ChillDKG: Distributed Key Generation for FROST

2024-09-18

Tim Ruffing & Jonas Nick

FROST #138

Open jesseposner wants to merge 21 commits into `BlockstreamResearch:master` from `jesseposner:frost`

Conversation 141 | Commits 21 | Checks 107 | Files changed 25

jesseposner commented on Jul 21, 2021 • edited

Contributor

This PR implements a BIP-340 compatible threshold signature system based on FROST (Flexible Round-Optimized Schnorr Threshold Signatures).

TODO

- [x] Key generation APIs

FROST #138

Open **jesseposner** wants to merge 21 commits into `BlockstreamResearch:master` from `jesseposner:frost`

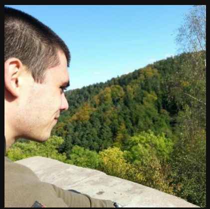
Conversation 141 | Commits 21 | Checks 107 | Files changed 25

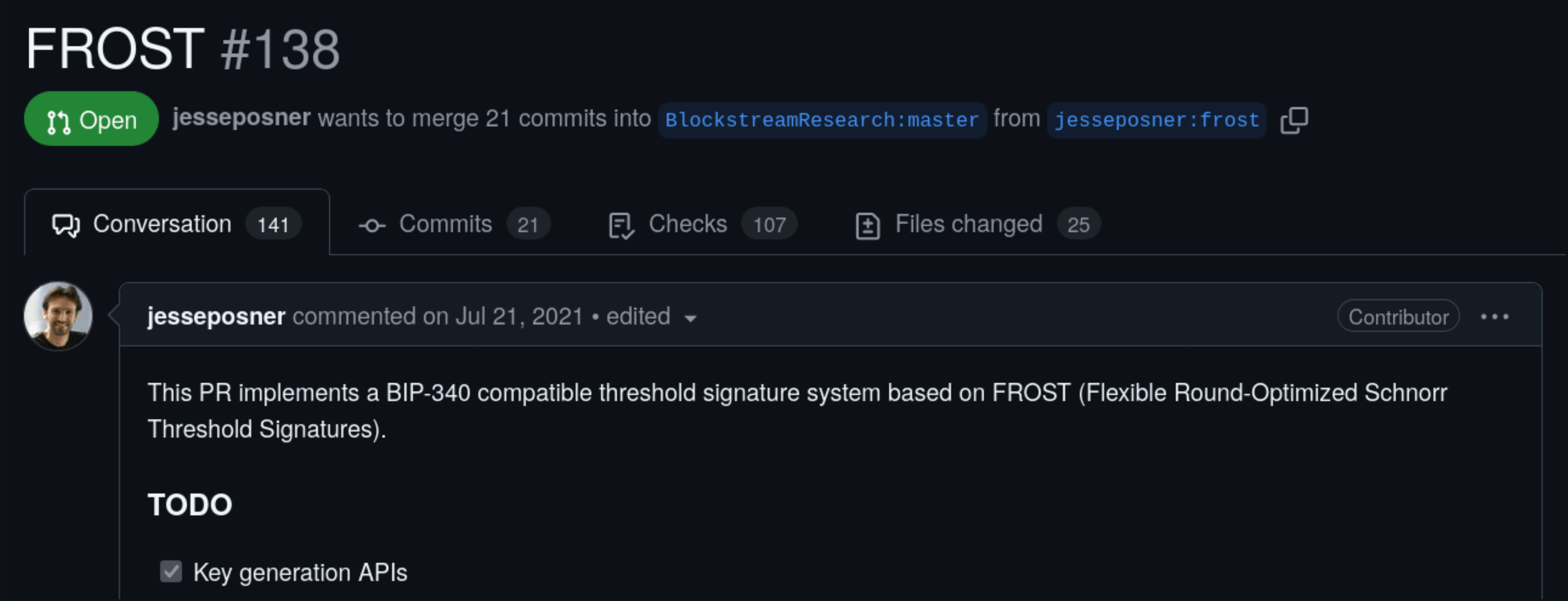
jesseposner commented on Jul 21, 2021 • edited · Contributor

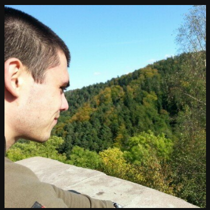
This PR implements a BIP-340 compatible threshold signature system based on FROST (Flexible Round-Optimized Schnorr Threshold Signatures).

TODO

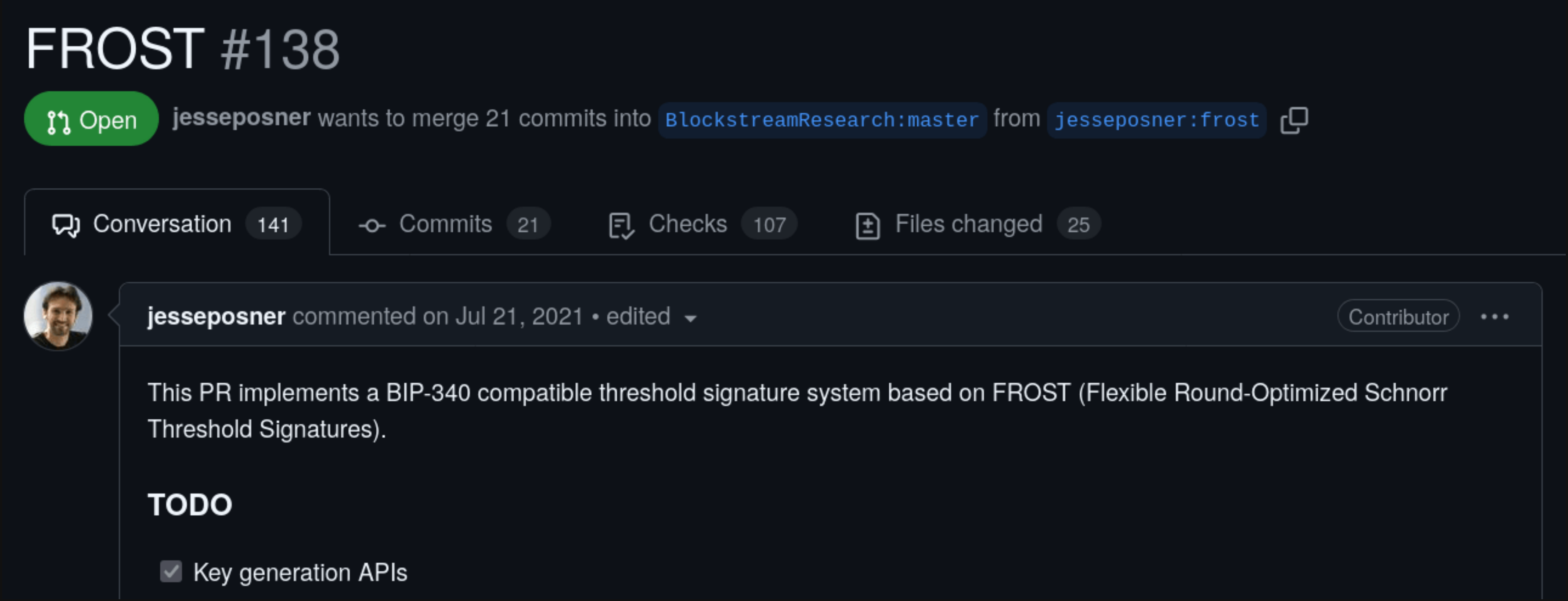
- [x] Key generation APIs



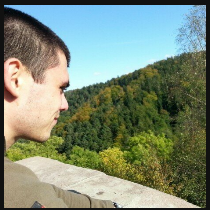

FROST #138
Open
jesseposner wants to merge 21 commits into BlockstreamResearch:master from jesseposner:frost
Conversation 141
Commits 21
Checks 107
Files changed 25
jesseposner commented on Jul 21, 2021 • edited
Contributor
This PR implements a BIP-340 compatible threshold signature system based on FROST (Flexible Round-Optimized Schnorr Threshold Signatures).
TODO
Key generation APIs



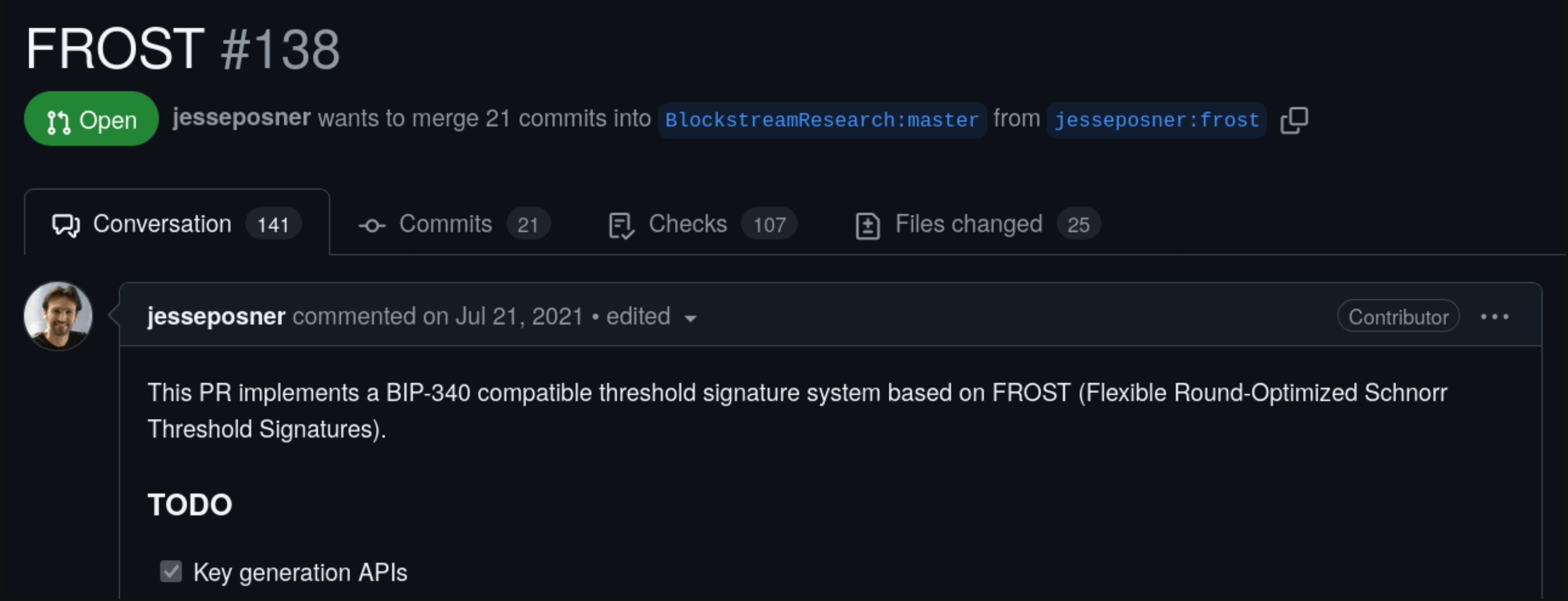
- "I'm not sure"

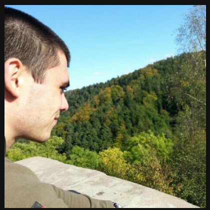




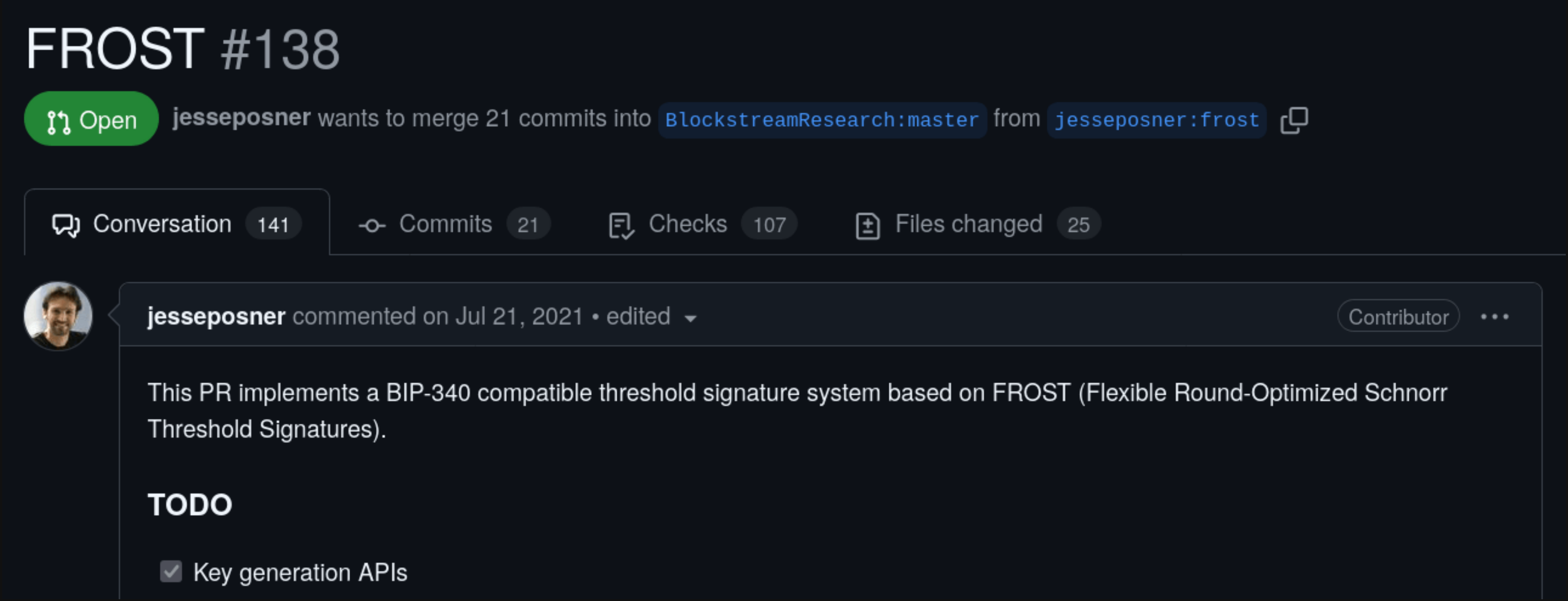


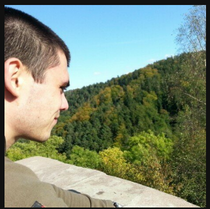
- "I'm not sure"
- "but isn't it dangerous right now"



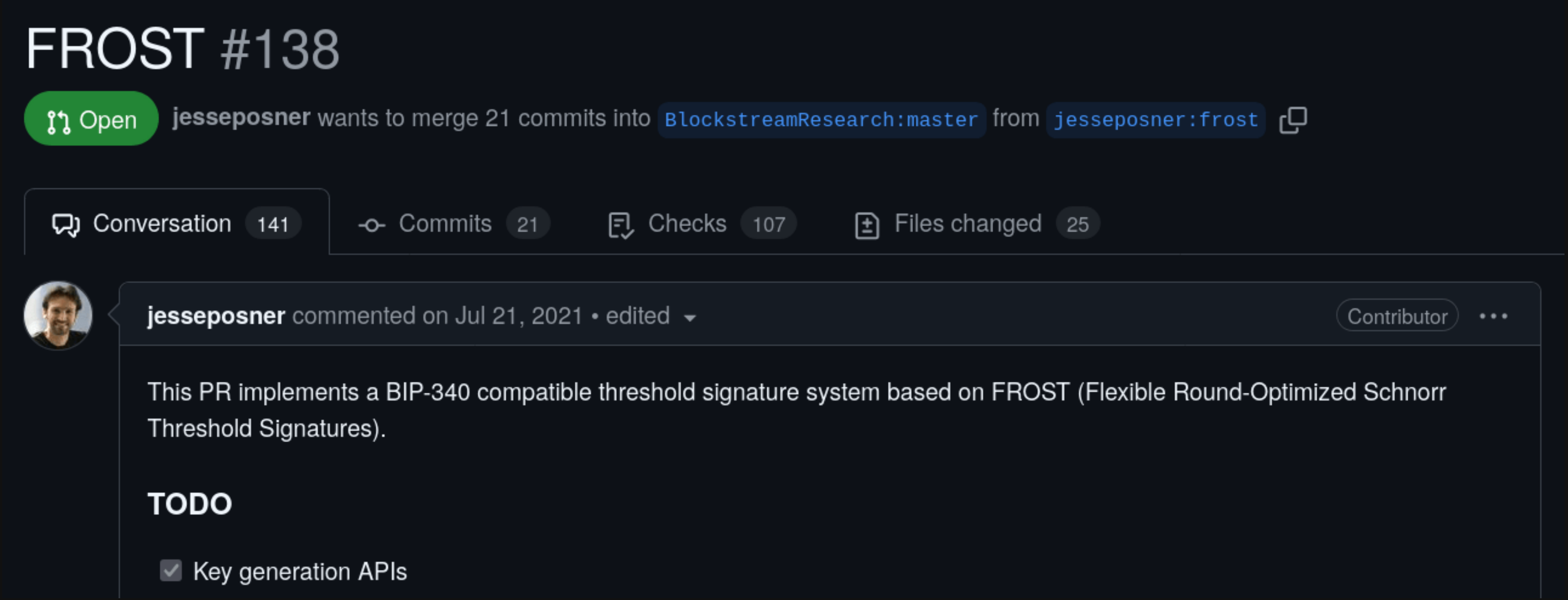


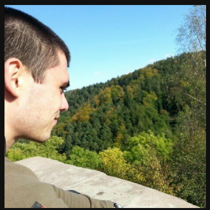
- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"



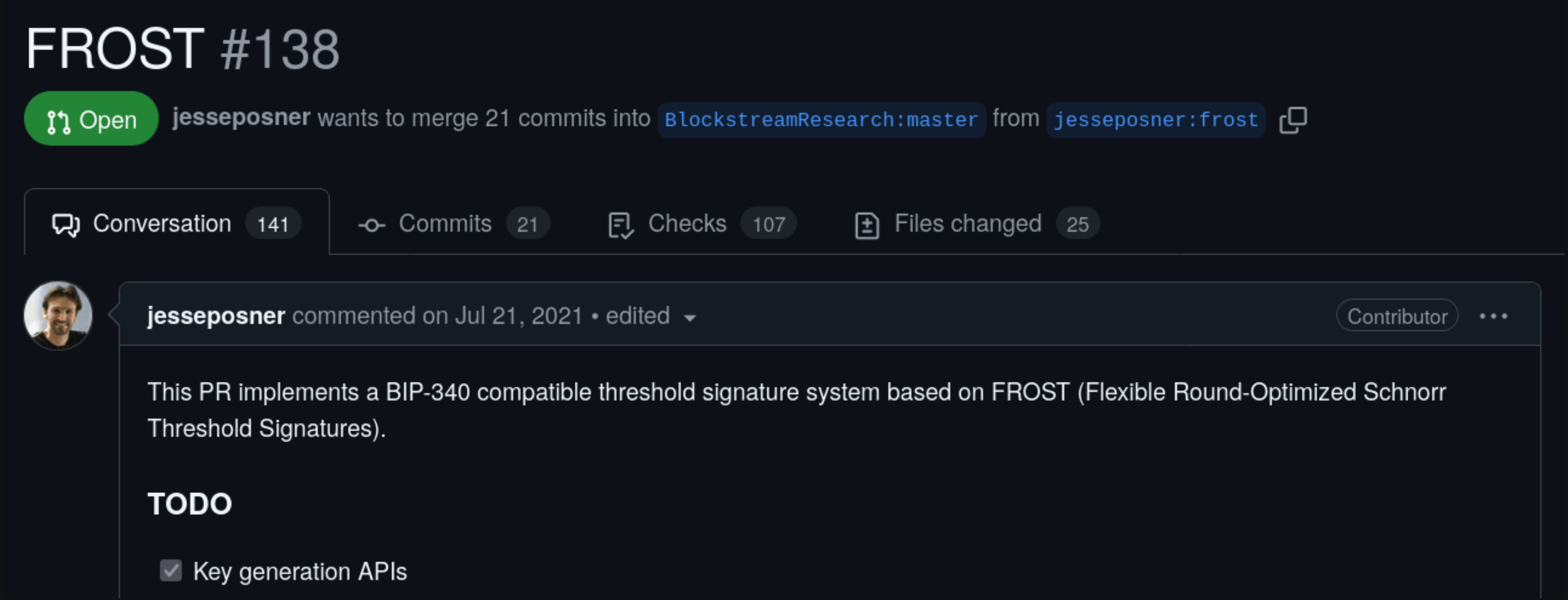


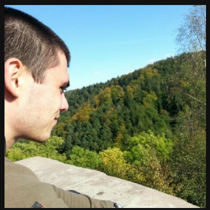
- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"
- "Couldn't it be a problem that there's no randomness?"





- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"
- "Couldn't it be a problem that there's no randomness?"
- "risks inventing complicated machinery that turns out to be broken"





- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"
- "Couldn't it be a problem that there's no randomness?"
- "risks inventing complicated machinery that turns out to be broken"
- "Sorry, I entirely forgot what we're trying to do"

FROST #138

Open jesseposner wants to merge 21 commits into `BlockstreamResearch:master` from `jesseposner:frost`

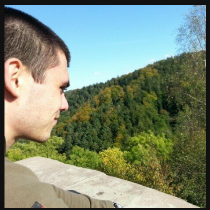
Conversation 141 | Commits 21 | Checks 107 | Files changed 25

jesseposner commented on Jul 21, 2021 • edited — Contributor

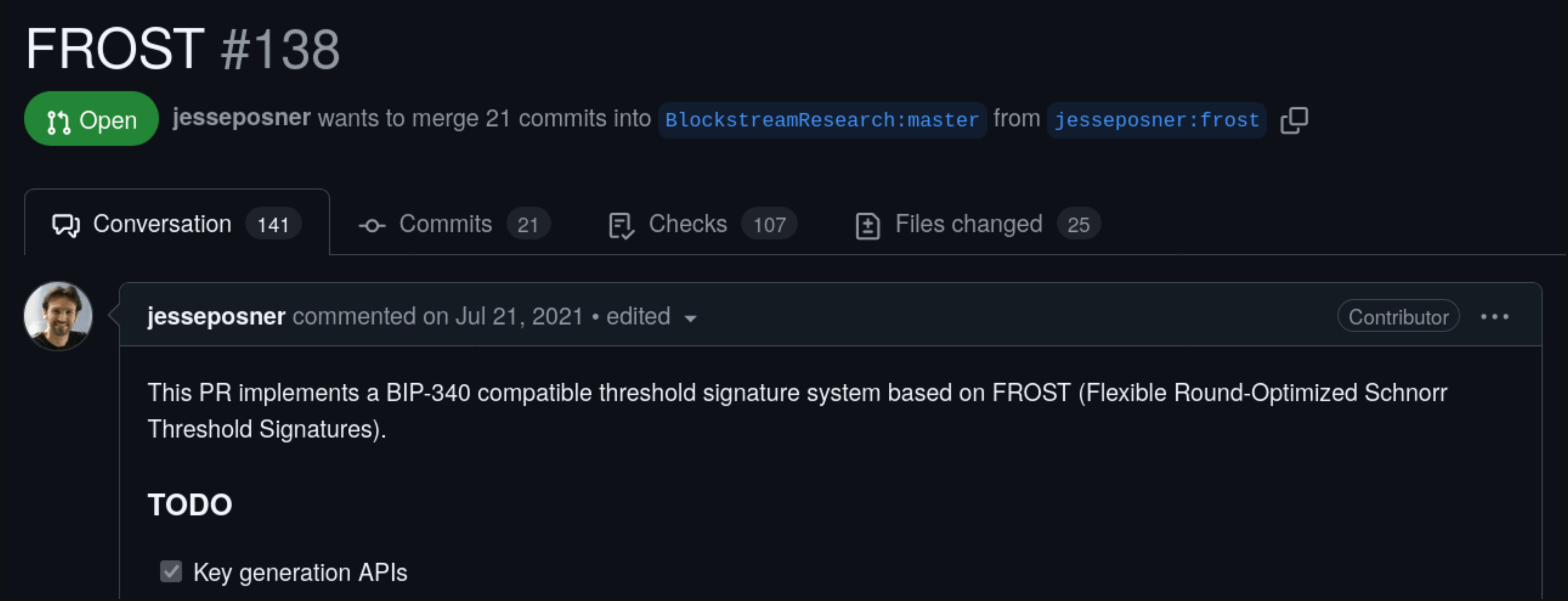
This PR implements a BIP-340 compatible threshold signature system based on FROST (Flexible Round-Optimized Schnorr Threshold Signatures).

TODO

- [x] Key generation APIs



- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"
- "Couldn't it be a problem that there's no randomness?"
- "risks inventing complicated machinery that turns out to be broken"
- "Sorry, I entirely forgot what we're trying to do"
- "Sorry, I'm doing a lot of handwaving"



- "I'm not sure"
- "but isn't it dangerous right now"
- "it's really hard to convince yourself that it works"
- "Couldn't it be a problem that there's no randomness?"
- "risks inventing complicated machinery that turns out to be broken"
- "Sorry, I entirely forgot what we're trying to do"
- "Sorry, I'm doing a lot of handwaving"
- "This can be mitigated by another communication round"

Chelsea Komlo and Ian Goldberg. FROST: Flexible round-optimized Schnorr threshold signatures.

FROST KeyGen

Round 1

1. Every participant P_i samples t random values $(a_{i0}, \dots, a_{i(t-1)}) \xleftarrow{\$} \mathbb{Z}_q$, and uses these values as coefficients to define a degree $t-1$ polynomial $f_i(x) = \sum_{j=0}^{t-1} a_{ij} x^j$.

2. Every P_i computes a proof of knowledge to the corresponding secret a_{i0} by calculating $\sigma_i = (R_i, \mu_i)$, such that $k \xleftarrow{\$} \mathbb{Z}_q$, $R_i = g^k$, $c_i = H(i, \Phi, g^{a_{i0}}, R_i)$, $\mu_i = k + a_{i0} \cdot c_i$, with Φ being a context string to prevent replay attacks.

3. Every participant P_i computes a public commitment $\vec{C}_i = \langle \phi_{i0}, \dots, \phi_{i(t-1)} \rangle$, where $\phi_{ij} = g^{a_{ij}}, 0 \le j \le t-1$

4. Every P_i broadcasts $\vec{C}_i, \sigma_i$ to all other participants.

5. Upon receiving $\vec{C}_\ell, \sigma_\ell$ from participants $1 \le \ell \le n, \ell \ne i$, participant P_i verifies $\sigma_\ell = (R_\ell, \mu_\ell)$, aborting on failure, by checking $R_\ell \stackrel{?}{=} g^{\mu_\ell} \cdot \phi_{\ell 0}^{-c_\ell}$, where $c_\ell = H(\ell, \Phi, \phi_{\ell 0}, R_\ell)$.

Upon success, participants delete $\{\sigma_\ell : 1 \le \ell \le n\}$.

Round 2

1. Each P_i securely sends to each other participant P_ℓ a secret share $(\ell, f_i(\ell))$, deleting f_i and each share afterward except for $(i, f_i(i))$, which they keep for themselves.

2. Each P_i verifies their shares by calculating: $g^{f_\ell(i)} \stackrel{?}{=} \prod_{k=0}^{t-1} \phi_{\ell k}^{i^k \bmod q}$, aborting if the check fails.

3. Each P_i calculates their long-lived private signing share by computing $s_i = \sum_{\ell=1}^{n} f_\ell(i)$, stores s_i securely, and deletes each $f_\ell(i)$.

4. Each P_i calculates their public verification share $Y_i = g^{s_i}$, and the group's public key $Y = \prod_{j=1}^{n} \phi_{j0}$. Any participant can compute the public verification share of any other participant by calculating

$$Y_i = \prod_{j=1}^{n} \prod_{k=0}^{t-1} \phi_{jk}^{i^k \bmod q}.$$

What is distributed key generation in FROST?

- **Interactive** protocol between n signers that takes t
- **Outputs** for each signer i:
  - the threshold public key
  - the **secret share** signer i will use for signing
- **Properties:**
  - t out of n signers can use their share to sign
  - At least t signers are required to produce a signature
    - In particular, there's **no "trusted dealer"** that generates and distributes the shares

The FROST RFC famously does not specify a DKG. It relies on a trusted dealer.

We should write a detailed specification of the key generation protocol...

Hien Chu, Paul Gerhart, Tim Ruffing, and Dominique Schröder. Practical Schnorr Threshold Signatures Without the Algebraic Group Model.

- Replaces broadcast abstraction with Eq protocol
- ... and other minor changes

Interactive Algorithm $\mathsf{SimplPedPoP}(i)$

Signer $\mathcal{S}_i$ is connected to each other signer $\mathcal{S}_j$ via secure point-to-point channels, which guarantee authentication and confidentiality. This can, e.g., be realized with a public-key infrastructure (PKI).

1. Signer $\mathcal{S}_i$ chooses a random polynomial $f_i(Z)$ over $\mathbb{Z}_p$ of degree $t-1$

$$f_i(Z) = a_{i,0} + a_{i,1}Z + \cdots + a_{i,t-1}Z^{t-1}$$

   and computes $A_{i,k} = g^{a_{i,k}}$ for $k = 0, \ldots, t-1$. Denote $x_i = a_{i,0}$ and $X_i = A_{i,0}$. Signer $\mathcal{S}_i$ computes a proof of possession of X_i as a Schnorr signature as follows. Signer $\mathcal{S}_i$ samples $\tilde{r}_i \leftarrow \mathbb{Z}_p$ and sets $\tilde{R}_i \leftarrow g^{\tilde{r}_i}$. Signer $\mathcal{S}_i$ computes $\tilde{c}_i \leftarrow \mathsf{H}_{\text{reg}}(X_i, \tilde{R}_i, i)$ and sets $\tilde{s} \leftarrow \tilde{r} + \tilde{c}_i x_i$. Signer $\mathcal{S}_i$ then derives a commitment $(A_{i,0}, \ldots, A_{i,t-1})$ and sends $((\tilde{R}_i, \tilde{s}_i), (A_{i,0}, \ldots, A_{i,t-1}))$ to all signers $\mathcal{S}_j$ for $j \in \{1, \ldots, n\} \setminus \{i\}$.
   Moreover, signer $\mathcal{S}_i$, for every $j \in \{1, \ldots, n\}$ (including $j = i$ itself), computes secret shares $\tilde{x}_{i,j} = f_i(j)$, and sends $\tilde{x}_{i,j}$ to signer $\mathcal{S}_j$.
2. Upon receiving proofs of possession, commitments and secret shares from all other signers, signer $\mathcal{S}_i$ verifies the Schnorr signatures by computing $\tilde{c}_j \leftarrow \mathsf{H}_{\text{reg}}(X_i, \tilde{R}_i, i)$ and checking that

$$\tilde{R}_j A_{j,0}^{\tilde{c}_j} = g^{\tilde{s}_j} \text{ for } j \in \{1, \ldots, n\} \setminus \{i\}.$$

   Moreover, signer $\mathcal{S}_i$ verifies the shares received from the other signers by checking

$$g^{\tilde{x}_{j,i}} = \prod_{k=0}^{t-1} A_{j,k}^{i^k}.$$

   If any check fails, signer $\mathcal{S}_i$ aborts.
   Otherwise, $\mathcal{S}_i$ runs interactive algorithm $\mathsf{Eq}(i, t_i)$ with all other signers $\mathcal{S}_j$ for $j \in \{1, \ldots, n\} \setminus \{i\}$ on local input

$$\eta_i \leftarrow \{(\tilde{R}_j, \tilde{s}_j), (A_{j,0}, \ldots, A_{j,t-1})\}_{j=1}^{n}.$$

3. When $\mathsf{Eq}(i, \eta_i)$ outputs true for $\mathcal{S}_i$, then $\mathcal{S}_i$ terminates the $\mathsf{SimplPedPoP}$ protocol successfully by outputting the joint public key $X \leftarrow \prod_{j=1}^{n} X_j$ and the local secret key $\tilde{x}_i \leftarrow \sum_{j=1}^{n} \tilde{x}_{j,i}$. When $\mathsf{Eq}(i, t_i)$ outputs false, then $\mathcal{S}_i$ aborts.

Fig. 3. Interactive Algorithm $\mathsf{SimplPedPoP}$.

SimplPedPop (simplified!)

SimplPedPop (simplified!)

1. Every signer generates n shares and computes a **VSS commitment** to the shares. (VSS: verifiable secret sharing)

SimplPedPop (simplified!)

1. Every signer generates n shares and computes a **VSS commitment** to the shares. (VSS: verifiable secret sharing)
2. Every signer sends the i-th generated share and the VSS commitment to the i-th signer.

SimplPedPop (simplified!)

1. Every signer generates n shares and computes a **VSS commitment** to the shares. (VSS: verifiable secret sharing)
2. Every signer sends the i-th generated share and the VSS commitment to the i-th signer.
3. Every signer computes the threshold public key from the received VSS commitments.

SimplPedPop (simplified!)

1. Every signer generates n shares and computes a **VSS commitment** to the shares. (VSS: verifiable secret sharing)
2. Every signer sends the i-th generated share and the VSS commitment to the i-th signer.
3. Every signer computes the threshold public key from the received VSS commitments.

How does the signer know that t can sign for the threshold public key?

4. Every signer **verifies** their received shares against the received VSS commitments.

4. Every signer **verifies** their received shares against the received VSS commitments.

Property of VSS: If every signer received the same VSS commitments, then the signers can indeed sign!

4. Every signer **verifies** their received shares against the received VSS commitments.

Property of VSS: If every signer received the same VSS commitments, then the signers can indeed sign!

- Hence, signers need to ensure that **no** malicious participant sent a different commitment to signer i than to signer $j \neq i$.

4. Every signer **verifies** their received shares against the received VSS commitments.

Property of VSS: If every signer received the same VSS commitments, then the signers can indeed sign!

- Hence, signers need to ensure that **no** malicious participant sent a different commitment to signer i than to signer $j \neq i$.
- That's what the equality (the broadcast) protocol is for.

Interactive Protocol

$\mathrm{Eq}(input)$ outputs $\{\mathrm{true}, \mathrm{false}\}$

Interactive Protocol

Eq($input$) outputs $\{\text{true}, \text{false}\}$

In SimplPedPop: $input$ contains the VSS commitments

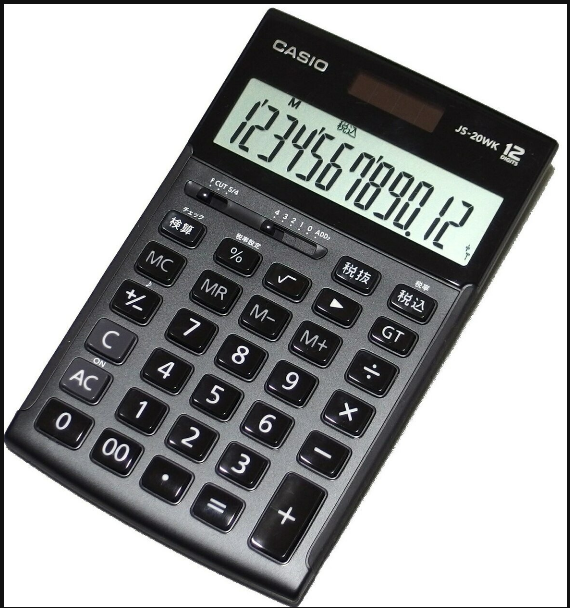
Interactive Protocol

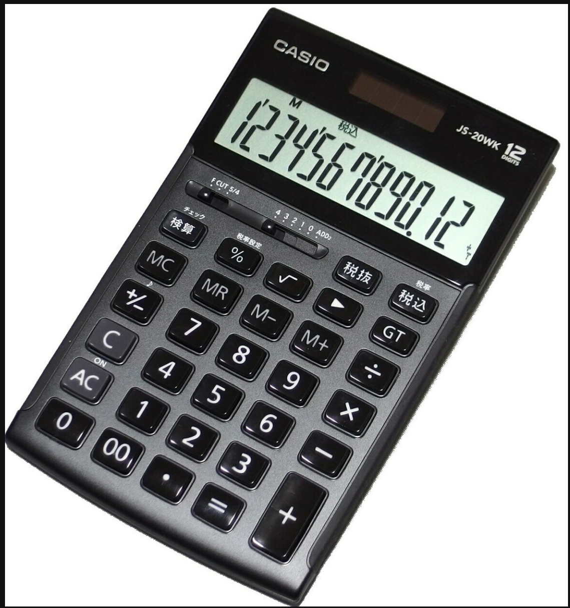
$\mathrm{Eq}(input)$ outputs $\{\mathrm{true}, \mathrm{false}\}$

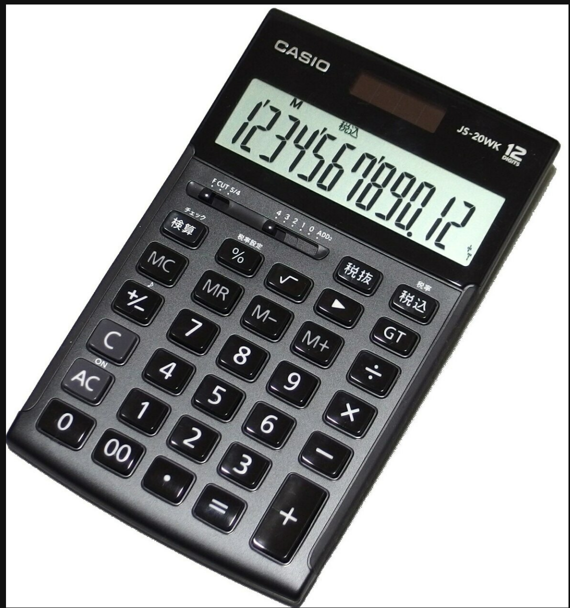
In SimplPedPop: $input$ contains the VSS commitments

Integrity: If some honest signers outputs true, all $input$ of honest signers are equal.

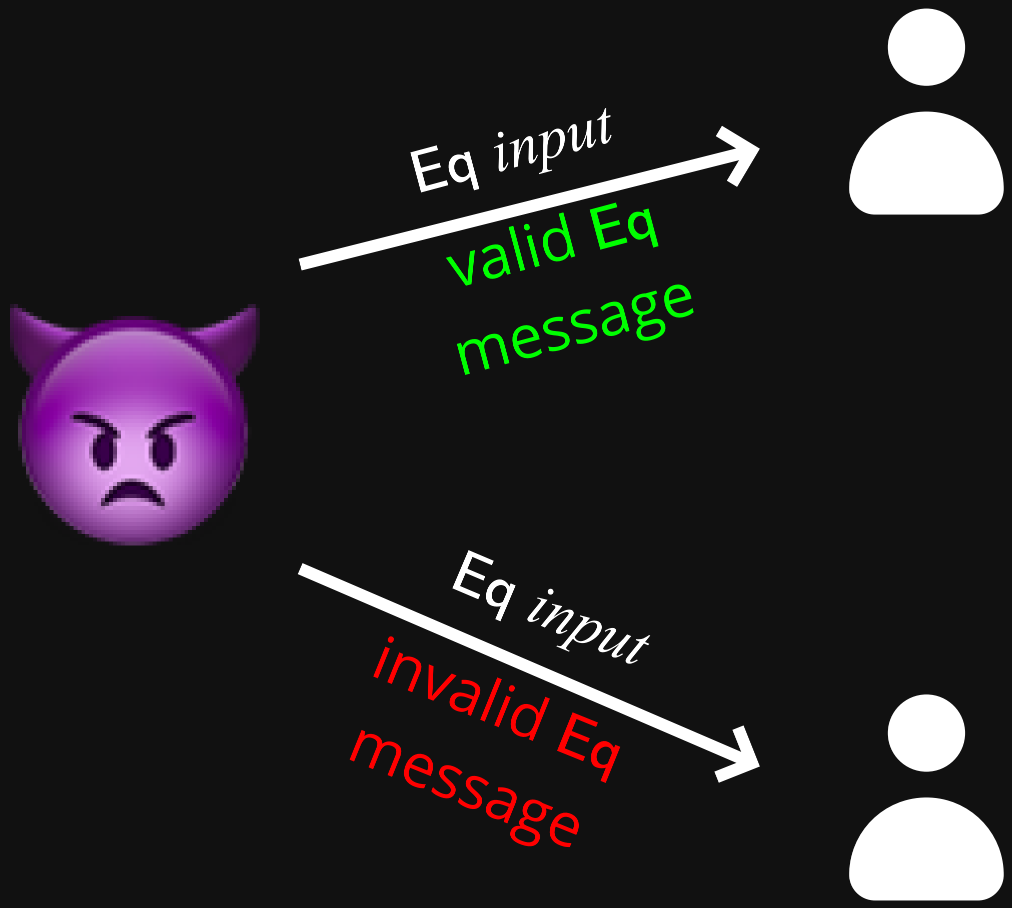
A Simple Eq



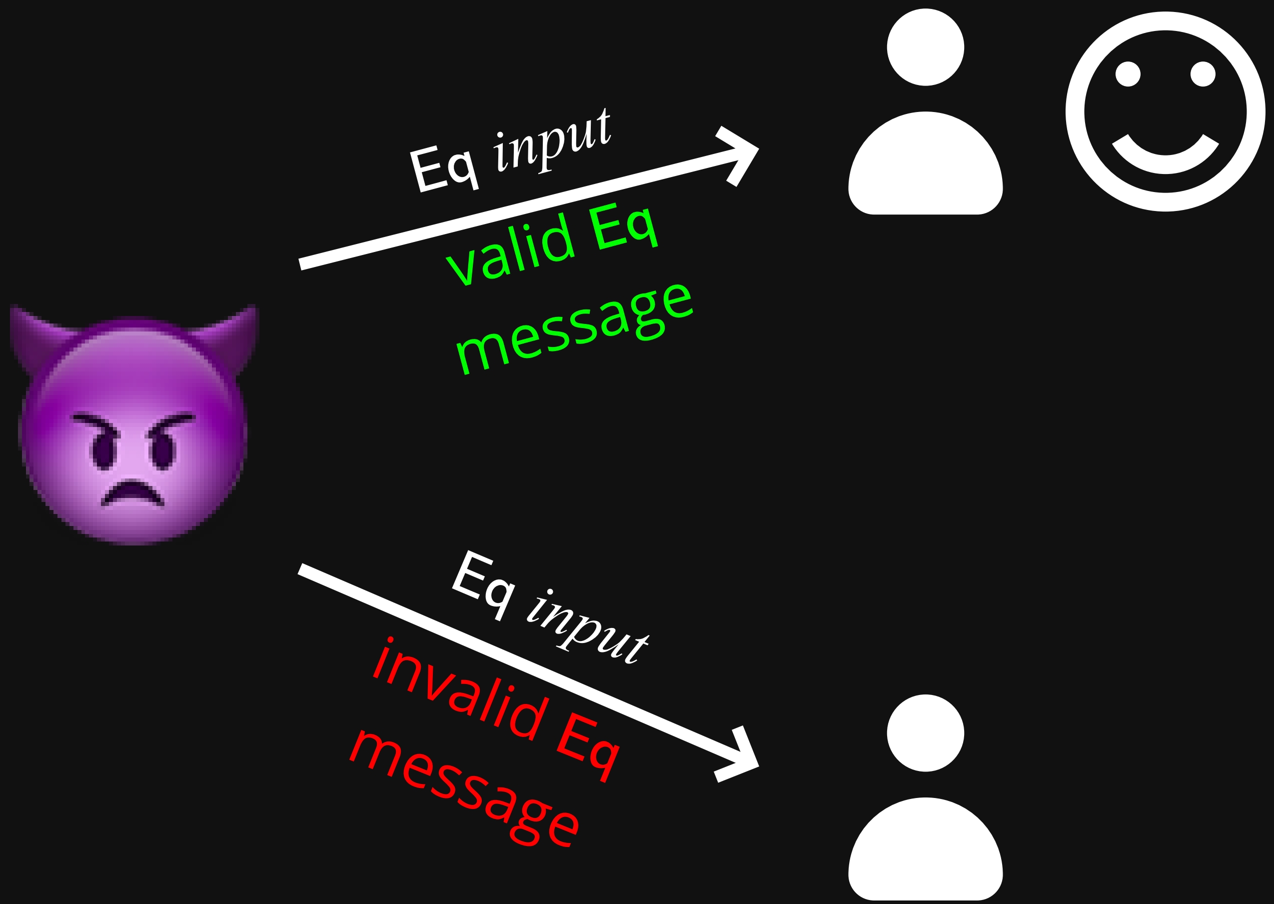




2-of-3 Example

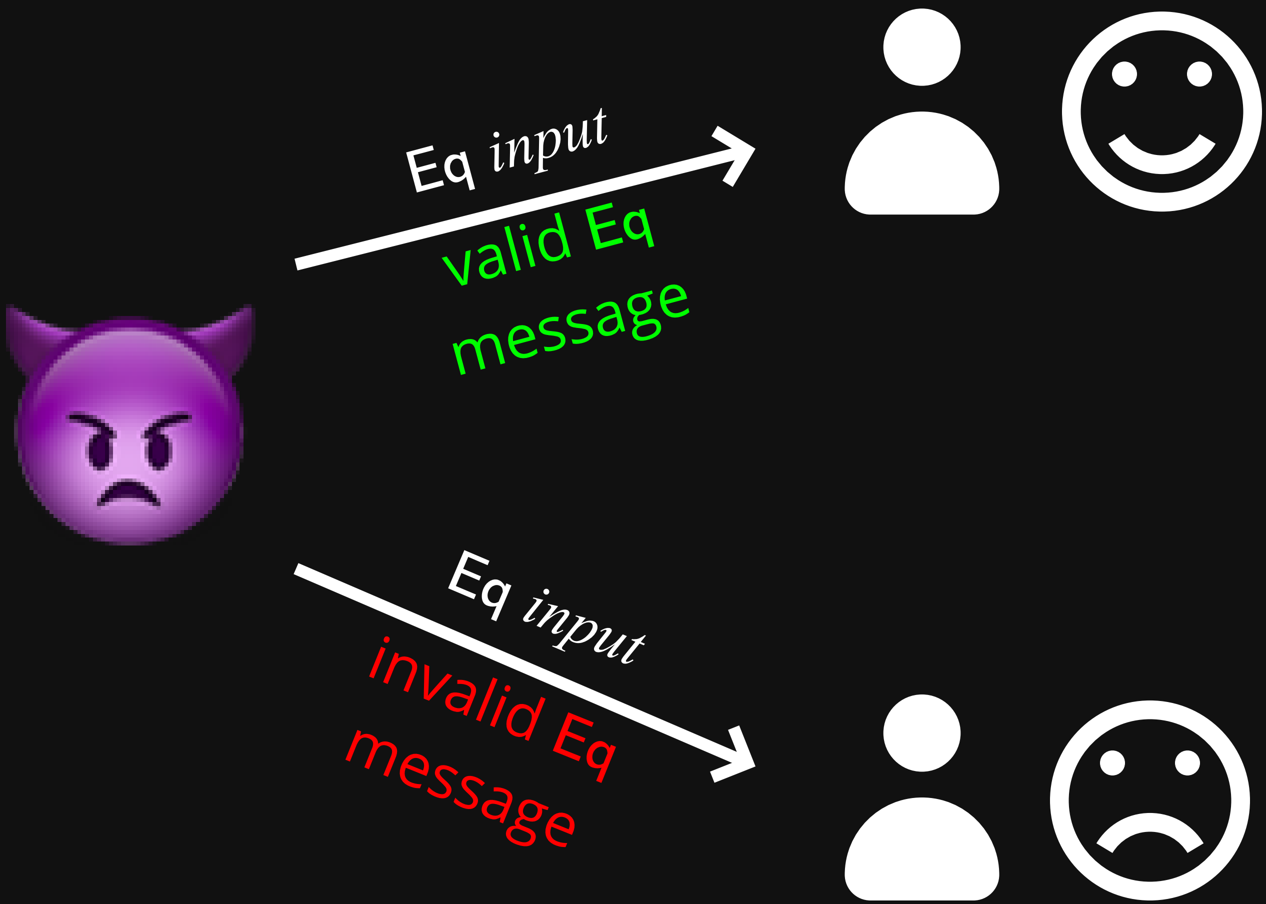


2-of-3 Example



Eq returns true,
DKG finished,
let's send money to threshold pk!

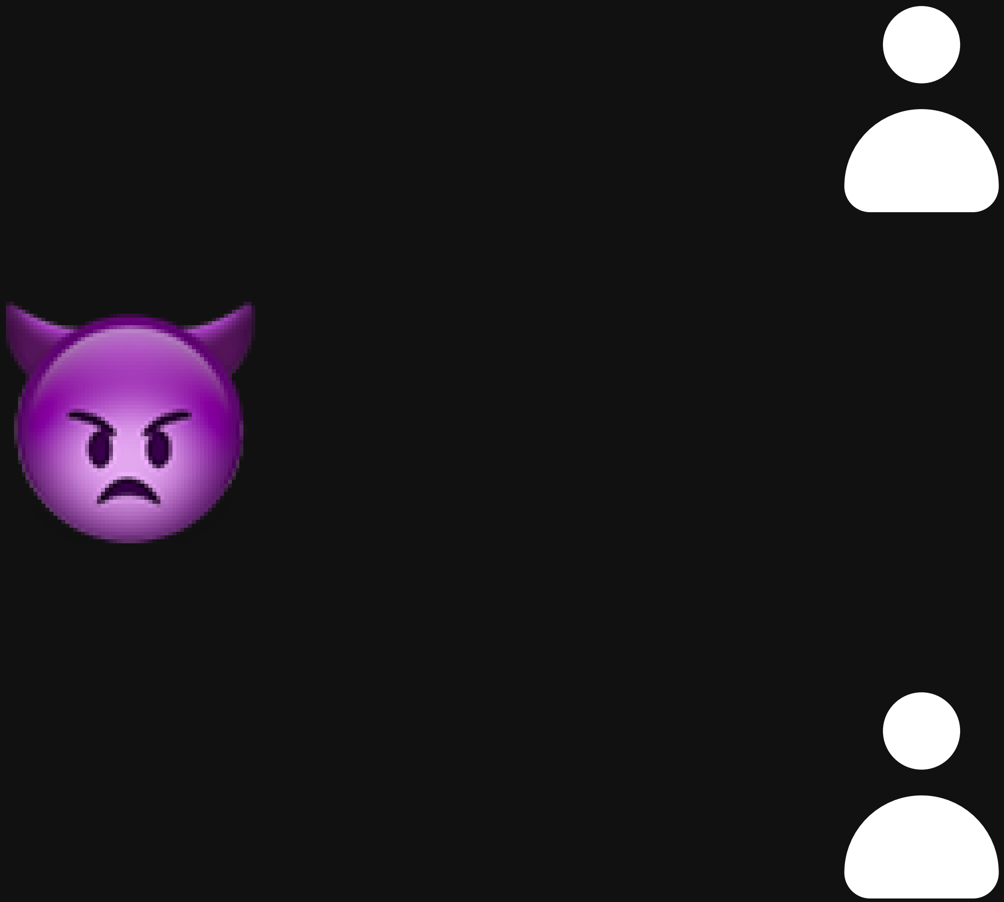
2-of-3 Example



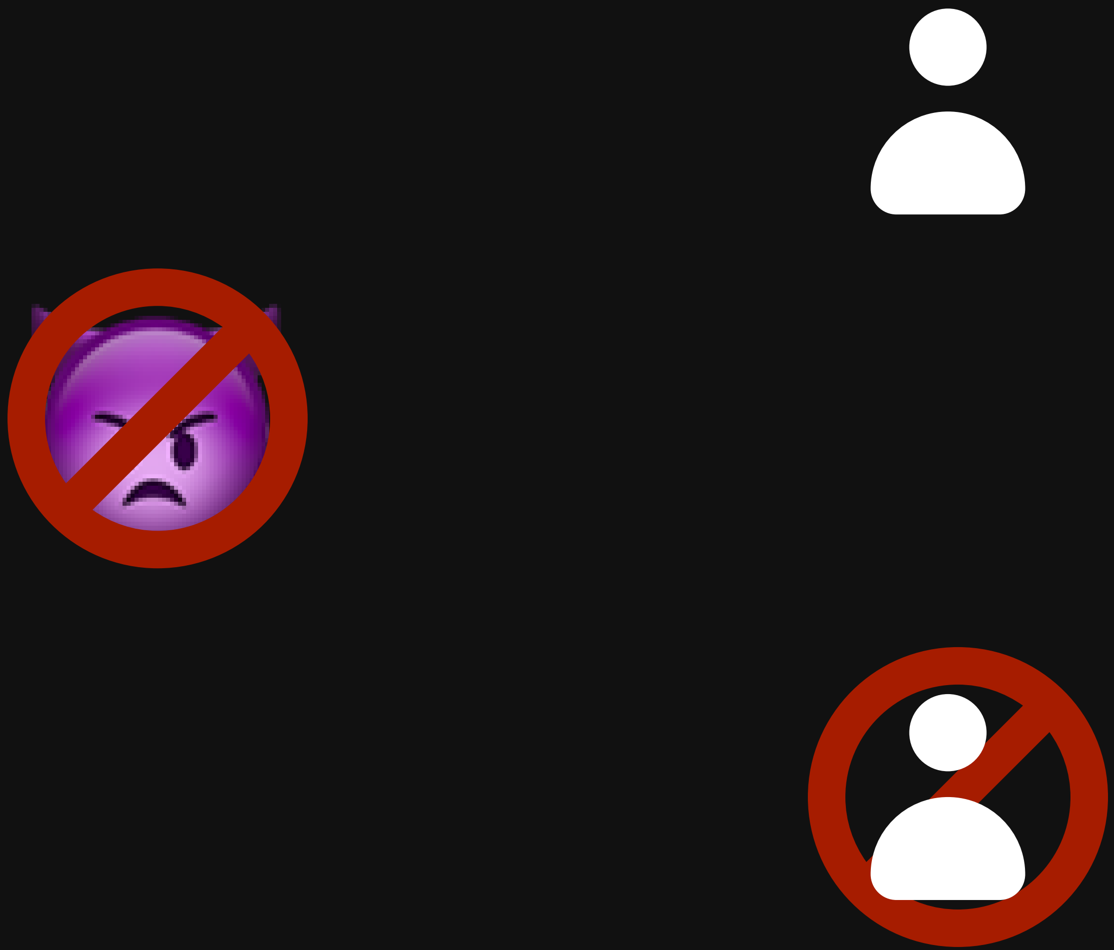
Eq returns true,
DKG finished,
let's send money to threshold pk!

DKG not finished

Just 1 signer left, but we need 2!
Money gone!



Just 1 signer left, but we need 2!
Money gone!



Just 1 signer left, but we need 2!
Money gone!

Integrity is not enough

Interactive Protocol

Eq($input$) outputs $\{\text{true}, \text{false}\}$

In SimplPedPop: $input$ contains the VSS commitments

Integrity: If some honest signer outputs true, all input of honest signers are equal.

Agreement: If some honest signer outputs true, then eventually all honest signers will output true.

Agreement is often an overlooked requirement in the FROST world.

Interim Summary

Interim Summary

- We want to specify the SimplPedPop DKG

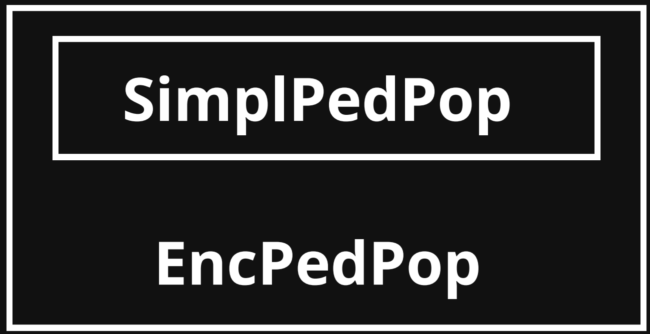
Interim Summary

- We want to specify the SimplPedPop DKG
- SimplPedPop requires some **Eq** protocol and secure channels, we want to spec those as well

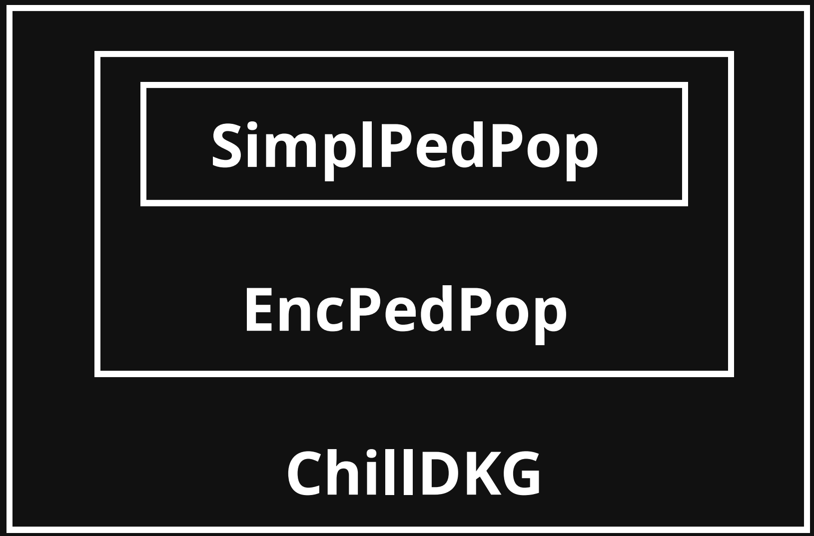
Design

SimplPedPop

Design



Design



EncPedPop

EncPedPop

- Every signer has **long-term ECDH key pair**

$$(\text{staticpub}, \text{staticpriv})$$

EncPedPop

- Every signer has **long-term ECDH key pair**
$$(\text{staticpub}, \text{staticpriv})$$
- Assumption: everyone has a **correct copy** of every other signer's staticpub.

EncPedPop

- Every signer has **long-term ECDH key pair**

$$(\mathsf{staticpub}, \mathsf{staticpriv})$$

- Assumption: everyone has a **correct copy** of every other signer's $\mathsf{staticpub}$.
- Encryption uses a one-time pad created through **ephemeral-static ECDH** key exchange between sender i and receiver j.

$$\mathsf{share}_{i,j} + \mathrm{ECDH}(\mathsf{ephemeral}_i, \mathsf{static}_j)$$

EncPedPop

- Every signer has **long-term ECDH key pair**

$$(\mathsf{staticpub}, \mathsf{staticpriv})$$

- Assumption: everyone has a **correct copy** of every other signer's $\mathsf{staticpub}$.
- Encryption uses a one-time pad created through **ephemeral-static ECDH** key exchange between sender i and receiver j.

$$\mathsf{share}_{i,j} + \mathsf{ECDH}(\mathsf{ephemeral}_i, \mathsf{static}_j)$$

- All signers' claimed $\mathsf{staticpub}, \mathsf{ephemeralpub}$ are **added** to Eq's input

ChillDKG

ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed

ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed
- Eq is instantiated with concrete protocol **"CertEq":**

ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed
- **Eq** is instantiated with concrete protocol **"CertEq":**

   1. Everyone sends a **signature** on their **Eq input** to everyone else.

ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed
- Eq is instantiated with concrete protocol **"CertEq":**

1. Everyone sends a **signature** on their Eq input to everyone else.
2. Signers terminate successfully when they receive valid signatures from all n participants (***"success certificate"***)

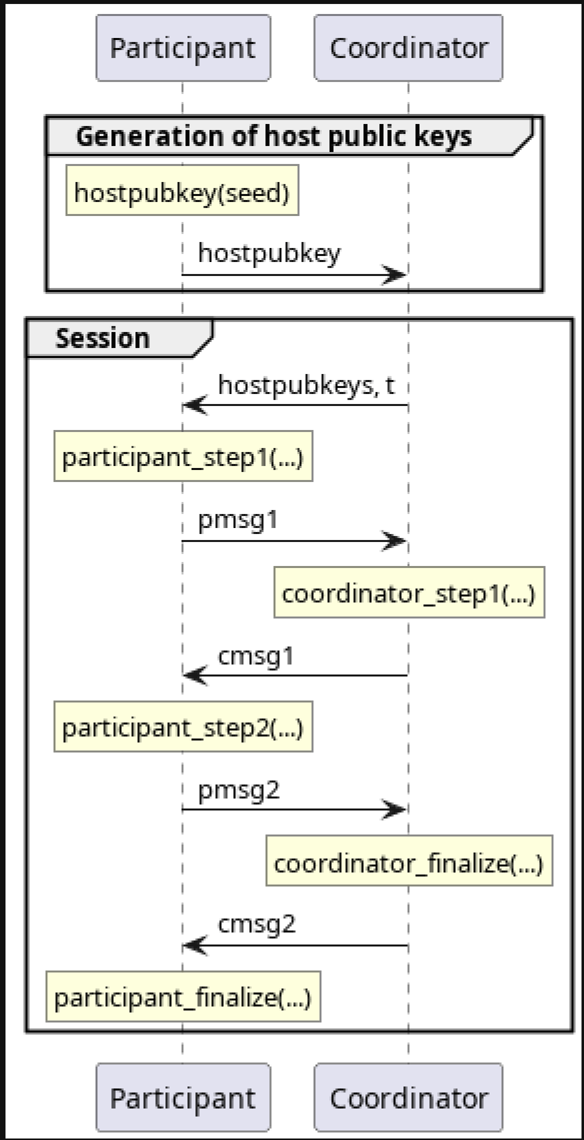
ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed
- **Eq** is instantiated with concrete protocol **"CertEq":**
  1. Everyone sends a **signature** on their **Eq input** to everyone else.
  2. Signers terminate successfully when they receive valid signatures from all n participants (***"success certificate"***)
- Integrity: ✅

ChillDKG

- Every signer has long-term **"host" key pair**, derived from a seed
- Eq is instantiated with concrete protocol **"CertEq":**
  1. Everyone sends a **signature** on their Eq input to everyone else.
  2. Signers terminate successfully when they receive valid signatures from all n participants (***"success certificate"***)
- Integrity: ✅
- Agreement: ✅ (can convince signer with success cert)

ChillDKG


Participant
Coordinator
Generation of host public keys
hostpubkey(seed)
hostpubkey
Session
hostpubkeys, t
participant_step1(...)
pmsg1
coordinator_step1(...)
cmsg1
participant_step2(...)
pmsg2
coordinator_finalize(...)
cmsg2
participant_finalize(...)
Participant
Coordinator

ChillDKG Backups

ChillDKG Backups

- In contrast to Schnorr sigs or MuSig, secret keys **cannot be derived** from the seed.

ChillDKG Backups

- In contrast to Schnorr sigs or MuSig, secret keys **cannot be derived** from the seed.
- Naive approach: backup **new secret data** per DKG session

ChillDKG Backups

- In contrast to Schnorr sigs or MuSig, secret keys **cannot be derived** from the seed.
- Naive approach: backup **new secret data** per DKG session
- ChillDKG: backup seed once, and backup "**recovery data"** per DKG session. Recovery data is...

ChillDKG Backups

- In contrast to Schnorr sigs or MuSig, secret keys **cannot be derived** from the seed.
- Naive approach: backup **new secret data** per DKG session
- ChillDKG: backup seed once, and backup "**recovery data"** per DKG session. Recovery data is...
  - ...**self-authenticating** and contains secret data in **encrypted** form
    - can be stored with an **untrusted** third-party

ChillDKG Backups

- In contrast to Schnorr sigs or MuSig, secret keys **cannot be derived** from the seed.
- Naive approach: backup **new secret data** per DKG session
- ChillDKG: backup seed once, and backup "**recovery data"** per DKG session. Recovery data is...
    - ...**self-authenticating** and contains secret data in **encrypted** form
        - can be stored with an **untrusted** third-party
    - ...the **same** for all participants
        - can be requested from **other** participants

BIP ChillDKG

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.
- Specification/reference implementation in **Python**

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.
- Specification/reference implementation in **Python**
- Provides (conditional) **agreement**

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.
- Specification/reference implementation in **Python**
- Provides (conditional) **agreement**
- **Simpler backups**: recover from static seed and public recovery data

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.
- Specification/reference implementation in **Python**
- Provides (conditional) **agreement**
- **Simpler backups**: recover from static seed and public recovery data
- Supports **any threshold** $t \leq n$

BIP ChillDKG

- Specification in the form of a Bitcoin Improvement Proposal (**BIP**)
- **Standalone** (fully specified), no external secure channels or consensus mechanism.
- Specification/reference implementation in **Python**
- Provides (conditional) **agreement**
- **Simpler backups**: recover from static seed and public recovery data
- Supports **any threshold** $t \leq n$
- Untrusted **coordinator** reduces communication overhead by aggregating some of the messages

In-Progress Feature

In-Progress Feature

- A **single** signer can cause ChillDKG not to succeed (e.g., by sending nothing, inconsistent VSS commitments, ...)

In-Progress Feature

- A **single** signer can cause ChillDKG not to succeed (e.g., by sending nothing, inconsistent VSS commitments, ...)
- In the setting we're considering, the signers **are not able to agree** on which signer is misbehaving
  - E.g., requires majority of signers to be **honest** or **synchronous** network

In-Progress Feature

- A **single** signer can cause ChillDKG not to succeed (e.g., by sending nothing, inconsistent VSS commitments, ...)
- In the setting we're considering, the signers **are not able to agree** on which signer is misbehaving
  - E.g., requires majority of signers to be **honest** or **synchronous** network
- However, we believe ChillDKG can be modified such that in case of failure, each honest signer can determine that **either a certain participant or the coordinator** are misbehaving.

More TODOs

- Collect and address feedback
- Add test vectors

https://github.com/BlockstreamResearch/bip-frost-dkg