggest that a quantum computer with a 1 kHz clock could recover a private key in about 66 seconds, weakening these protections.

A further concern involves the potential implications of quantum computing for Bitcoin's PoW consensus mechanism. Although classical ASIC miners currently provide superior performance, quantum computers could exploit Grover's algorithm [51] to achieve a quadratic

speedup in hash computation. This improvement would allow quantum miners to identify valid hashes roughly twice as quickly as classical counterparts. While this advantage would not compromise the fundamental integrity of PoW, it could significantly centralize mining power among quantum-capable entities, thereby increasing the risk of 51% attacks.

4.2. Ethereum

Ethereum faces several potential vulnerabilities in the advent of quantum computing, primarily because it relies on cryptographic primitives based on elliptic curve mathematics. The network uses ECDSA for transaction authentication, BLS signatures for maintaining consensus among validators, and KZG commitments for data availability sampling. Each of these mechanisms depends on the hardness of the Elliptic Curve Discrete Logarithm Problem (ECDLP), which can be efficiently solved by Shor's algorithm on a sufficiently powerful quantum computer, thereby compromising their security.

A further vulnerability arises from Ethereum's use of Verifiable Delay Functions (VDFs) in its PoS consensus. VDFs enforce sequential computation to introduce a minimum, verifiable delay, ensuring that validator selection remains random and resistant to manipulation. However, quantum computers could execute these functions significantly faster than classical systems, effectively reducing the intended delay. This speed advantage could allow adversaries to predict or influence validator selection, thereby undermining the randomness and fairness of the PoS process. In extreme cases, such manipulation could allow attackers to increase their likelihood of being chosen as validators, disrupt consensus formation, or even conduct double-spending and block reorganization attacks.

4.3. Algorand

The principal quantum vulnerability in Algorand's architecture arises from its reliance on a Verifiable Random Function (VRF), which utilizes elliptic curve-based public key cryptography for randomness generation and validator selection. A sufficiently advanced quantum computer executing Shor's algorithm could efficiently compute discrete logarithms, allowing an adversary to forge or predict VRF outputs. This would compromise the unpredictability and integrity of the randomness in PPoS consensus. Such a breach could enable malicious actors to manipulate validator selection, influence consensus outcomes, or disrupt network security, thereby weakening the protocol's foundational trust assumptions.

4.4. Solana

Solana uses EdDSA for digital signatures and the SHA-256 hash function as the cryptographic foundation of its PoH consensus mechanism. The network also integrates a Verifiable Delay Function (VDF) to establish a verifiable and sequential timeline of transactions. However, both EdDSA and VDFs depend on classical cryptographic assumptions vulnerable to quantum attacks. A sufficiently powerful quantum computer could exploit Shor's

algorithm to compromise the elliptic curve signatures and Grover’s algorithm to accelerate hash inversion, posing significant risks to the network’s long-term cryptographic integrity.

4.5. Avalanche

Avalanche’s exposure to quantum threats arises primarily from its use of elliptic curve cryptography, specifically the secp256k1 curve, across multiple network layers. Both the Exchange Chain (X-Chain) and the Platform Chain (P-Chain) use secp256k1 for key generation and use a double-hashing scheme-SHA-256 followed by RIPEMD-160-to derive 20-byte address identifiers. Although the Ava Labs team has argued that double hashing provides an additional layer of protection, this does not mitigate the underlying quantum vulnerability of the elliptic curve itself.

Furthermore, Avalanche uses ECDSA for transaction authentication. During transaction execution, the hash of the public key is revealed, potentially exposing it to quantum decryption attacks. While Avalanche’s block finality time of approximately two seconds significantly reduces the attack window compared to Bitcoin, a quantum computer capable of executing Shor’s algorithm faster than this interval could still derive private keys and compromise transaction security.

4.6. Monero

Monero uses several cryptographic mechanisms to provide privacy, yet many of them are inherently vulnerable to quantum attacks. Its core primitive, ring signatures, derives anonymity from the hardness of ECDLP, which a sufficiently powerful quantum computer could break using Shor’s algorithm, thereby exposing the true signer. Stealth addresses, which generate one-time destination addresses to hide recipient identities, rely on the same assumption and are thus equally susceptible. A quantum adversary capable of solving ECDLP could recover private keys, link stealth addresses to real wallets, and fundamentally compromise Monero’s anonymity and confidentiality guarantees.

Ring Confidential Transactions (RingCT) [52] face similar quantum risks. Although RingCT hides transaction amounts using Pedersen Commitments, its security ultimately relies on ECC, allowing a quantum adversary to break underlying signatures and undermine anonymity. However, the probabilistic structure of Monero’s ring signatures means an attacker must still identify the meaningful input within a ring and solve multiple commitments simultaneously, adding complexity and uncertainty to the attack.

Bulletproofs [53], used in Monero to reduce proof size and improve efficiency, also rely on discrete logarithm assumptions and are therefore vulnerable to quantum attacks. A powerful quantum computer could decrypt historical transaction data, exposing previously hidden amounts or address relationships. While the direct financial impact of such retrospective disclosure may be limited, the loss of privacy could enable coercive or extortion-based attacks.

4.7. XRP Leger

XRPL uses multiple cryptographic primitives to maintain transaction integrity and network security, but these mechanisms are not quantum-resistant. The system primarily uses Ed25519 for transaction signing, while the Wallet Propose Admin RPC command uses secp256k1. Both signature schemes rely on ECC, making them vulnerable to Shor’s algorithm, which can efficiently compute discrete logarithms on a quantum computer. So, it would be susceptible to quantum attacks capable of deriving private keys, forging signatures, and compromising transaction authenticity.

5. Defenses Against Quantum Adversaries

In response to vulnerabilities to quantum adversaries, a growing body of research and development has focused on designing blockchain mechanisms that remain resilient in a post-quantum setting. In this section we answer the question *RQ2: What solutions have been proposed by blockchain applications to tackle a quantum adversary?* We examine the range of solutions proposed by different blockchain applications to address this challenge. A summary of our findings is provided in Table 2.

5.1. Bitcoin

Researchers have proposed two main strategies to address Bitcoin’s quantum vulnerabilities. One is a hard fork that requires users to migrate their funds within a set timeframe. The other introduces a quantum-resistant signature scheme compatible with the existing architecture, enforcing a strict migration deadline after which coins left in vulnerable addresses would be burned to prevent quantum exploitation.

Building on the first approach, Bitcoin Post-Quantum (BPQ) [54] constitutes the most advanced initiative toward a quantum-secure version. Hard-forked from the original network on December 22, 2018, BPQ implements the Extended Merkle Signature Scheme (XMSS), which uses Winternitz One-Time Signatures (W-OTS) to divide messages into 67 chunks of 256 bits each before aggregating them into a single verifiable signature. This approach offers strong quantum resistance but increases signature sizes by approximately 4 \times to 32 \times relative to ECDSA.

To offset the resulting data overhead without degrading performance, BPQ expands the block weight limit from 4 MB to 32 MB, allocating about 16 MB to the witness segment. Network addresses begin with the prefix “pq1,” signifying compliance with post-quantum cryptographic standards. Additionally, BPQ replaces traditional PoW with one based on the birthday problem, preserving classical efficiency while limiting the quantum advantage provided by Grover’s algorithm and maintaining competitive mining equilibrium.

5.2. Ethereum

Ethereum has undertaken both immediate and long-term initiatives to strengthen its resilience against the emerging threat of quantum computing. The transition

Blockchain	Safeguards	Key Vulnerabilities	Transition Plans	Research Areas
Bitcoin	None	ECDSA	None	Bitcoin PQ
Ethereum	None	ECDSA, BLS, KZG, VDF	Integrating W-OTS, zk-STARKs	Integrating FALCON
Algorand	FALCON	VRF	Integrating PQ VRF	X-VRF, LB-VRF
Solana	W-OTS Vaults	Optional W-OTS	None	None
Avalanche	None	ECDSA	None	Integrating Lattice-Based Cryptography
Monero	None	EdDSA	Integrating FCMP++ protocol	PQ Ring Signatures
XRPL	None	EdDSA, ECDSA	None	Integrating Lattice-Based Signatures

TABLE 2. POST-QUANTUM TRANSITION PLANS AND SAFEGUARDS

from PoW to PoS in Ethereum 2.0 reduced some quantum exposure by eliminating PoW’s reliance on computationally intensive hashing processes [55]. Nevertheless, the protocol’s continued use of BLS signatures for validator consensus maintains vulnerability to quantum attacks, as they depend on ECC [56].

To mitigate this risk, researchers have explored adopting PQ signature schemes such as XMSS, SPHINCS+, and Lamport signatures [57]. These algorithms offer strong quantum resistance but introduce scalability challenges, as their signatures can be up to ten times larger than traditional elliptic curve-based ones, thereby reducing transaction throughput and network efficiency [58].

Looking forward, Ethereum 3.0-tentatively projected for release around 2027-aims to integrate Winternitz One-Time Signatures (W-OTS) and zkSTARKs to enhance both security and privacy in a post-quantum environment [57], [59]. Although STARK-based proofs are computationally demanding, they provide scalability and transparency without trusted setup parameters. To accelerate this development, BTQ, in collaboration with StarkWare, demonstrated the first verification of FALCON signature on StarkNet, an Ethereum Layer-2 network-marking a step toward quantum-safe infrastructure within the ecosystem [60].

Several strategies have been proposed for transitioning Ethereum into a fully post-quantum-secure environment. The first approach involves utilizing account abstraction, which introduces flexibility by incorporating a FALCON verifier contract for signature validation [61], [62]. This would permit adoption of PQ signature scheme-but at the cost of higher gas consumption, reducing transaction efficiency [63].

A second proposal advocates a hard fork introducing a new transaction type that uses FALCON in place of the current BLS signatures [61]. While this would directly mitigate quantum vulnerability, it could tightly bind Ethereum’s architecture to a single cryptographic scheme, complicating future upgrades and limiting adaptability.

A third proposal leverages the Ethereum Object Format (EOF) within the Execution Layer, allowing arbitrary EVM code to perform transaction validation via account abstraction [55], [59]. This enhances flexibility by supporting multiple PQ signature schemes and could alleviate some scalability issues linked to large signatures. However, it introduces additional security risks, particularly the potential for DoS attacks, since allowing arbitrary code execution could enable malicious actors to overload the network with computationally expensive verification routines [59].

Ongoing research efforts also focus on reducing the size of post-quantum signatures through signature aggregation techniques, either natively or by leveraging

quantum-safe SNARKs and STARKs [64], [65]. These aggregation approaches aim to balance cryptographic strength with the scalability requirements of Ethereum’s next-generation consensus architecture.

5.3. Algorand

Algorand is actively engaged in developing post-quantum Verifiable Random Functions (VRFs) to safeguard its consensus mechanism against emerging quantum threats [66], [67]. Early research efforts focused on the X-VRF model, which combined the XMSS with a random oracle to produce pseudorandom outputs suitable for validator selection [68]. However, in 2024, researchers at the University of Alberta demonstrated critical vulnerabilities in the X-VRF construction, showing that its underlying assumptions fail to hold under realistic adversarial conditions, rendering it insecure and unsuitable for deployment in a post-quantum environment [69].

In response, Algorand’s cryptographic research team introduced LB-VRF (Lattice-Based VRF), designed to deliver quantum-resistant randomness generation while maintaining efficiency. LB-VRF achieves a result size of 84 bytes, a proof size of approximately 5 KB, an evaluation time of 3 milliseconds, and a verification time of 1 millisecond-figures that represent substantial improvements over previous PQ constructions [70]. These performance metrics suggest that LB-VRF could become a viable candidate for integration into Algorand’s PPoS consensus [66].

Despite these advancements, the LB-VRF has notable limitations. It has not scaled beyond a 1000 nodes due to its high data overhead(~8 MB per instance) and its dependence on short-lived key pairs that can generate only a limited number of outputs before rotation [68], [70]. These requirements add operational complexity hindering long-term scalability. Ongoing work by researchers and the Algorand Foundation aims to refine the design and realize practical PQ consensus. In this direction, Algorand has already integrated FALCON into its state proofs, providing quantum-resistant attestations for securing blockchain history and enabling safe cross-chain operations [66], [67].

5.4. Solana

Solana’s long-term approach to quantum security remains uncertain. The network still relies on quantum-vulnerable primitives such as EdDSA and SHA-256, and no comprehensive public roadmap outlines a path to full post-quantum resilience. Public statements suggest that Solana’s priorities have shifted toward scalability rather than advanced cryptographic security [71]. Although an

optional quantum-resistant “Winternitz Vault” has been introduced [7], [72], it is non-default and does not represent a system-wide transition.

5.5. Avalanche

In light of the vulnerabilities of ECC, Ava Labs has acknowledged the quantum risks facing the Avalanche network and is actively exploring lattice-based cryptography as a countermeasure. However, the team remains cautious about deploying such schemes on the main network [73], as lattice-based signatures are roughly an order of magnitude larger than current elliptic curve signatures. This increase in data size could strain network bandwidth and reduce transaction throughput, potentially affecting Avalanche’s performance and scalability.

5.6. Monero

Monero’s regular six-month hard fork schedule provides the network with an inherently adaptable framework, allowing it to integrate protocol upgrades and adopt post-quantum signature schemes more rapidly than many other blockchain systems as quantum threats become more imminent [74]. The Monero community and development teams have actively engaged in PQC research, combining academic analysis with technical experimentation to strengthen the network’s long-term quantum resilience.

In 2020, Monero conducted a comprehensive academic review of its quantum security, identifying key vulnerabilities within its existing cryptographic primitives and proposing potential strategies for transitioning toward quantum-safe alternatives. This review, published on GitHub, laid the groundwork for the network’s ongoing PQC initiatives and has since served as a reference for subsequent research efforts [75].

By 2022, attention turned to the Seraphis [76] protocol, a proposal introducing a modular transaction framework that separates membership proofs from ownership and balance (unspent output) proofs. This modularization improved efficiency and flexibility in proof generation. However, the analysis concluded that Seraphis offered limited PQC guarantees and presented migration challenges, as its underlying cryptographic assumptions remained vulnerable to quantum attacks [74], [77].

In 2024, Monero’s focus shifted toward evaluating the FCMP++ protocol [78], which demonstrated a more robust and comprehensive approach to quantum resilience. FCMP++ supports full-chain membership proofs, spend authorization, and linkability while maintaining full-set privacy within the RingCT model. Beyond quantum resistance, FCMP++ also introduces enhanced functionalities—including transaction chaining, outgoing view keys, and forward secrecy—that collectively improve scalability, privacy, and adaptability in a PQ context.

Monero also explored additional frameworks with potential PQC applicability. One such candidate is MatRiCT [79], a Confidential Transaction protocol delivering performance improvements over prior PQC proposals, reportedly enabling transaction generation and verification in approximately 23 milliseconds, with proof sizes two orders of magnitude smaller than other PQ designs. Another emerging proposal, GLYPH [80], employs a hash-based

ring PQ signature scheme, offering enhanced resistance to quantum attacks while maintaining compatibility with Monero’s existing privacy architecture.

5.7. XRP Ledger

Ripple has initiated efforts to advance post-quantum cryptographic research aimed at strengthening the security of XRPL against future quantum threats. As part of this initiative, Ripple has partnered with the ADAPT Research Centre and Trinity College Dublin-supported by Ripple’s University Blockchain Research Initiative (UBRI)-to establish the Ripple Blockchain Collaboratory. This partnership focuses on advancing research in post-quantum cryptography, zero-knowledge proofs, and secure validator infrastructure [81], [82].

These initiatives form part of a broader effort within the ecosystem to enhance cryptographic resilience and develop practical frameworks for quantum-resistant blockchains. Ongoing research includes technical analyses that outline migration paths toward quantum-safe signature schemes, ensuring long-term security [83]–[85].

6. Performance Challenges of PQ Adoption

As blockchain systems transition to post-quantum (PQ) signature schemes, a key concern arises regarding the trade-off between enhanced cryptographic security and system efficiency. In this section, we address *RQ3: What is the impact on performance when existing blockchain applications shift to a PQ signature scheme?* We analyze the performance implications of such a transition, focusing on core operational metrics—transaction throughput, latency, and block interval time—to evaluate how these are affected by the integration of PQ signatures.

6.1. Impact on Transaction Throughput (TPS)

Real-time throughput refers to the number of transactions a blockchain processes per second under actual operating conditions, while the *maximum theoretical throughput* represents the upper bound achievable under ideal conditions with fully utilized blocks and minimum-size transactions. The theoretical TPS is given by

$$\text{Theoretical TPS} = \frac{\text{Maximum Block Size}}{\text{Minimum Transaction Size} \times \text{Block Time}}$$

This assumes every block is perfectly filled with the smallest valid transactions and produced exactly at the block interval. Real-world TPS is lower due to latency, propagation delays, transaction complexity, and variable gas usage. The real-time and theoretical throughput of the systems examined in this study are shown in Table 6. Because PQ signature schemes increase transaction size, their adoption would raise the minimum transaction size and therefore reduce a blockchain’s theoretical TPS.

We compute the theoretical TPS for seven representative blockchain protocols under both classical signatures (ECDSA/Ed25519) and a PQ configuration(ML-DSA-44), the most size-efficient variant in the standardized ML-DSA family. We denote the resulting throughput as TPS_{PQ} , representing the number of transactions per second achievable when PQ signatures replace classical ones. These

values serve as conservative lower bounds on throughput once PQ overheads are accounted for. Detailed derivations appear below, with results summarized in Table 3.

Bitcoin (1 P2WPKH Transaction). Bitcoin has a block interval time of approximately 600 seconds and a maximum block size of 1,000,000 vB. The average transaction size for a single P2WPKH input/output transaction using ECDSA is about 109.5 vB. Replacing ECDSA (71 bytes) with an ML-DSA-44 signature (2420 bytes) increases the transaction size to $(109.5 - \frac{71}{4} + \frac{2420}{4}) = 696.75$ vB. The theoretical throughputs are therefore $1,000,000 / (109.5 \times 600) \approx 15.22$ for classical and, $TPS_{PQ} = 1,000,000 / (696.75 \times 600) \approx 2.39$ for PQ. This corresponds to a relative throughput of $2.39 / 15.22 \approx 0.16$, an approximate **84% decrease** in theoretical TPS due to ML-DSA-44.

Ethereum and Avalanche (C-Chain). In Ethereum, each transaction pays a minimum intrinsic gas cost of 21,000 units, with calldata adding 68 gas per nonzero byte and 4 gas per zero byte; contract creation typically adds an additional 32,000 gas. Although signature verification is part of transaction validation, Ethereum provides no official breakdown of how much of the 21,000 gas is dedicated to this step. ECDSA verification is implicitly included in the fixed cost and does not incur extra gas per signature byte.

Given Ethereum’s maximum block gas limit of 30 million gas units and an average block time of about 12 seconds [49], the theoretical TPS can be estimated as $30,000,000 / (21,000 \times 12) \approx 119$. This value represents the *upper theoretical bound* for Ethereum’s transaction throughput under classical cryptographic assumptions.

Avalanche’s C-Chain employs the same Ethereum Virtual Machine (EVM) and thus follows an equivalent gas accounting model. Each transaction on the C-Chain therefore inherits similar intrinsic gas costs and signature validation characteristics, leading to comparable theoretical throughput estimates when operating under classical cryptography. So, if a PQ signature scheme such as ML-DSA-44 were adopted, both Ethereum and Avalanche’s C-Chain may need to adjust intrinsic gas parameters and base fees to account for the higher computational and network overhead of validating and transmitting PQ signatures.

Solana. Solana defines transaction throughput primarily as a function of compute-unit (CU) capacity and block production frequency. Each block (or slot) is permitted a maximum of 60 million compute units, while the average block interval is approximately 0.4 seconds under nominal network conditions. For a baseline lightweight transaction (a native SOL transfer) consuming $\sim 2000\text{-}3000$ CU-s the compute-bounded throughput becomes $60,000,000 / (2,500 \times 0.4) \approx 60,000$. Solana additionally enforces a serialized transaction size limit of 1,232 bytes. Because an ML-DSA-44 signature alone exceeds this limit, such a PQ signature scheme cannot be accommodated within a single L1 transaction under current protocol parameters.

Even if a smaller PQ signature such as FALCON were to fit within the 1,232-byte constraint, the theoretical TPS cannot be computed in closed form. Under Solana’s *Compute Budget Program*, byte size and compute cost are decoupled: while transaction limits as small as 300 CUs may be specified, the actual CU-s consumed depend entirely

on the verifier’s algorithmic complexity rather than its message length. So, the effective throughput of FALCON-based or other PQ-augmented verification remains indeterminate without empirical measurement of the verifier’s CU profile. Nevertheless, it can be stated with certainty that such PQ-based verification would incur a higher computational load than the native Ed25519 scheme, thereby leading to a definite reduction in achievable throughput relative to the current baseline performance.

Monero (1 Input/2 Output Transaction). Monero has a block interval time of approximately 120 seconds. Its maximum block size is at most twice the median of the last 100 blocks, providing an adaptive bound. A typical transaction (1 input, 2 outputs) is about 1.5 kB using CLSAG. Under ML-DSA-44, we approximate the transaction size to increase to ≈ 3.7 kB. The throughputs scale as $TPS = (2 \times \text{median}_{100}) / (1.5 \times 120)$ for classical, and, $TPS_{PQ} = (2 \times \text{median}_{100}) \times (3.7 \times 120)$ for PQ. Taking the ratio, $TPS_{PQ}/TPS = 1.5/3.7 \approx 0.41$, indicating an approximate **59% decrease** in theoretical TPS for equivalent block capacity.

Algorand. Algorand has a block interval time of approximately 2.85 seconds and a block size limit of 5,000,000 bytes. The average baseline transaction size is around 200 bytes, including a 64 byte Ed25519 signature. Replacing Ed25519 with ML-DSA-44 (2420 bytes) increases the transaction size to $(200 - 64 + 2420) = 2556$ bytes. Thus, the theoretical throughputs become $5,000,000 / (200 \times 2.85) \approx 8771$ for classical, and, $TPS_{PQ} = 5,000,000 / (2556 \times 2.85) \approx 686$ for PQ. Hence, $(686/8771) \approx 0.078$, which represents an approximate **92% reduction** in theoretical TPS.

XRPL. XRPL does not enforce a fixed maximum ledger size or block size limit. So, we adapt the throughput formula to better reflect XRPL’s continuous ledger operation: $TPS = B / (s \times T)$ where, B = bytes of transaction data per ledger close, s = average transaction size (in bytes), T = ledger close interval (in seconds).

For comparing the effects of ECDSA and PQC (ML-DSA-44) signatures, the relative throughput depends only on the ratio of transaction sizes and consequently the signature sizes of the corresponding signature schemes: $TPS_{PQ}/TPS = s_{ECDSA}/s_{PQ}$, and the percentage decrease in theoretical TPS is given by $1 - (s_{ECDSA}/s_{PQ})$. Since the transaction size will only be impacted by the change in signatures, this corresponds to an approximate **85% reduction** in theoretical throughput when replacing ECDSA with ML-DSA-44.

Blockchain	Theoretical TPS	Theoretical TPS _{PQ}
Bitcoin	~ 15	~ 2
Ethereum	~ 119	Cannot be estimated
Avalanche (C-Chain)	$\sim 4,500$	Cannot be estimated
Monero	~ 1000	~ 410
Solana	$\sim 60,000$	Cannot be estimated
Algorand	$\sim 8,771$	~ 686
Ripple	$\sim 3,400$	~ 510

TABLE 3. COMPARISON OF THROUGHPUT (TRANSACTIONS PER SECOND) ACROSS DIFFERENT BLOCKCHAIN PLATFORMS UNDER CLASSICAL AND PQ (ML-DSA-44) CONFIGURATIONS.

6.2. Impact on Storage

All blockchains considered in Table 7 currently employ elliptic-curve-based signature schemes such as

ECDSA or Ed25519, which produce signatures of approximately 64-73 bytes and public keys of 32-33 bytes when represented on-chain. In contrast, a PQ scheme such as ML-DSA-44 generates signatures of roughly 2,420 bytes and public keys of approximately 1,312 bytes. Substituting ML-DSA-44 in place of existing elliptic-curve schemes would therefore increase the byte size per signature by a factor of $\sim 35 - 40\times$. The estimated storage requirements resulting from the direct substitution of classical signature algorithms with ML-DSA-44 are presented in Table 4. These values represent upper-bound estimates, as they do not account for any compression mechanisms that may be applied. Even pruned nodes, which discard historical data after validation, would experience similar transient scaling effects since they must still download, verify, and temporarily store the larger PQ signatures prior to pruning.

Blockchain	Estimated Storage
Bitcoin	Full: $\sim 21 - 24$ TB Pruned: $\sim 350 - 400$ GB
Ethereum (Geth)	Full: $> 22 - 26$ TB Archive: $> 420 - 480$ TB
Ethereum (Erigon)	Full: $\sim 38 - 44$ TB Archive: $\sim 63 - 72$ TB
Avalanche (C-Chain)	Full: $\sim 12 - 14$ TB Archive: $\sim 70 - 80$ TB
Monero	Full: $\sim 8 - 9$ TB Pruned: $\sim 3.3 - 3.8$ TB
Solana	Validator: $35 - 160$ TB Archive: $\sim 10 - 16$ PB
Algorand	Full: $\sim 0.7 - 0.8$ TB Archive: ColdDataDir $\sim 105 - 120$ TB + HotDataDir $\sim 3.5 - 4$ TB
XRP Ledger (XRPL)	Full history: $\sim 910 - 1040$ TB Non-full-history: $\geq 1.75 - 2$ TB

TABLE 4. APPROXIMATE STORAGE REQUIREMENTS FOR DIFFERENT BLOCKCHAIN PLATFORMS UNDER PQ (ML-DSA-44) CONFIGURATION.

6.3. Impact on Block Interval Time

Table 5 summarizes the approximate block intervals across a range of major blockchain platforms operating under conventional signature schemes (e.g., ECDSA or Ed25519). If post-quantum signature schemes such as ML-DSA-44 were substituted, the block intervals themselves would not be expected to change. The block interval-defined as the targeted time between successive block productions-is a critical protocol parameter that governs consensus stability, network synchronization, and resistance to chain forks. Modifying this parameter would necessitate a reparameterization of the consensus mechanism, which is typically calibrated to block propagation latency, validator responsiveness, and probabilistic finality guarantees. Consequently, the adoption of PQ signatures affects transaction-level and network-layer performance but does not directly alter temporal consensus parameters such as block interval.

7. Systemic Shifts in PQ Blockchains

The integration of PQ signature schemes is likely to trigger systemic and behavioral changes in blockchain networks beyond raw performance impacts, influencing block processing, consensus dynamics, and miner incentives. In this section, we address *RQ4: What are the side effects and behavioral changes on blockchain applications?* We

Blockchain	Block Interval
Bitcoin	~ 10 minutes
Ethereum	~ 12 seconds
Avalanche (C-Chain)	$\sim 1.4 - 1.8$ seconds
Monero	~ 2 minutes
Solana	~ 0.4 seconds
Algorand	~ 2.82 seconds
XRP Ledger (XRPL)	~ 4 secs

TABLE 5. APPROXIMATE BLOCK INTERVALS ACROSS DIFFERENT BLOCKCHAIN PLATFORMS UNDER CLASSICAL CONFIGURATIONS.

assess how adopting PQ cryptography affects the stability and economic viability of blockchain ecosystems.

7.1. Impact on Convergence of Consensus

Integrating PQ cryptographic primitives can disrupt consensus convergence by altering the timing of block propagation and validation. PQ schemes produce substantially larger signatures and keys, and maintaining throughput under these conditions naturally pushes systems toward increasing block size. However, larger blocks propagate more slowly, raising network latency and extending verification time. As propagation delay approaches the block interval, nodes fall out of sync, weakening consensus convergence. In PoW systems, this increases fork and orphan rates, while in PoS and PoH protocols, slower propagation or verification can cause validators to miss slots or rounds, directly impairing the protocol's ability to finalize blocks.

Empirical studies confirm this relationship: Klarman et al. [86] report that in Bitcoin, with a mean block interval of 600 seconds, an average propagation delay of 11.6 seconds corresponds to a fork probability of about 1.9%. Increasing block size by a factor of ten - intended to boost throughput to roughly 30 transactions per second, extends propagation to 116 seconds, raising fork probability to 17.6%. Such delays would hinder timely consensus, requiring many more confirmations to achieve finality.

Similar behavior has been observed in other blockchains using PoS protocol. In Ethereum, larger blocks correlate with longer propagation times: blocks over 500 kB have roughly a 2% chance of taking more than 4 seconds to propagate, compared to negligible delays for smaller blocks [87]. In Algorand, Gilad et al. [88] show that propagation delay grows linearly with block size, implying that larger PQ-era blocks could slow the consensus rounds and reduce the rate at which the network reaches agreement.

In PoH protocols, delayed block propagation or slow signature verification can cause validators to miss slots or rounds, weakening convergence and finality. Empirical analyses of Solana show this effect in practice: network logs attribute skipped slots to propagation delays in the Turbine broadcast layer, where late-arriving shreds prevent validators from meeting slot deadlines [89]. These findings indicate that, despite Turbines scalability optimizations, larger block sizes amplify propagation delays and increase the likelihood of missed slots, reducing overall consensus efficiency.

Overall, the adoption of PQ primitives introduces substantial communication and verification overheads that directly impact the temporal dynamics of consensus. Unless protocol parameters are carefully re-optimized, the

resulting slowdown in block dissemination and validation could hinder convergence guarantees across consensus mechanisms, threatening both performance and stability in PQ blockchains.

7.2. Impact on Financial Incentives

The economics of block size hinge on a trade-off between fee revenue and block propagation risk. Larger blocks allow miners to collect more fees but take longer to propagate, increasing the chance that a competing block arrives first and causing the slower block to be orphaned. As a result, expected miner revenue does not grow monotonically with block size; instead, it peaks at an optimal point where additional fee gains are offset by the rising probability of orphaning.

Rizun et al. [90] formalized this trade-off by modeling expected miner profit as $(1 - \pi(Q)) \times F(Q)$, where $F(Q)$ is the cumulative fee function increasing with block size Q , and $\pi(Q)$ is the orphan probability, which grows with propagation time. Similarly, Houy et al. [91] similarly showed that while adding transactions increases fees, it also raises the chance of orphaning, leading rational miners to self-limit block size to maximize expected profit.

Empirical and simulation studies support this theoretical relationship. Chen et al. [92] modeled miners' block-size choices as an evolutionary game and found that, although fees increase with block size, larger blocks introduce higher latency and reduce the probability of block acceptance. Dimitri et al. [93] likewise showed that miner revenue is bounded, as the marginal delay cost eventually outweighs additional fee gains beyond a certain block-size threshold.

Taken together, prior works show that while larger blocks increase nominal revenue, they also raise propagation delays and orphaning risk, producing diminishing and eventually negative-returns beyond an optimal size. With bulkier PQ signatures, blocks will propagate more slowly, increasing the likelihood of being orphaned and reducing miners' expected payoff even if rewards remain unchanged. As propagation delay becomes more influential in block acceptance, miners may adopt more conservative block sizes or withdraw from participation altogether. In equilibrium, this shift reduces overall profitability and intensifies centralization pressures toward nodes able to offset network latency.

8. Open Problems

Transition. A core challenge is securely transitioning existing non-PQ accounts to PQ-protected ones while preserving user identity, asset ownership, and historical continuity. No standard migration mechanism exists that avoids exposing classical secrets or introducing new risks. Difficulties include proving ownership without revealing vulnerable keys, migrating large user populations without centralization, and supporting periods where classical and PQ credentials coexist. ZKPs offer tools for verifying control of legacy accounts without disclosure, but integrating them with PQ primitives adds complexity. Designing secure, efficient, and scalable migration pathways that protect legacy accounts throughout the transition remains unresolved.

Confidentiality and Privacy. Another challenge is redesigning blockchain confidentiality and privacy mechanisms to remain secure in a post-quantum environment. Current systems depend on commitments, homomorphic encryption, ZK proofs, and ring signatures that become insecure against quantum adversaries. The problem is to develop quantum-safe primitives that maintain anonymity, correctness, and performance while integrating cleanly with existing blockchain architecture.

In UTXO-based privacy systems such as Monero and Zcash, confidential transactions rely on quantum-vulnerable assumptions to hide amounts, identities, and linkability. The challenge is to construct quantum-safe mechanisms that preserve strong anonymity sets, efficient verification, and scalable confidential transfers without compromising usability or deployability.

Account-based blockchains such as Ethereum, Solana, face a parallel but distinct challenge. Existing confidential-transaction proposals rely on homomorphic encryption and ZK proofs that are also tied to quantum-insecure foundations. The problem is designing quantum-resistant confidentiality layers that integrate cleanly with execution environments, avoid excessive overhead, and support composability with complex smart-contract logic. Creating a performant PQ analogue of existing confidential-account schemes is still an unsolved research direction.

Communication. The implications of quantum-safe communication protocols, such as PQ-secure TLS, on blockchain consensus mechanisms present an emerging area of concern. Validator coordination, peer-to-peer messaging, and block propagation rely heavily on secure and efficient communication channels. Replacing classical TLS with quantum-safe alternatives may introduce latency overheads or affect message authentication efficiency, ultimately influencing consensus performance and network stability. Understanding and mitigating these effects is essential for ensuring that PQ resilience does not compromise the scalability or reliability of blockchain networks.

9. Conclusion

The emergence of quantum computing poses a profound disruption to blockchain security and performance across contemporary distributed ledger systems. The core reliance on elliptic-curve and hash-based cryptography exposes fundamental vulnerabilities to quantum algorithms, necessitating a transition toward post-quantum alternatives. Integrating quantum-resistant primitives introduces significant performance trade-offs, affecting scalability, latency, and consensus efficiency. In this paper, we study how post-quantum attackers reshape these dynamics, revealing that quantum adaptation extends beyond cryptographic substitution to encompass systemic shifts in protocol design, governance, and interoperability. Ensuring resilience in the quantum era will require coordinated standardization of post-quantum schemes, adoption of hybrid cryptographic infrastructures, and a sustained balance between security, performance, and decentralization.

References

- [1] M. Corporation. (2025, February) Microsoft unveils majorana 1, the worlds first quantum processor powered by topological

- qubits. Accessed November 2025. [Online]. Available: <https://news.microsoft.com/source/features/innovation/microsofts-major-ana-1-chip-carves-new-path-for-quantum-computing/>
- [2] G. Q. AI. (2024, December) Meet willow, our state-of-the-art quantum chip. Accessed November 2025. [Online]. Available: <https://blog.google/technology/research/google-willow-quantum-chip/>
- [3] CoinMarketCal. (2025, September) Defi looks vast with \$160b in tvl, but capital concentrates in a handful of protocols. Accessed November 2025. [Online]. Available: <https://coinmarketc.com/en/news/defi-looks-vast-with-160b-in-tvl-but-capital-concentrate-s-in-a-handful-of-protocols>
- [4] CoinMarketCap. (2025, September) Ethereum ecosystem market capitalization. Accessed November 2025. [Online]. Available: <https://coinmarketcap.com/view/ethereum-ecosystem/>
- [5] P. W. Shor, "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer," *SIAM Journal on Computing*, vol. 26, no. 5, pp. 1484–1509, 1997. [Online]. Available: <https://doi.org/10.1137/S0097539795293172>
- [6] Algorand Foundation, "Algorand state proofs: Post-quantum secure design," <https://developer.algorand.org/docs/get-details/stateproofs/>, 2023, accessed: 2025-01-22.
- [7] Cointelegraph, "Solana is now quantum-resistant, solana dev claims," 2025, accessed: 2025-11-04.
- [8] Bitcoin Project. (2025) Bitcoin official website. Accessed: 2025-11-03. [Online]. Available: <https://bitcoin.org/>
- [9] Ethereum Foundation. (2025) Ethereum official website. Accessed: 2025-11-03. [Online]. Available: <https://ethereum.org/>
- [10] Algorand Foundation. (2025) Algorand official website. Accessed: 2025-11-03. [Online]. Available: <https://algorand.org/>
- [11] Monero Project. (2025) Monero official website. Accessed: 2025-11-03. [Online]. Available: <https://www.getmonero.org/>
- [12] Avalanche Foundation. (2025) Avalanche official website. Accessed: 2025-11-03. [Online]. Available: <https://avax.network/>
- [13] Solana Foundation. (2025) Solana official website. Accessed: 2025-11-03. [Online]. Available: <https://solana.com/>
- [14] XRPL Foundation. (2025) Xrp ledger (xrpl) official website. Accessed: 2025-11-03. [Online]. Available: <https://xrpl.org/>
- [15] National Institute of Standards and Technology (NIST), "PQC: Post-Quantum Cryptography," 2024, available at <https://csrc.nist.gov/projects/post-quantum-cryptography>. [Online]. Available: <https://csrc.nist.gov/projects/post-quantum-cryptography>
- [16] ——, "NIST Releases First 3 Finalized post-quantum Post-Quantum Encryption Standards," August 13, 2024, available at <https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards>. [Online]. Available: <https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards>
- [17] ——, "FIPS 203 (initial public draft), Module-Lattice-Based Key-Encapsulation Mechanism Standard," August 24, 2023.
- [18] ——, "FIPS 204 (initial public draft), Module-Lattice-Based Digital Signature Standard," August 24, 2023.
- [19] ——, "FIPS 205 (initial public draft), Stateless Hash-Based Digital Signature Standard," August 24, 2023.
- [20] ——. (2025, March) Nist selects hqc as fifth algorithm for post-quantum encryption. Accessed November 2025. [Online]. Available: <https://www.nist.gov/news-events/news/2025/03/nist-selects-hqc-fifth-algorithm-post-quantum-encryption>
- [21] D. Moody, R. Perlner, A. Regenscheid, A. Robinson, and D. Cooper, "Transition to post-quantum cryptography standards," National Institute of Standards and Technology, Gaithersburg, MD, Internal Report, Initial Public Draft NIST IR 8547 (ipd), November 2024, accessed November 2025. [Online]. Available: <https://doi.org/10.6028/NIST.IR.8547.ipd>
- [22] Z. Foundation, "Zcash protocol specification," Electric Coin Company / Zcash Foundation, Tech. Rep., 2016. [Online]. Available: <https://zips.z.cash/protocol/protocol.pdf>
- [23] V. Buterin, "Ethereum: A next-generation smart contract & decentralized application platform," 2014, white Paper, available at <https://ethereum.org/en/whitepaper/>.
- [24] V. Buterin and V. Griffith, "Casper the friendly finality gadget," 2019. [Online]. Available: <https://arxiv.org/abs/1710.09437>
- [25] V. Buterin, D. Hernandez, T. Kamphfner, K. Pham, Z. Qiao, D. Ryan, J. Sin, Y. Wang, and Y. X. Zhang, "Combining ghost and casper," 2020. [Online]. Available: <https://arxiv.org/abs/2003.03052>
- [26] A. Kiayias, A. Russell, B. David, and R. Oliynykov, "Ouroboros: A provably secure proof-of-stake blockchain protocol," in *Advances in Cryptology - CRYPTO 2017*, ser. Lecture Notes in Computer Science, vol. 10401. Springer, 2017, pp. 357–388. [Online]. Available: <https://eprint.iacr.org/2016/889.pdf>
- [27] G. Wood, "Polkadot: Vision for a heterogeneous multi-chain framework," Polkadot Project, Tech. Rep., 2016. [Online]. Available: <https://github.com/polkadot-io/polkadot-white-paper/blob/master/>
- [28] Block.one, "Eos.io technical white paper v2," Tech. Rep., 2018. [Online]. Available: <https://academy.bit2me.com/wp-content/uploads/2021/05/eos-whitepaper.pdf>
- [29] T. Foundation, "Tron white paper version 2.0," Tech. Rep., 2018. [Online]. Available: https://tron.network/static/doc/white_paper_v_2_0.pdf
- [30] S. Inc., "Steem white paper: An incentivized, blockchain-based, public content platform," Steemit, Tech. Rep., 2016. [Online]. Available: <https://steem.com/SteemWhitePaper.pdf>
- [31] L. Foundation, "Lisk white paper," Lisk Foundation, Tech. Rep., 2018. [Online]. Available: <https://www.allcryptowhitepapers.com/wp-content/uploads/2018/05/Lisk-White-Paper.pdf>
- [32] IETF Crypto Forum Research Group (CFRG), "Verifiable random functions (vrf) draft rfc," Internet Engineering Task Force (IETF), Tech. Rep. draft-irtf-cfrg-vrf-13, 2019. [Online]. Available: <https://www.ietf.org/archive/id/draft-irtf-cfrg-vrf-13.html>
- [33] M. Castro and B. Liskov, "Practical byzantine fault tolerance and proactive recovery," *ACM Transactions on Computer Systems (TOCS)*, vol. 20, no. 4, pp. 398–461, 2002. [Online]. Available: <https://dl.acm.org/doi/10.1145/571637.571640>
- [34] C. Miller-Bier *et al.*, "A distributed operating system for permissioned blockchains hyperledger fabric," arXiv, Tech. Rep., 2018. [Online]. Available: <https://arxiv.org/pdf/1801.10228.pdf>
- [35] J. Kwon, "Tendermint: Consensus without mining," Tendermint Inc, Tech. Rep., 2014. [Online]. Available: <https://tendermint.com/static/docs/tendermint.pdf>
- [36] A. Kumar *et al.*, "The zilliqa technical whitepaper," Zilliqa Research, Tech. Rep., 2017. [Online]. Available: <https://docs.zilliqa.com/whitepaper.pdf>
- [37] J.P Morgan, "Quorum whitepaper: An enterprise-focused version of ethereum," J.P. Morgan Chase & Co., Tech. Rep., 2018, accessed November 2025. [Online]. Available: <https://github.com/jpmorganchase/quorum-docs/blob/master/Quorum%20Whitepaper%20v0.2.pdf>
- [38] D. Schwartz, N. Youngs, and A. Britto, "The ripple protocol consensus algorithm," Ripple Labs Inc., Tech. Rep., 2014, accessed November 2025. [Online]. Available: https://ripple.com/files/ripple_consensus_whitepaper.pdf
- [39] N. Barry, G. Losa, D. Mazières, J. McCaleb, and S. Polu, "The stellar consensus protocol (scp)," Internet Research Task Force (IRTF), DINRG, Expired Internet-Draft draft-mazieres-dinrg-scp-05, November 2018, accessed November 2025. [Online]. Available: <https://datatracker.ietf.org/doc/draft-mazieres-dinrg-scp/>
- [40] Team Rocket, "Snowflake to avalanche: A novel metastable consensus protocol family for cryptocurrencies," arXiv preprint arXiv:1906.08936, 2019, v2 (Aug 2020). Accessed November 2025. [Online]. Available: <https://arxiv.org/abs/1906.08936>
- [41] VeChain Foundation, "Vechain thor blockchain: Development plan and whitepaper," VeChain Foundation, Tech. Rep., 2018, accessed November 2025. [Online]. Available: <https://www.vechain.org/assets/whitepaper/whitepaper-1-0.pdf>

- [42] Energy Web Foundation, “Ew-dos: The energy web decentralised operating system part 1 : Vision & purpose,” Energy Web Foundation, Tech. Rep., 2020, accessed November 2025. [Online]. Available: <https://resource-platform.eu/wp-content/uploads/EnergyWeb-EWDOS-PART1-VisionPurpose-202006-vFinal.pdf>
- [43] I. Barinov, V. Baranov, and P. Khahulin, “Poa network whitepaper: An open permissioned ethereum-based network using proof of authority,” POA Network, Tech. Rep., 2018, accessed November 2025. [Online]. Available: <https://kando.tech/sites/default/files/2021-10/POA%20Whitepaper.pdf>
- [44] Goerli Dezentral gGmbH, “Goerli testnet: A cross-client proof-of-authority test network for ethereum,” Goerli Dezentral gGmbH, Tech. Rep., 2019, accessed November 2025. [Online]. Available: <https://goerli.net/>
- [45] Kovan Testnet Community, “Kovan testnet proposal: A public proof-of-authority ethereum testnet,” Kovan Testnet Community, Tech. Rep., 2017, accessed November 2025. [Online]. Available: <https://kovan-testnet.github.io/website/proposal/>
- [46] D. Boneh, B. Bünz, and B. Fisch, “Verifiable delay functions,” in *Advances in Cryptology CRYPTO 2018*, ser. Lecture Notes in Computer Science, vol. 10991. Springer, 2018, pp. 757–788, presented at CRYPTO 2018, Santa Barbara, CA. [Online]. Available: <https://eprint.iacr.org/2018/601.pdf>
- [47] A. Yakovenko. (2018) Inside solana: Performance at scale. Solana Labs. Accessed November 2025. Reports 47,370 TPS and 800 ms block times across 200 distributed nodes. [Online]. Available: <https://medium.com/solana-labs/inside-solanas-internal-scalability-test-cce13aa8c859>
- [48] S. Nakamoto, “Bitcoin: A peer-to-peer electronic cash system,” <https://bitcoin.org/bitcoin.pdf>, 2008.
- [49] Ethereum Foundation, “Proof-of-stake (pos) consensus mechanism,” <https://ethereum.org/en/developers/docs/consensus-mechanisms/pos/>, 2024, accessed: 2025-11-11.
- [50] ———, “Single slot finality,” <https://ethereum.org/en/roadmap/single-slot-finality/>, 2024, accessed: 2025-11-11.
- [51] L. K. Grover, “A fast quantum mechanical algorithm for database search,” in *Proceedings of the 28th Annual ACM Symposium on the Theory of Computing (STOC)*. New York, NY, USA: ACM, 1996, pp. 212–219. [Online]. Available: <https://doi.org/10.1145/237814.237866>
- [52] S. Noether, A. Mackenzie, and M. C. Team, “Ring confidential transactions,” Monero Research Lab, Tech. Rep. MRL-0005, February 2016, monero Research Lab Report MRL-0005. [Online]. Available: <https://www.getmonero.org/resources/research-lab/pubs/MRL-0005.pdf>
- [53] B. Bünz, J. Bootle, D. Boneh, A. Poelstra, P. Wuille, and G. Maxwell, “Bulletproofs: Short proofs for confidential transactions and more,” in *2018 IEEE Symposium on Security and Privacy (SP)*. IEEE, 2018, pp. 315–334. [Online]. Available: <https://doi.org/10.1109/SP.2018.00020>
- [54] B. P.-Q. Project, “Bitcoin post-quantum: Secure anonymous cryptocurrency for the post-quantum era,” <https://bitcoinqp.org/>, 2025, accessed: 2025-11-03.
- [55] Ethereum Foundation, “Future-proofing ethereum: Preparing for quantum resistance,” <https://ethereum.org/roadmap/future-proofing/>, 2024, accessed: 2025-11-04.
- [56] P. Chojecki, “Quantum computers threat to ethereum,” <https://pchojecki.medium.com/quantum-computers-threat-to-ethereum-3598580b69f5>, 2023, accessed: 2025-11-04.
- [57] BTQ Technologies, “Ethereums roadmap toward post-quantum cryptography,” <https://www.btq.com/blog/ethereums-roadmap-post-quantum-cryptography>, 2024, accessed: 2025-11-04.
- [58] Hackernoon, “Comparing on-chain post-quantum signature verification for ethereum,” <https://hackernoon.com/comparing-on-chain-post-quantum-signature-verification-for-ethereum>, 2024, accessed: 2025-11-04.
- [59] T. Q. Insider, “Ethereum prepares for quantum-resistant future amid security push,” <https://thequantumin insider.com/2024/10/30/ethereum-prepares-for-quantum-resistant-future-amid-security-push/>, 2024, accessed: 2025-11-04.
- [60] BTQ Technologies, “Completing the first falcon signature verification in starkware: Initiating the transition to a quantum-safe ethereum,” 2024, accessed: 2025-11-04. [Online]. Available: <https://www.btq.com/blog/completing-the-first-falcon-signature-verification-in-starkware-initiating-the-transition-to-a-quantum-safe-ethereum>
- [61] E. Community, “The road to post-quantum ethereum transaction is paved with account abstraction (aa),” <https://ethresear.ch/t/the-road-to-post-quantum-ethereum-transaction-is-paved-with-account-abstraction-aa/21783>, 2024, accessed: 2025-11-04.
- [62] ———, “Falcon as an ethereum transaction signature: The good, the bad and the gnarly,” <https://ethresear.ch/t/falcon-as-an-ethereum-transaction-signature-the-good-the-bad-and-the-gnarly/21512>, 2024, accessed: 2025-11-04.
- [63] E. M. Forum, “Eip-7592: Falcon signature verification pre-compile,” <https://ethereum-magicians.org/t/eip-7592-falcon-signature-verification-pre-compile/18053>, 2024, accessed: 2025-11-04.
- [64] P. . S. E. (PSE), “Post-quantum signature aggregation with falcon and labrador,” <https://pse.dev/blog/post-quantum-signature-aggregation-with-falcon-and-LaBRADOR>, 2024, accessed: 2025-11-04.
- [65] Anonymous, “Hybrid post-quantum signatures for bitcoin and ethereum,” *Preprints.org*, 2025, <https://www.preprints.org/manuscript/202509.2079>.
- [66] T. A. Foundation, “Algorand’s path to post-quantum readiness,” <https://algorand.co/technology/post-quantum>, 2024.
- [67] ———, “Realizing post-quantum security with algorand,” <https://www.certik.com/resources/blog/realizing-post-quantum-security-with-algorand>, 2022.
- [68] Z. Li, T. G. Tan, P. Szalachowski, V. Sharma, and J. Zhou, “Post-quantum vrf and its applications in future-proof blockchain systems,” *arXiv preprint arXiv:2109.02012*, 2021.
- [69] O. Bodagh and R. Safavi-Naini, “Short paper: Breaking x-vrf, a post-quantum verifiable random function,” in *Proceedings of FC 2024 (Short Papers)*, 2024, university of Calgary, Alberta, Canada. <https://ifca.ai/fc24/preproceedings/213.pdf>.
- [70] M. F. Esgin, V. Kuchta, A. Sakzad, and R. Steinfeld, “Practical post-quantum few-time verifiable random function with applications to algorand,” in *Financial Cryptography and Data Security (FC 2021), Part II*, 2021, p. 560578.
- [71] AInvest, “Preparing for quantum risk in crypto: The case for post-quantum blockchain assets,” 2025, accessed: 2025-11-04.
- [72] T. Q. Insider, “Solana takes a step toward pqc era with quantum-resistant vault,” 2025, accessed: 2025-11-04.
- [73] X. Insights, “Avalanche founder: quantum computing technology lattice-based cryptography was designed from the beginning to be resistant to quantum attacks,” *Xangle*, 2024, accessed: 2025-11-04.
- [74] Q. C. Staff, “Is monero quantum secure? explore the leading privacy coin,” <https://www.quantumcanary.org/insights/is-monero-quantum-secure-explore-the-leading-privacy-coin>, 2025, accessed: 2025-11-04.
- [75] I. . D. C. Lab, “Identifying practical post-quantum strategies for monero,” <https://ccs.getmonero.org/proposals/research-post-quantum-monero.html>, 2020, accessed: 2025-11-04.
- [76] koe, “Seraphis: A privacy-preserving transaction protocol abstraction (wip),” 2022, draft v0.0.16, publicly available on GitHub. [Online]. Available: <https://raw.githubusercontent.com/UK-oeHB/Seraphis/master/Seraphis-0-0-16.pdf>
- [77] T. M. Project, “What is seraphis, and why should you care?” <https://www.getmonero.org/2021/12/22/what-is-seraphis.html>, 2021, accessed: 2025-11-04.
- [78] L. . Parker, “Fcmp++: Full-chain membership proofs + spend authorization + linkability,” https://moneroresearch.info/index.php?action=attachments_ATTACHMENT_CORE&filename=95effbc6d6ad425edb788df9480e0dc64d4d3713&id=220&method=downloadAttachment&resourceId=227, Monero Research Lab, Technical Specification MRL-TechSpec-001, 2024, accessed: 2025-11-04.

- [79] M. F. Esgin, R. K. Zhao, R. Steinfeld, J. K. Liu, and D. Liu, “Matrict: Efficient, scalable and post-quantum blockchain confidential transactions protocol,” in *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*, ser. CCS ’19. New York, NY, USA: Association for Computing Machinery, 2019, p. 567584. [Online]. Available: <https://doi.org/10.1145/3319535.3354200>
- [80] A. Chopra, “GLYPH: A new instantiation of the GLP digital signature scheme,” Cryptology ePrint Archive, Paper 2017/766, 2017. [Online]. Available: <https://eprint.iacr.org/2017/766>
- [81] Ripple. (2024) Quantum computings impact on blockchain: Insights from professor massimiliano sala. Accessed: 2025-11-03. [Online]. Available: <https://ripple.com/insights/Quantum-Computing%27s-Impact-on-Blockchain-Insights-from-Professor-Massimiliano-Sala/>
- [82] A. Malhotra, “RippleX’s XRPL R&D Vision 2025 and Beyond,” YouTube, APEX 2025 Conference, 2025, ripple Research Manager, Post-Quantum Cryptography Resistance for XRPL, 2024. [Online]. Available: <https://www.youtube.com/watch?v=UzbHAbtLXQ>
- [83] M. Taghi. (2025, Aug.) Getting ready to transition to post-quantum security in xrpl. Accessed: 2025-11-03. [Online]. Available: <https://taghi.io/post/2025/08/20/Getting-Ready-to-Transition-to-Post-Quantum-Security-in-XRPL.html>
- [84] XRPL Foundation. (2024) Xrpl standards discussion #79: Post-quantum cryptography readiness. GitHub Discussions, Accessed: 2025-11-03. [Online]. Available: <https://github.com/XRPLF/XRP-L-Standards/discussions/79>
- [85] ——. (2025) Xrpl standards discussion #295: Post-quantum signature support. GitHub Discussions, Accessed: 2025-11-03. [Online]. Available: <https://github.com/XRPLF/XRPL-Standards/discussions/295>
- [86] U. Klarman, S. Basu, A. Kuzmanovic, and E. G. Sirer, “bloxroute: A scalable trustless blockchain distribution network (white paper version 1.2),” bloXroute Labs Inc., Department of Electrical Engineering & Computer Science, Northwestern University & Department of Computer Science, Cornell University, Tech. Rep., Nov. 2019, white paper, ver. 1.2. [Online]. Available: <https://bloxroute.com/wp-content/uploads/2019/11/bloxrouteWhitepaper.pdf>
- [87] Post-pecktra effects on ethereum: Reorg rate, propagation, and block size. Ethereum Research forum post. [Online]. Available: <https://ethresear.ch/t/post-pecktra-effects-on-ethereum-reorg-rate-propagation-and-block-size/23018>
- [88] Y. Gilad, R. Hemo, S. Micali, G. Vlachos, and N. Zeldovich, “Algorand: Scaling byzantine agreements for cryptocurrencies,” in *Proceedings of the 26th Symposium on Operating Systems Principles (SOSP 17)*, 2017, pp. 51–68. [Online]. Available: <https://dspace.mit.edu/bitstream/handle/1721.1/137789/p51-gilad.pdf>
- [89] “Slot 72677728 log deep dive,” <https://www.validators.app/log-deep-dives/slot-72677728>, accessed November 2025.
- [90] P. R. Rizun, “A transaction fee market exists without a block size limit,” 2016. [Online]. Available: <https://api.semanticscholar.org/CorpusID:19451777>
- [91] N. Houy, “The bitcoin mining games,” Groupe d’Analyse et de Thorie economique (GATE), Universit de Lyon, Working Papers 1412, Tech. Rep., 2014. [Online]. Available: <https://shs.hal.science/halshs-00958224v1/document>
- [92] J. Chen, Y. Cheng, Z. Xu, and Y. Cao, “Evolutionary equilibrium analysis for decision on block size in blockchain systems,” 2021. [Online]. Available: <https://arxiv.org/abs/2110.09765>
- [93] N. Dimitri, “Transaction fees, block size limit, and auctions in bitcoin,” *Ledger*, vol. 4, 06 2019.

Appendix A. Real vs. Theoretical TPS of Blockchains

The table below presents a comparative analysis of real-time and theoretical transaction throughput across seven major blockchain platforms.

Blockchain	Real-time TPS	Theoretical TPS
Bitcoin	~ 3–7	~ 15
Ethereum	~ 15–30	~ 119
Avalanche (C-Chain)	~ 100	~ 4,500
Monero	~ 4	~ 1000
Solana	~ 500–1,000	~ 60,000
Algorand	~ 1,000	~ 8,771
Ripple	~ 350	~ 3,400

TABLE 6. COMPARISON OF THROUGHPUT (TRANSACTIONS PER SECOND) ACROSS DIFFERENT BLOCKCHAIN PLATFORMS UNDER CLASSICAL CONFIGURATIONS.

Appendix B. Storage in Current Blockchains

The table below provides an overview of the storage requirements associated with seven major blockchain platforms under classical configurations.

Blockchain	Storage
Bitcoin	Full: ~600 GB Pruned: ~10 GB
Ethereum (Geth)	Full: >650 GB Archive: >12 TB
Ethereum (Erigon)	Full: ~920 GB Archive: ~1.8 TB
Avalanche (C-Chain)	Full: ~350 GB Archive: ~2 TB
Monero	Full: ~230 GiB Pruned: ~95 GiB
Solana	Validator: 1–4 TB Archive: ~300–400 TB
Algorand	Full: ~20 GB Archive: ColdDataDir ~3 TB + HotDataDir ~100 GB
XRP Ledger (XRPL)	Full history: ~26 TB Non-full-history: ≥50 GB

TABLE 7. APPROXIMATE STORAGE REQUIREMENTS FOR DIFFERENT BLOCKCHAIN PLATFORMS UNDER CLASSICAL CONFIGURATIONS.