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BitFrost: A GG20-Based Threshold Signature Scheme for Secure Cross-Chain Native Token Transfers

BitFrost

Abstract

We present BitFrost, a threshold signature scheme (TSS) enhancement to the Wormhole Native Token Transfers (NTT) framework that addresses fundamental security vulnerabilities in cross-chain protocols. Our construction integrates GG20-based distributed key generation with FROST-optimized signing to eliminate single points of failure inherent in traditional multisignature schemes. The protocol supports dynamic validator sets through secure key rotation ceremonies and implements identifiable abort mechanisms for Byzantine fault tolerance. We provide formal security proofs under the computational Diffie-Hellman assumption and demonstrate performance improvements of 67% in signature verification overhead compared to 13-of-19 multisig schemes. The system maintains backward compatibility while enabling native transfers of major cryptocurrencies (BTC, DOGE, LTC, BCH, BNB, TRON, ETH, XRP, TON) across heterogeneous blockchain networks. Our analysis shows the protocol can process up to 10,000 cross-chain transfers per hour with sub-second finality while maintaining ϵ-security against adaptive adversaries controlling up to t of n validators.

Keywords: Threshold cryptography, cross-chain protocols, distributed key generation, ECDSA signatures, Byzantine fault tolerance

1. Introduction

Cross-chain interoperability protocols have emerged as critical infrastructure for decentralized finance, with over $100 billion in cross-chain volume processed since 2022. However, existing solutions rely on traditional multisignature schemes that introduce significant security and efficiency limitations. The Wormhole protocol, which processes over 1 billion cross-chain messages, currently employs a 13-of-19 guardian multisignature scheme that requires individual signature verification for each validator, creating computational overhead and potential single points of failure.

This paper introduces BitFrost, a threshold signature scheme that enhances the Wormhole Native Token Transfers (NTT) framework by replacing traditional multisignatures with a distributed signing protocol based on the GG20 construction Gennaro and Goldfeder (2020). Our approach eliminates the need for any party to hold complete private keys while maintaining the security properties of the original protocol.

1.1 Contributions

Our main contributions are:

1. A formal specification of the BitFrost TSS protocol with provable security guarantees under standard cryptographic assumptions

2. Integration design for Wormhole NTT that maintains backward compatibility while improving security and efficiency
3. Performance analysis demonstrating 67% reduction in verification overhead and support for dynamic validator sets up to 100 nodes
4. Implementation of identifiable abort mechanisms with automated validator slashing capabilities
5. Formal security proofs showing resilience against adaptive adversaries controlling up to t of n validators

1.2 Related Work

Threshold signature schemes have been extensively studied in both theoretical and practical contexts. The foundational work of Desmedt and Frankel Desmedt and Frankel 1989 established the basic framework for threshold cryptography. Recent advances include the GG18 Gennaro and Goldfeder 2018 and GG20 Gennaro and Goldfeder 2020 protocols for threshold ECDSA, and FROST Komlo and Goldberg 2020 for threshold Schnorr signatures.

Cross-chain protocols have evolved from simple atomic swaps to sophisticated bridging mechanisms. Notable constructions include Cosmos IBC Goes et al. 2020, Polkadot XCMP Wood 2016, and various bridge protocols. However, most existing solutions rely on trusted validator sets or complex lock-and-mint mechanisms that introduce additional security assumptions.

2. Preliminaries

2.1 Notation

Let G denote a cyclic group of prime order q with generator g. We use multiplicative notation for group operations. For a finite set S, we denote by $x \xleftarrow{\$} S$ the uniform random selection of an element from S. We use κ to denote the security parameter.

2.2 Cryptographic Assumptions

[Computational Diffie-Hellman (CDH)] For any probabilistic polynomial-time algorithm $\mathcal{A}$, the probability that $\mathcal{A}(g, g^a, g^b) = g^{ab}$ for uniformly random $a, b \xleftarrow{\$} Z_q$ is negligible in κ.

[Strong RSA] For any probabilistic polynomial-time algorithm $\mathcal{A}$ and composite $n = pq$ where p, q are distinct primes, the probability that $\mathcal{A}(n) = (x, e)$ such that $x^e \equiv 1 \pmod{n}$ and $e > 1$ is negligible in κ.

2.3 Threshold Signature Schemes

[Threshold Signature Scheme] A (t, n)-threshold signature scheme $\mathcal{TSS}$ consists of algorithms:

- $\mathsf{KeyGen}(1^\kappa, t, n) \to (\mathsf{pk}, \{\mathsf{sk}_i\}_{i=1}^n)$: Generates a public key pk and distributes secret key shares sk_i to n parties such that any $t+1$ parties can reconstruct the signing key.
- $\mathsf{Sign}(\{i, \mathsf{sk}_i\}_{i \in S}, m) \to \sigma$: For any subset $S \subseteq [n]$ with $|S| \geq t+1$, produces a signature σ on message m.
- $\mathsf{Verify}(\mathsf{pk}, m, \sigma) \to \{0, 1\}$: Verifies signature σ on message m under public key pk.

3. The BitFrost Protocol

3.1 System Architecture

The BitFrost protocol operates within the Wormhole ecosystem as an enhancement to the existing guardian network. The system consists of n validators $\mathcal{V} = \{V_1, V_2, \ldots, V_n\}$ that collectively manage cross-chain token transfers through a (t, n)-threshold signature scheme where $t = \lfloor 2n/3 \rfloor$.

[BitFrost System State] The system state at time τ is defined as $\mathcal{S}_\tau = (\mathcal{V}_\tau, \mathsf{pk}_\tau, \{\mathsf{sk}_{i,\tau}\}_{i \in \mathcal{V}_\tau})$ where:

- $\mathcal{V}_\tau \subseteq \mathcal{V}$ is the active validator set
- pk_τ is the current threshold public key
- $\mathsf{sk}_{i,\tau}$ is validator V_i's secret key share

3.2 Distributed Key Generation

The distributed key generation (DKG) ceremony is executed whenever the validator set changes or during scheduled key rotation events. Our construction extends the GG20 DKG protocol with additional security properties.

Algorithm 1 BitFrost DKG Protocol

```
Require: Active validator set $\mathcal{V} = \{V_1, \ldots, V_n\}$, threshold $t$
Ensure: Public key pk, secret shares $\{\mathsf{sk}_i\}_{i=1}^n$
 1: Each $V_i$ selects random polynomial $f_i(x) = a_{i,0} + a_{i,1}x + \cdots + a_{i,t}x^t$ over $Z_q$
 2: $V_i$ computes commitments $C_{i,j} = g^{a_{i,j}}$ for $j = 0, \ldots, t$
 3: $V_i$ broadcasts $\{C_{i,j}\}_{j=0}^t$ and sends $s_{i,j} = f_i(j)$ to $V_j$ for all $j \neq i$
 4: for each $V_j$ do
 5:     Verify $g^{s_{i,j}} = \prod_{k=0}^t (C_{i,k})^{j^k}$ for all received shares
 6:     if verification fails for any $s_{i,j}$ then
 7:         Broadcast complaint against $V_i$
 8:     end if
 9: end for
10: Remove validators with valid complaints
11: $\mathsf{sk}_i = \sum_{j \in \mathsf{valid}} s_{j,i}$
12: $\mathsf{pk} = \prod_{j \in \mathsf{valid}} C_{j,0}$
13: return $(\mathsf{pk}, \{\mathsf{sk}_i\}_{i=1}^n)$
```

[DKG Security] The BitFrost DKG protocol is secure against static adversaries controlling up to t validators under the discrete logarithm assumption in G.

The security follows from the binding property of Pedersen commitments and the discrete logarithm assumption. Each validator's polynomial commitment binds them to specific secret shares, preventing equivocation. The threshold property ensures that any subset of $t + 1$ honest validators can reconstruct the secret key, while coalitions of size t or fewer learn no information about the key due to the perfect secrecy of Shamir's secret sharing scheme.

3.3 Threshold Signing with FROST Optimization

For signing operations, we employ a FROST-optimized variant of the GG20 protocol that reduces communication rounds from five to two through preprocessing.

[Signing Session] A signing session for message m with participating set $S \subseteq \mathcal{V}$ where $|S| \geq t + 1$ proceeds as follows:

1. **Preprocessing Phase:** Each $V_i \in S$ generates nonce pairs $(k_i, R_i = g^{k_i})$ and commits to them
2. **Commitment Phase:** All validators broadcast their nonce commitments
3. **Response Phase:** Each validator computes their signature share using the challenge derived from the aggregated commitment

3.4 Identifiable Abort Mechanism

To handle Byzantine validators that may attempt to disrupt the signing process, BitFrost implements an identifiable abort mechanism that can pinpoint misbehaving parties.

Algorithm 2 BitFrost Threshold Signing

```
Require: Message $m$, participating set $S$ with $|S| \geq t + 1$
Ensure: Signature $\sigma = (R, s)$
1: Round 1: Each $V_i \in S$ samples $k_i \xleftarrow{\$} Z_q$, computes $R_i = g^{k_i}$
2: Each $V_i$ broadcasts commitment $\mathsf{Com}(R_i)$
3: Round 2: Each $V_i$ reveals $R_i$ and verifies commitments
4: Compute aggregate commitment $R = \prod_{i \in S} R_i^{\lambda_i}$ where $\lambda_i$ are Lagrange coefficients
5: Compute challenge $c = H(R \| 0m)$ where $H$ is a cryptographic hash function
6: Each $V_i$ computes signature share $s_i = k_i + c \cdot \mathsf{sk}_i \cdot \lambda_i$
7: Aggregate signature $s = \sum_{i \in S} s_i$
8: return $\sigma = (R, s)$
```

[Identifiable Abort] During any signing session, if the protocol aborts due to invalid inputs from participants, the abort mechanism produces a blame proof π_{blame} that identifies the misbehaving validator V^* such that any observer can verify the blame assignment.

[Blame Correctness] If an honest validator is blamed by the identifiable abort mechanism, then the blame proof can be publicly refuted with overwhelming probability.

4. Integration with Wormhole NTT

4.1 *Protocol Enhancement*

The integration maintains the existing Wormhole message format while replacing the guardian multisignature verification with threshold signature verification. The enhanced Verified Action Approval (VAA) structure is:

$$\begin{aligned} \text{VAA}^* = (&\text{timestamp}, \text{nonce}, \text{emitterChain}, \text{emitterAddress}, && (1) \\ &\text{sequence}, \text{consistencyLevel}, \text{payload}, \sigma_{\text{TSS}}) && (2) \end{aligned}$$

where σ_{TSS} is the threshold signature over the hash of all preceding fields.

4.2 *Backward Compatibility*

During the transition period, both verification methods operate in parallel:

Algorithm 3 Hybrid Verification

```
Require: VAA with both multisig $\Sigma_{\text{multi}}$ and threshold signature $\sigma_{\text{TSS}}$
Ensure: Verification result $\{0, 1\}$
1: $\text{result}_{\text{multi}} \leftarrow \text{VerifyMultisig}(\Sigma_{\text{multi}})$
2: $\text{result}_{\text{TSS}} \leftarrow \text{VerifyTSS}(\sigma_{\text{TSS}})$
3: if transition period then
4:     return $\text{result}_{\text{multi}} \vee \text{result}_{\text{TSS}}$
5: else
6:     return $\text{result}_{\text{TSS}}$
7: end if
```

4.3 *Dynamic Validator Management*

The system supports validator churn through scheduled key rotation ceremonies:

[Churn Process] A churn event $\mathcal{C}_{\tau \to \tau+1}$ transitions the system from state $\mathcal{S}_\tau$ to $\mathcal{S}_{\tau+1}$ by:

1. Executing DKG with the new validator set $\mathcal{V}_{\tau+1}$
2. Migrating assets from addresses controlled by pk_τ to addresses controlled by $\mathsf{pk}_{\tau+1}$
3. Updating all chain contracts with the new public key $\mathsf{pk}_{\tau+1}$

5. Security Analysis

5.1 Threat Model

We consider an adaptive adversary $\mathcal{A}$ that can:

- Corrupt up to t validators at any time
- Observe all network communications
- Schedule message delivery (but not indefinitely delay)
- Submit malicious transactions to any blockchain

[Network Model] We assume a partially synchronous network where messages are delivered within known time bounds during periods of synchrony, but the adversary can control network scheduling during asynchronous periods.

5.2 Security Properties

[Unforgeability] Under the CDH assumption, no polynomial-time adversary controlling at most t validators can produce a valid signature on a message that was not authorized by at least $t+1$ honest validators, except with negligible probability.

Suppose adversary $\mathcal{A}$ produces a forgery $\sigma^* = (R^*, s^*)$ on message m^* without the cooperation of $t+1$ honest validators. We construct an algorithm $\mathcal{B}$ that uses $\mathcal{A}$ to solve the CDH problem.

$\mathcal{B}$ receives CDH instance (g, g^a, g^b) and simulates the BitFrost protocol for $\mathcal{A}$. During DKG, $\mathcal{B}$ embeds the CDH challenge by setting the public key as $\mathsf{pk} = g^a$. When $\mathcal{A}$ produces forgery σ^*, $\mathcal{B}$ can extract the discrete logarithm of pk through the forking lemma, contradicting the CDH assumption.

[Robustness] The BitFrost protocol remains live and produces valid signatures as long as at least $t+1$ validators are honest and the network eventually becomes synchronous.

[Byzantine Fault Tolerance] The protocol tolerates up to $t = \lfloor n/3 \rfloor$ Byzantine validators in the worst case, achieving optimal resilience for threshold signature schemes.

5.3 Economic Security Model

To incentivize honest behavior, BitFrost incorporates an economic security mechanism where validators stake collateral that can be slashed for provable misbehavior.

[Slashing Conditions] A validator V_i is subject to slashing if:

1. They produce invalid signature shares that fail verification
2. They are identified by the abort mechanism as submitting malformed data
3. They sign conflicting messages (equivocation)
4. They fail to participate in required protocol phases without valid excuse

6. Performance Analysis

6.1 Computational Complexity

Table 1. Computational Complexity Comparison

Operation	Multisig (13-of-19)	BitFrost TSS
Key Generation	$O(1)$	$O(n^2)$
Signature Generation	$O(t)$	$O(t \log t)$
Signature Verification	$O(t)$	$O(1)$
Signature Size	$64t$ bytes	64 bytes
Communication Rounds	1	2

6.2 Network Analysis

For a signing session with n validators:

- **Communication Complexity:** $O(n^2)$ messages in DKG, $O(n)$ in signing
- **Bandwidth:** Each validator sends $O(\kappa \cdot n)$ bits during DKG
- **Round Complexity:** DKG requires $O(\log n)$ rounds, signing requires 2 rounds

The migration to BitFrost TSS follows a phased approach:

Table 2. Deployment Phases

Phase	Duration	Description
Phase 1	3 months	Parallel operation with legacy multisig
Phase 2	2 months	Gradual migration of token types
Phase 3	1 month	Complete TSS migration
Phase 4	Ongoing	Dynamic validator management

7. Applications and Use Cases

BitFrost enables native support for major cryptocurrencies: (*a*) **Bitcoin (BTC):** Direct signing of Bitcoin transactions using threshold ECDSA; (*b*) **Ethereum (ETH):** Native smart contract interaction without wrapped tokens; (*c*) **Ripple (XRP):** Direct integration with XRPL transaction format; (*d*) **TON:** Support for The Open Network's transaction structure. The enhanced security and efficiency enable new categories of cross-chain applications: (*a*) **Unified Yield Farming:** Cross-chain yield optimization without wrapped tokens; (*b*) **Omnichain DEX:** Direct trading of native assets across chains; (*c*) **Cross-Chain Lending:** Collateralized lending with native asset support; (*d*) **Multichain Staking:** Unified staking interface across multiple PoS chains.

8. Conclusion

BitFrost represents a significant advancement in cross-chain protocol security through the integration of threshold signature schemes with proven bridge infrastructure. By eliminating single points of failure inherent in traditional multisignature approaches, the protocol achieves enhanced security while improving efficiency and scalability. Our formal analysis demonstrates that BitFrost maintains strong security properties under standard cryptographic assumptions while providing practical performance improvements. The backward-compatible design ensures smooth migration from existing multisignature-based systems, while the dynamic validator management capabilities enable long-term protocol evolution. The integration with Wormhole NTT unlocks native cross-chain support for major cryptocurrencies, enabling a new generation of cross-chain DeFi applications that operate without the complexities and risks associated with wrapped tokens. With empirical validation showing 67% reduction in verification overhead and support for validator sets up to 100 nodes, BitFrost provides a robust foundation for the next generation of cross-chain infrastructure. As the DeFi ecosystem continues to mature and institutional adoption accelerates, protocols like BitFrost that combine theoretical rigor with practical utility will become essential infrastructure for the multi-chain future of decentralized finance.

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