PQFabric: A Permissioned Blockchain Secure from Both Classical and Quantum Attacks

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Abstract—Hyperledger Fabric is a prominent and flexible solution for building permissioned distributed ledger platforms. It supports modular consensus protocols, which allows for selecting distinct trust models and performance trade-offs. Access control and identity management intrinsically relies on credentials issued by a certificate authority (CA) of a Membership Service Provider (MSP), which in turn is under a root CA that can be instantiated as a Fabric-CA or an external CA. The default MSP instantiation relies on the Blockchain Cryptographic Service Provider interface (BCCSP), which only handles standard PKI methods for authentication, accommodating basically RSA and ECDSA classical signatures. Also, MSP-issued credentials use only a single signature scheme, making the credential-related functions highly attached to single classical standard primitives. Unfortunately, it is well known that RSA and ECDSA are vulnerable to quantum attacks and an ongoing post-quantum standardization process run by NIST aims to identify quantum-safe drop-in replacements for such cryptographic primitives in a few years. In this paper, we propose a redesign of the credential-management procedures and related specifications in order to incorporate hybrid digital signatures (i.e., protection against both classical and quantum attacks using two signature schemes) that include the quantum-safe signatures from the upcoming NIST standards. We also validate our proposal by providing an implementation of Fabric that integrates with the Open Quantum Safe library. Our implementation employs the crypto-agility concept, which allows for plugging in different algorithms in the MSP Credentials and performing comparative benchmarks with them. Moreover, our proposal is backwards compatible with the Fabric client implementations, and no SDK changes would be required for the client Node.JS code.

Index Terms—Post-quantum cryptography, digital signatures, Blockchain, Hyperledger Fabric

1 Introduction

In recent years, the research community has drawn ever closer to the construction of a quantum computer, one with the potential to break classical public key cryptography. In advance of this threat, the National Institute of Standards and Technology (NIST) is looking to establish standards for cryptographic algorithms that show promise at securing against both quantum and classical attacks. The NIST post-quantum standardization process is in its third round of evaluation and has narrowed down the initial 82 submission candidates to only 15. These include 9 key encapsulation mechanisms (KEMs) for confidentiality purposes and 6 digital signature candidates for authenticity. The signature candidates are subdivided into finalists (there are three of them) and alternates (the remaining three). Some of the finalists are expected to be selected for standardization at the end of Round 3, about an year from now. A fourth round is also expected in order to select alternate candidates for later standardization.

Open source implementations of such algorithms, for instance those provided by the Open Quantum Safe (OQS) project [1] continually change in order to keep up-to-date with both the progress in cryptanalysis and parameter modifications and also with new optimizations. However, designing, approving, and implementing post-quantum cryptographic standards is only the first step. There is also the gargantuan task of integrating these algorithms into the wide range of existing systems that depend on and are highly coupled with classical public key cryptography. The integration itself will be a new test of these algorithms, particularly as they are integrated into high-performance systems. Moreover, during the integration, these systems must remain secure against classical attacks, even in the face of potential flaws in or changes to post-quantum cryptography algorithms. This scenario demands a requirement for a double layer of protection against classical and quantum attacks, which can be achieved by means of hybrid signatures, i.e., one classical signature and one post-quantum.

A prominent class of applications that will need to be an early adopter of these algorithms is the blockchain distributed ledger. Blockchain technology is fundamentally reliant on cryptographic primitives, especially authentication, in order to validate the origin of the transactions that are to be added to the chain. In our work, we focus on Hyperledger Fabric, a permissioned blockchain in use in production systems.

In addition to the need for blockchains to make this post-quantum transition earlier rather than later, there are several typical features of blockchains that make them a rigorous testbed for new cryptography algorithms. Industry-deployed blockchains are high-throughput, with recent research in Hyperledger Fabric achieving 20,000 transactions per second [2]. Each transaction proposal along with everything processing step in the network contains a signature, and the code path to commit each transaction includes both signing and verification algorithms. As such, signature size and algorithm speed both have direct and significant impact on the performance of the system. In addition, as large distributed systems that can neither ensure synchronous updates nor handle extended downtime for a migration, blockchains are among the more complex use cases for post-quantum migration. Lessons learned maintaining performance and backwards compatibility in this context can be broadly applicable as other systems integrate with post-quantum algorithms later on.

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Contributions: In our research, we built PQFabric, which is to our knowledge the first version of the Hyperledger Fabric enterprise permissioned blockchain whose signatures are secure against both classical and quantum computing threats. Our design proposal is backwards compatible for easy migration and flexible enough to support different post-quantum cryptographic schemes, making it future-proof to NIST upcoming standards and PQS implementation changes. We highlight the inconsistencies we found between NIST, Golang, and hybrid signature schemes that will need to be resolved for smooth integration going forward. Next, through benchmark tests of an instantiation of Fabric, we provide a baseline performance comparison between transactions that use classical and hybrid quantum-classical cryptography, finding that depending on the signature algorithm used PQFabric can achieve comparable performance. We profile PQFabric to provide insight into its bottlenecks, showing that signature and public key length, not signature algorithm execution time, are major contributors to Fabric slowdown. Finally, we offer our implementation as a testbed for future work focusing on improving blockchain transaction throughput with post-quantum cryptography algorithms.

2 Review of Hyperledger Fabric and related work

Hyperledger Fabric [3] consists of a highly flexible and customizable framework for deploying relatively scalable permissioned blockchains. Fabric offers a set of features that were learned from previous bad experiences and reformulations. One of them consists of achieving better scalability through a paradigm called execute-order-validate, which was originally used in the context of improving the performance of State Machine Replications [4]. In this setting, instead of ordering the transactions first and then all peers having to execute all the ordered transactions (order-execute-validate), it is possible that just a few peers execute the transactions first and thus doing a prevalidation of the transactions before that get actually ordered. This allows for a number of optimizations introduced in Fabric [3]. Moreover, the execution/validation and ordering of the transaction proposals are decoupled and thus performed by different entities (peers/endorsers and orderers, respectively). As a result, the consensus protocol run by the orderers, which is responsible for establishing the order of a current set of transaction proposals, can be updated after the bootstrapping of the blockchain network. The transaction proposals generated by the clients are first executed by only a subset of the endorsing peers in the blockchain who also perform an initial validation against the pre-configured policies for the respective types of peers in the blockchain who also perform an initial validation by the clients are first executed by only a subset of the endorsing peers. This is called the transaction.

We now provide a set of definitions of interest used in the context of the Fabric Blockchain.

1. **Asset.** When a transaction is executed in a Fabric blockchain it will simply result in a state change of an asset. Asset is generic here and can be anything with a monetary value.

2. **Consortium.** Consists of a set of organizations that want to conduct business through a common permissioned blockchain.

3. **Membership Service Provider (MSP).** The MSP is an abstraction for credential/identity management. It is responsible for issuing certificates to peers, orderers and users and thus giving them suitable authentication and authorization.

4. **Transaction.** A recurrent example are proposals trying to protect the classical Confidential Transactions (ringCT) protocol. The RingCT

5. **Transaction Proposal.** Users submit transaction proposals to the blockchain network in order to change the state of their assets in the ledger. The proposal includes the user's identity, the chaincode (smart contract) function to be executed and its related parameters, a transaction identifier, among others.

6. **Orderer.** Upon reception of a set of transactions (the number of transactions that are supposed to go on a block, which is configurable), verifies all endorsers’ signatures, and runs a consensus protocol to order the transactions that will be part of a block candidate. Orderers also sign the block candidate computed and send it back to peers for final validation and inclusion in the ledger.

7. **Client or User.** A client or user is an actor who owns access credentials (including digital certificates) to a particular blockchain network, and can submit transaction proposals to the peers. The user is also responsible for collecting enough endorsements (the amount is defined in a blockchain policy) from the peers for each transaction proposal and re-transmit them to the ordering service.

8. **Peer or endorsing peer or endorser.** Peer responsibility includes verifying users’ signatures in the transaction proposals, executing and validating the proposal according to pre-specified policies (agreed for the consortium), endorsing and digitally signing the resulting outcome of the validated proposal, and also notifying the user with the outcome. Peers also receive block candidates from the orderers and perform final validation and addition to the ledger.

2.1 Related Work

We now briefly review other blockchain proposals in the literature aiming for quantum-safe solutions.

We recall that the goal of this work is to provide the main PKI functionalities with quantum-safe protections. PKI in Fabric allows for reliable authentication and authorization throughout the blockchain interactions as exemplified in Section 2. Protecting the PKI translates to migrating classical digital signature primitives into hybrid ones containing a post-quantum counterpart. Many of the potentially related works in the literature do not target the same goal.

A recurrent example are proposals trying to protect the classical Confidential Transactions (ringCT) protocol. The RingCT
3 Solution Proposal

3.1 Signature Requirements

In designing a hybrid quantum-classical signature for use in hyperledger fabric, we have two key requirements.

1) In the future quantum computing world, the system must be as protected as the strongest currently developed post-quantum cryptography standards will allow.

2) In the current classical computing world, the system must be no less protected than current cryptography standards.

To satisfy the first requirement, it would be straightforward to use an OQS algorithm directly. Previous work [10] has treated the qTesla algorithm alone as a hybrid scheme sufficient to meet the second requirement as well, because qTesla was at the time believed to be theoretically secure against both quantum and classical attacks. However, we argue that this is not sufficient, even if qTesla was theoretically secure. A cryptographic algorithm is only as secure as its implementation, and these new implementations are relatively untested and unproven. If a flaw is found in the implementation of a post-quantum algorithm, we must still have the classical signature. Otherwise, a revealed vulnerability in the post-quantum implementation would violate the second requirement.

3.2 System Requirements

In designing PQFabric software, we have two core system requirements.

1) Backwards compatibility: Hyperledger fabric is a large distributed system whose nodes and clients cannot all be simultaneously upgraded. In addition, we believe it is unreasonable to expect that organizations running fabric will retire their existing blockchain and start a new one from a genesis block in order to migrate to post-quantum cryptography. As a result, our solution must be backwards-compatible. The blockchain must be able to gradually migrate from classical cryptography to post-quantum cryptography without unreasonable or synchronous downtime, and client software running classical cryptography must be able to coexist with PQFabric.

2) Cryptoqality: Our solution must be flexible to ongoing changes in post-quantum cryptographic standards, as NIST continues to finalize the list of post-quantum signature algorithms. It must be compatible with all the remaining candidates, agnostic to which algorithm is eventually chosen, and selecting any of them must be a straightforward configuration change.

3.3 Signature Proposal

As a result, we propose a hybrid quantum-classical signature scheme for transactions using both post-quantum and classical cryptography. Each node in the fabric has two private keys, one classical and one post-quantum. Nodes sign each transaction twice (once with each key) and concatenate the two signatures. Both signatures must be verified.

3.4 Security analysis of the proposal

In order to migrate the trust mechanisms in Fabric to a quantum world, two cryptographic primitives are to be considered: hash functions and digital signatures. Although there is no exponential quantum speed up for breaking hash functions, slightly larger hashes may be necessary in some cases. An analysis for different usages of hash functions is carried out.

Moreover, Fabric utilizes MSP-generated credentials in order to provide authentication and authorization services. Fabric credentials are based on X.509 certificates containing a public key for a classical signature algorithm. Peers are grouped into organizations and every organization forms one trust domain, such that a peer trusts all peers within its organization but no peer of another organization. The MSP of an organization is responsible for issuing credentials to peers, orderers and the users for that organization. Therefore digital signatures play a central role in in permissions and trust for the blockchain operations.

We first recap the concept of hash functions and their security in both classical and quantum scenarios. Let $H : \{0,1\}^* \to \{0,1\}^n$ be a hash function that maps arbitrarily large bit strings into fixed-length n-bit strings. Generally speaking, we say that $H$ is called preimage resistant if for a given hash value $y \in \{0,1\}^n$, it is computationally hard to find a preimage $x$ such that $H(x) = y$. In addition, if given an input $x$ and an output $y = H(x)$, it is hard to find another input message $x'$ such that $H(x') = y$, then we say that $H$ is second-preimage resistant. Furthermore, if it is hard to find any pair $(x,x')$ such that $H(x) = H(x')$, we say $H$ is collision resistant. Note that there is a subtle difference between the second-preimage and the collision resistance properties. The former assumes that the adversary is given a previously computed hash value $y$ for some message $x$ and they are supposed to find a second distinct message that maps to that same hash value. There is no freedom in the hash output values. On the other hand, the latter avoids such requirements and let the attacker search for any pair of inputs and any hash value. Thus attacking the latter becomes an easier task if producing the candidates for $x, x'$ is relatively cheap (constant time). Table 1 summarizes the expected hash security on a classical and on a quantum realm. Note that a $2^{n/3}$ time complexity for breaking the collision resistance property could be achieved by running the parallel Rho method [11] on a very large special-purpose classical machine with multiple parallel CPU's. This was shown to be monetarily cheaper than using a dedicated quantum hardware for the same task as pointed out in [12].

shall we look at how hash functions are employed in the Fabric block hashing structure, i.e., the actual blockchain. The block structure [17] consists of the following components: a header (detailed below); data, which is a collection of transactions, metadata, and a block number. The header of each block $B_i$ contains two hashes:
TABLE 1: Expected security for an n-bit output hash against classical and quantum attacks.

| property       | classical security (bits) | quantum security (bits) |
|----------------|---------------------------|-------------------------|
| (second) preimage | n                         | \( n/2 \) [13, 19]     |
| collision       | n/2 or n/3                | n/3 [15, 16]           |

- the Current Block Hash (CBH_i), which is a hash of all transactions in the current block, and
- the Previous Block Hash (PBH_i), which is simply a copy of the “Current Block Hash” of the previous block \( B_{i-1} \).

From the above structure only the “Current Block Hash” needs to be considered. We argue next that collision resistance is not necessary in practice for such hash and thus only second-preimage resistance should be enough. Assuming an \( n \)-bit hash output, and blocks configured with \( k \) transactions, an attacker trying to produce collisions is faced with a preprocessing task of generating about \( 2^{n/2} \) (by the birthday bound) distinct sets of \( k \) transactions each. There is a major issue in achieving such a task. One attempt would be to obtain distinct sets of transactions by simply permuting a original set of valid transactions, but such approach is pointless from an attacker point of view, since the goal is to add a new non-legitimate transaction that would favor the attacker in some sense. Therefore, the attacker would have to at least generate one fake transaction. On the other hand, each transaction involves a signature of its proponent (user) along with the signatures of a set of endorsers. If the attacker was able to produce such one fake transaction, producing a large number of transaction sets variations would become easier (by permutations and small variations on the faked transaction). Fortunately producing such a fake transaction is a hard problem on its own even with a quantum computer, since it involves forging a hybrid signature from our construction. The argument above suggests that although collisions attacks would damage the security of the “Current Block Hash”, mounting such attack involves breaking hard problems on the underlying signatures. Thus it can be a plausible assumption that 256-bit hash outputs are enough here (since they offer 128-bit security against preimage and second-preimage attacks). The current version of Fabric implementation hardcodes SHA256 for the Current Hash Block and the official code is expected to migrate to a configurable hash in a near future (adding the possibility of using larger hashes in case better ways to find collisions are found).

4 Implementation

In a 2018 guide for businesses using Hyperledger Fabric, IBM researchers wrote in a brief section on quantum cryptography that “Hyperledger Fabric provides a pluggable cryptographic provider, which allows replacing these algorithms for digital signatures with others.” [18] However, the process is not that simple. In this section, we will describe the basic structure of our implementation followed by the existing code assumptions in Hyperledger Fabric that required changes for a hybrid quantum-classical scheme.

4.1 Core Structure

In our implementation,\(^2\) we built off of Hyperledger Fabric 1.4. We used LibOQS 0.4.0 [19] for the implementations of post-quantum cryptographic signature algorithms. LibOQS is written in C while Hyperledger Fabric is written in Go, so we wrote a CGO wrapper around LibOQS.\(^3\) The wrapper imports LibOQS as a dynamic library, loading it once when the wrapper package is first called. Eventually, we assume that these quantum-safe cryptographic functions would be built into the Go core library, so we followed the API conventions used in Go’s ECDSA implementation.

- type SecretKey struct {
  Sk []byte
  PublicKey
}
- type PublicKey struct {
  Pk []byte
  Sig OQSSigInfo
}
- type OQSSigInfo struct {
  Algorithm SigType
}

The secret key contains a public key field, which in turn contains a field for the SigInfo struct with QOS algorithm type. The algorithm may be set by configuration and is not expected to change over the lifetime of the blockchain except by careful migration (see section 6.2). The Go representation of the LibOQS library and Sig object are loaded together and maintain pointers to LibOQS C functions. Our implementation only uses post-quantum cryptography for signing and verifying messages, so the wrapper only includes KeyImport, Sign, and Verify.

There are three main areas of the Hyperledger Fabric codebase that we modified to allow hybrid quantum signatures.

1) Blockchain Cryptographic Service Provider (BCCSP): The BCCSP module is designed to provide a uniform cryptography interface to the core Fabric that is not dependent on a particular cryptographic algorithm or implementation. It is a specific implementation of the more general Cryptographic Service Provider (CSP). The bulk of our modifications here were to add a new key type and associated interface with KeyImport, KeyPair, Sign, Verify, and so on. We also made changes to the Signer module shared by all BCCSP keys; for more details see section 4.2.

2) Membership Service Provider (MSP): In theory, the BCCSP modifications should be all that is necessary. However, as discussed in section 4.4.1, hybrid quantum-classical cryptography requires two keys, which is not a transparent change for the MSP\(^4\)

3) Cryptogen: This binary is not an officially supported part of Hyperledger Fabric, but it provides a template for generating the cryptographic material required to run Fabric from its configuration files. Entities running Fabric may generate

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2. Our code is available at https://github.com/ameliaholcomb/fastfabric1.4-oqs

3. Recently, LibOQS has published its own Go wrapper, which can be found at https://github.com/open-quantum-safe/liboqs-go. This wrapper also uses dynamic linking.

4. The MSP also needed to modified because, while signing functionality is fully factored out into a shared Signer in the BCCSP module, the corresponding verify functions are not. Presumably this is an oversight; it would not be difficult to add a Verifier in the BCCSP.
this material however they choose, but any equivalent of the “cryptogen” binary would also need to be modified to generate post-quantum key material and x509 certificates.

One might also modify the client to use quantum-safe cryptography. For the time being, since we were primarily concerned with the integrity of the blockchain as a whole, rather than transactions submitted by a single client, we did not include this in the scope of our work. Moreover, as the client code provided is written in Javascript and makes no use of the MSP or BCCSP common packages, it is a large refactoring project disjoint from the previous work, but of less interest to the research community.

4.2 Signature Structure

Golang’s crypto library includes a Signer interface [20], with the methods

```go
Public(rand io.Reader, digest []byte, opts SignerOpts) (signature []byte, err error)
```

Hyperledger Fabric’s BCCSP module offers an implementation of crypto.Signer that determines the signature algorithm to be called based on the type of the private key used in Signer creation. We modified the BCCSP Signer to implement hybrid signatures.

First, we added an optional post-quantum key field to the bccsp.Signer struct, filled out at Signer creation. If the post-quantum key is absent, signer.Sign() simply returns the result cDigest := Sign(classicalKey, digest, ...). If a post-quantum key is present, however, the digest is signed twice, once with the classical key and once with the post-quantum key. The two signatures were then concatenated using asn1 as follows:

```go
signature := hybridSignature{
    ClassicalDigest: asn1.BitString{
        Bytes: cDigest,
        BitLength: 8 * len(cDigest),
    },
    QuantumDigest: asn1.BitString{
        Bytes: qDigest,
        BitLength: 8 * len(qDigest),
    },
}
ret, _ := asn1.Marshal(signature)
```

We modified verification code correspondingly: If the provided identity contained a post-quantum public key, the hybrid signature was unpacked according to this scheme and each portion verified separately.

The very careful reader may notice that the structure of a hybrid post-quantum signer does not quite match that of Go’s crypto.Signer. First, the crypto library explicitly assumes that there is only a single public key, and enforces this assumption in the type signature of the Public() method. We discuss this problem, as it appeared here and elsewhere, in 4.4.1. Second, there is a subtle incompatibility between the crypto library and LibOQS: while crypto.Signer.Sign() accepts a digest, LibOQS’s Sign() functions expect an unhashed message. We discuss this issue further in 4.4.2.

One natural optimization is to verify the two signature portions in parallel. We did not implement this optimization, however we examine the expected benefit in section 6. Finally, for a discussion of the backwards-compatibility properties of this scheme, see 4.4.3.

4.3 Identity Structure

Though we only set out to replace the Sign and Verify functions in Hyperledger Fabric, which are fully implemented in liboqs, we quickly found that these were inseparable from their associated cryptographic standards, such as x509 certificates. For example, nodes provide their own identity (in the form of an x509 certificate) with their signature on a transaction. The verifier checks the provided signature with the public keys present in the certificate. Naturally, this means the certificate must include a post-quantum public key so that the verifier can verify the hybrid post-quantum signature. In addition, because the identity is provided by the proposing entity itself, the verifying node must also check that the post-quantum public key material is signed by a trusted authority.

To create and sign these hybrid x509 certificates, we followed the standard proposed in [21], which adds three non-critical extensions to the x509 certificate:

- Subject-Alt-Public-Key-Info: The post-quantum public key for the certificate.
- Alt-Signature-Value: The signed key material of the certificate (classical and post-quantum public key), signed by the issuer’s post-quantum key.
- Alt-Signature-Algorithm: The post-quantum algorithm used to sign the certificate key material.

This standard naturally accommodates the fact that the second public key is optional, and it is straightforward to build the extension without any modifications to the Go standard x509 library. It is slightly less straightforward to verify without modifying the standard library, however. We wrote

```go
oqs.Validate(
    validationChain []*x509.Certificate)
```

which takes the validation chain output of cert.Verify() from the standard x509 library and verifies the post-quantum signatures down the chain from the root certifying authority. The msp calls oqs.Validate() immediately after cert.Verify().

4.4 Integration Challenges

Overall, the main Hyperledger Fabric codebase did a remarkably good job of encapsulating its cryptographic interface in the BCCSP and making few assumptions about key or algorithm type. We suspect integrating other codebases with quantum-safe cryptography may be more of a refactoring effort. (For example, moving outside of the well-structured Fabric code to the auxiliary Cryptogen binary code, we quickly encountered functions like GetECFPublickey, which can return only an ECDSA public key.) However, there are still a few challenges in the integration that may help reveal the complex code assumptions that will change under a hybrid quantum-classical cryptography scheme.
4.4.1 Two Keys

The hybrid quantum-classical cryptography scheme necessitated by the requirements in 3.1 implies that two private (and public) keys are needed. One might envision creating a HybridKey type that encapsulates two lower-level keys. However, Sign() is a method on a Signer or other higher level object, and hybridization is fundamentally a change to signatures, not to keys. Thus, we implemented a hybrid Signer type instead. The hybrid Signer conflicted with assumptions at both the higher MSP layer and the lower Go crypto library layer.

First, placing an additional key in the Signer broke the encapsulation between the BCCSP and MSP because the MSP:

- Extracts cryptographic keys from an x509 certificate. It does this both on initialization (extracting public keys from its x509 certificate and importing the corresponding private key from its keystore) and during signature verification (deserializing the public keys from another node’s identity proto).
- Stores the public and private keys for the node directly in an internal proto structure called an Identity.
- Provides its own stored keys to the BCCSP when signing a message.

In these three areas, the MSP had to be modified to extract, store, and use a second key.

Second, placing an additional key in the Signer conflicted with the Golang library because its crypto.Signer has an interface method Public(), which returns a single public key. In the case of Hyperledger Fabric, the Public() function is never used, and so we were able to sidestep the issue entirely. However, it is important to highlight that the Golang crypto interface method is not currently compatible with hybrid Signers.

4.4.2 Hashing

Our PQFabric integration also revealed inconsistencies between the NIST standard specifications and the core Golang crypto library. Specifically, the NIST Sign API takes an unhashed message [22], while the Go crypto library uses a Signer interface that expects a pre-hashed digest [20]. Several finalist algorithms have taken advantage of NIST’s API to select an appropriate hash function internally based on the security parameters specified, or to provide optimizations when the same hash is required twice. Hyperledger Fabric, meanwhile, makes use of the Go library’s flexibility to provide pluggable hash functions.

In our implementation, we simply allowed LibOQS to internally re-hash a hashed message. This may have a small performance cost but does not impact security (it provides as much security as the less secure hash). We could have removed the hashing step on the Hyperledger Fabric side, but it would have taken heavy contortions to do this while still maintaining code compatibility with a purely classical Fabric.

4.4.3 Backwards Compatibility

Our scheme is backwards compatible in the sense that no individual node or client has to use post-quantum keys: every node checks whether the signing identity contains a post-quantum key before deciding whether a hybrid signature verification is required. This allows, for example, all the peers and orderers to use quantum-safe cryptography while the client still has not been upgraded (as we did). However, every node on the blockchain must at least have a software update that allows it to verify post-quantum hybrid signatures before any one node can use them. A vanilla fabric node will not know how to unpack a hybrid signature to verify just its classical part.

4.4.4 Cryptoagility

In the existing code base, developers must add a new key type and implement its interface functions in the BCCSP package for each new algorithm. In order to use LibOQS algorithm implementations and keep up-to-date with changes to the NIST finalists at each stage, we needed an implementation that was algorithm-agnostic, without a separate key type for each post-quantum signature algorithm.

This presented some challenges for code integration because, unlike with other keys, the Go data type did not uniquely determine the algorithm to be used. We introduced the OQSSigInfo struct, a member of an OQS PublicKey, so that Go operations requiring an algorithm identifier, such as marshalling/unmarshalling keys or creating an Alt-Signature-Algorithm x509 extension (see section 4.3), could obtain a key algorithm.

This challenge will not be an issue for developers who wait for complete standardization and a per-language implementation of post-quantum cryptographic algorithms. However, in the meantime, while NIST solicits feedback on integration of these non-standard algorithms into production systems, maintaining cryptoagility is an additional consideration.

5 Evaluation and Results

We evaluated our implementation on a network consisting of one orderer and two peers, each running on a different machine. The client (itself on a fourth machine) sent all transactions to a single peer, while the second peer was also available as an endorser. Each machine was equipped with an Intel® Xeon® CPU E5-2620 v2 processors at 2.1 GHz, with 24 hardware threads, 64GB RAM, and an SSD.

The chaincode is the same as the one used in [2], which provides simple balance accounts and allows transferring value from one account to another. A single transaction thus touches exactly two accounts. Our experimental setup had 20,000 accounts, and each benchmark ran 10,000 transactions, batched into blocks of size 100, with 100 blocks sent from each of 10 parallel threads. The transactions were set up to ensure that no two touched the same accounts, so that database contention would not be a factor. The endorsement policy required only one peer to endorse a transaction. The benchmark measured wall time on the peer between receiving a block of transactions and committing that block. For each round of benchmarks, we trimmed off the first and last few blocks in our data analysis for ramp up and ramp down.

Our baseline cryptographic setup signs transactions only with ECDSA. We then compared this to the same benchmark run with nodes configured to sign and verify using hybrid schemes pairing ECDSA with each of Crystals-Dilithium-2 [23], Falcon-512 [24], and qTesla-I [25], as implemented in liboqs 0.4.0. Though qTesla is no longer in the running as a NIST

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5. Throughout the paper, we refer to the hybrid schemes by their post-quantum algorithm only.
Fig. 1: Per-block commit latency range for different signature algorithms.

Fig. 2: Average throughput, in transactions per second, of different signature algorithms.

finalist, we still decided to evaluate its performance. We did this because it was specifically considered in recent published work on post-quantum Hyperledger Fabric [10], and because it has interesting performance characteristics with its unusually long public key length.

As shown in Figure 1, ECDSA alone has the lowest block latency (median 49 ms), followed by the hybrid of ECDSA+Falcon-512 (median 60 ms) ECDSA+Dilithium2 (median 68 ms), followed by ECDSA+qTesla I (median 110 ms). Their average throughput, shown in Figure 2, follows the opposite pattern, with throughputs of 2084, 1788, 1545, and 995 transactions per second, respectively. This general trend is expected given the benchmarking of these post-quantum signature schemes is the range of block latencies. While ECDSA, Falcon, and Dilithium had relatively consistent performance across blocks, qTesla block commit latencies varied widely. The schemes had standard deviations of 11.0, 10.0, 13.6, and 31.2, respectively. We were unable to determine the cause of this variation.

### 6 Discussion

#### 6.1 Performance

Overall, we found that PQFabric, while having a higher block latency and lower throughput than classical Fabric, does not experience severe performance degradation, depending on the post-quantum signature algorithm used. The hybrid Falcon-512 scheme saw only a 14% decrease in throughput, on average, compared to the pure ECDSA scheme. Indeed, Falcon-512 alone is faster than ECDSA; much of the slowdown comes from having to sign and verify twice. This is significant and surprising: we expected hybrid signatures might severely slow down transactions, but a hybrid ECDSA+Falcon-512 scheme seems usable as-is with no further performance optimizations.

We proceed to examine representative CPU profiles for benchmarks of each signature scheme. The two functions that see the greatest increase in CPU share for the hybrid schemes are oqs.{Sign|Verify} and sw.Hash. The first is expected; this is the additional execution time required to perform the post-quantum signature algorithm, on top of the ECDSA algorithm. The time spent in Hash is more surprising. Some of the slowdown may be accounted to the slower larger hash required by post-quantum signatures, however that does not explain the variation between post-quantum algorithms. There are two main callers of Hash() that contribute to its CPU time. The first is from signature verification in the msp. The hash function is called on the received message. The second caller is VerifyBlock, usually from the gossip service. In this case, the hash function is called on the entire block. This block contains both the signatures and the public keys of all of the endorsements received. For post-quantum signatures these may be quite large, dramatically increasing the CPU time spent on hashing. Table 2 shows the percent of time each signature scheme spent on hashing throughout the entire benchmark, compared to its signature and public key length.

It is notable that signature algorithm speed is actually only a small contributor to the performance slowdown in schemes with larger key and signature sizes. We see that for hyperledger fabric, the signature and public key size are a direct and significant performance tradeoff for fast signature algorithms, because the key and signature themselves must be hashed in the block. In fact, while the Falcon benchmark spent more absolute time in Sign() than qTesla, the qTesla benchmark was overall significantly slower because of the time spent hashing. It seems the biggest performance impact on PQFabric is from keeping a small key and signature size.

One other interesting performance difference between the signature schemes is the range of block latencies. While ECDSA, Falcon, and Dilithium had relatively consistent performance across blocks, qTesla block commit latencies varied widely. The schemes had standard deviations of 11.0, 10.0, 13.6, and 31.2, respectively. We were unable to determine the cause of this variation.

As mentioned above, hashing is a significant contributor to
slowdown in the hybrid post-quantum fabric, which is governed by key and signature size. However, the simplest proposal for improving the block latency and transaction throughput for PQFabric may be to parallelize the post-quantum and classical verification. In table 3, we show the expected maximal performance gain from doing so. We compute the percent of execution time spent on the shorter of the two verifications (PQ algorithm vs ECDSA), and report the percent speedup expected by dropping that execution time. Note that these profiles are only a representative sample, so the percent speedups should be taken as rough intuition only.

As we can see, the expected speedup is relatively modest, especially for algorithms like qTesla which had a significant portion of execution time spent on hashing. Dilithium, which had relatively strong performance overall, stood to get the most benefit, because its execution time was most similar to ECDSA. Thus, the parallelization was most effective.

### 6.2 Live Migration

Large distributed systems like blockchains require special consideration when transitioning to quantum-safe cryptography because universal downtime and a synchronous update for all nodes may not be possible. Software migrations like this one require not only assurance of comparable performance post-update, but also a careful story around backwards compatibility, gradual rollouts, and rollbacks. Though we did not attempt a live migration of a classical-crypto blockchain, our PQFabric implementation allows for a live migration with the following steps:

1. **Slow rollout of PQFabric software to all core blockchain nodes** (orderers, peers, and endorsers). Clients do not yet need to upgrade. PQFabric is backwards-compatible, so nodes will continue signing classically until their configuration changes to hybrid mode, and verifying signatures classically until the identity provided with the signature changes to a hybrid one. They will also continue to validate x509 certificates classically. This is intended to be a no-op update and, until step 4, can be rolled back at any time. PQFabric and vanilla fabric nodes can coexist until step 4.

2. **Certifying authority update.** The certifying authority is given a post-quantum key and re-issues node certificates following a typical key rollover procedure. At this point, all node certificates contain an Alt-Signature-Value field, but no Alt-Subject-Public-Key-Info, because the nodes themselves do not have post-quantum keys. The nodes still do not verify the alternate signature when receiving certificates.

3. **Second node rollout for PQFabric software to read and verify alternate signature fields in x509 certificates.** This could either happen through a software update (this is the way we implemented it) or the change could be incorporated into a policy update to the transaction validation system chaincode. At this point, the nodes still do not sign their own messages with hybrid signatures, but they do verify the alternate signature field, when present, in x509 certificates.

4. **Slow rollout of post-quantum keys to nodes, by bringing down the node, generating a post-quantum keypair, updating the node’s configuration files (including x509 certificate), and then bringing the node back up again. On startup, the node’s MSP will read its own x509 certificate to determine its public/private keys. It will load the post-quantum key from the certificate and begin signing with hybrid signatures. All other nodes are running PQFabric software and will verify the hybrid signature, even while they continue to sign with classical signatures.**

5. **Eventual rollout of post-quantum keys and software to clients, as client integration becomes available.**

### 6.3 Future Work

In our paper, we evaluated PQFabric with a simple endorsement policy requiring only one signature. Changing this will affect block size (by requiring more signatures per block), but it will also increase the amount of time spent signing and verifying. This can help establish a clearer relationship between signature and public key size, versus signing and verifying efficiency.

In addition, we expect future work to focus on the hashing bottleneck we have highlighted in this paper. If public keys and signatures can be more efficiently encoded into blocks or saved elsewhere, while still preserving security properties, it may allow significant speedups for post-quantum algorithms with large public keys and signatures.

### 7 Conclusion

In this work, we built PQFabric, which is to our knowledge the first version of Hyperledger Fabric whose signatures are secure against both quantum and classical computing threats. Our implementation meets practical production system requirements for backwards compatibility and cryptoagility without sacrificing its security. Through our implementation, we offer insight into incompatibilities and integration challenges that production systems are likely to face in their own quantum-safe transition. We provide benchmarks showing that, depending on the post-quantum cryptographic algorithm selected, PQFabric can achieve comparable latency and throughput performance to classical-only fabric. Finally, we offer CPU profile analysis of our software to identify the cause of latency increases, allowing us to suggest target areas for performance improvements. We believe that our work substantially contributes to the discussion on post-quantum cryptographic standards, and hope that it will be useful to both those developing the standards and those seeking to implement them.

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