1

Facilitating Security and Trust among Multiple Parties through Blockchain Techniques

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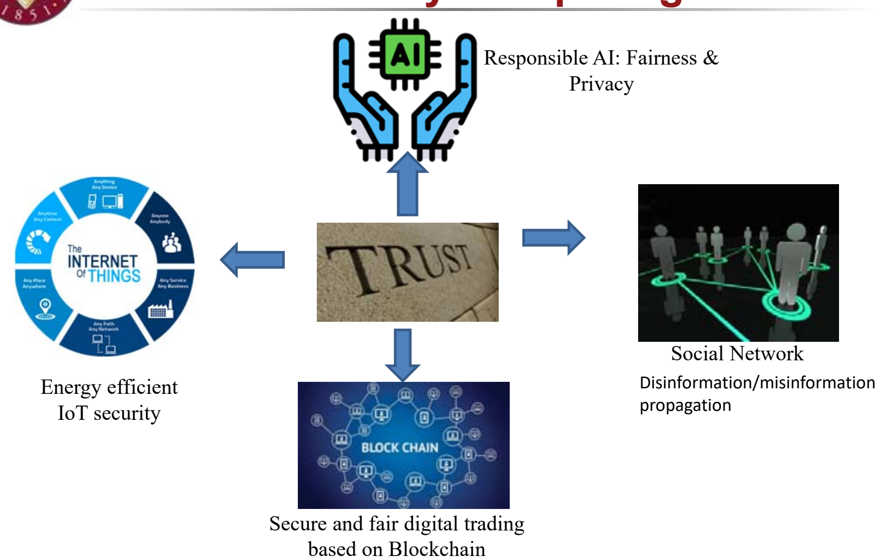
Research Interests – Trustworthy Computing



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A Smart Computing World With Emerging Challenges for Security & Trust

Enabling Technologies: Internet of Things, AI/ML, 6G, …

Image from Internet

How to facilitate trustworthy interactions among highly decentralized, heterogeneous entities?

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4

Outline

- ❑ Blockchain basis + Multi-signature
- ❑ Secure and Efficient Multi-Signature Schemes for Fabric
- ❑ Group-Oriented Multi-Signature Supporting Monotonic Endorse Policies in Hyperledger Fabric

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Blockchain – Data Organization

Blockchain: A chain structure connecting blocks of transactions

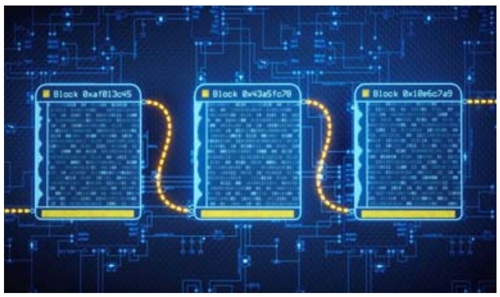
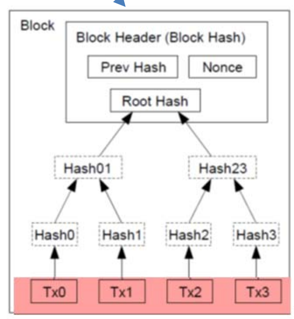


Image from https://www.hoyes.com/blog/can-blockchain-technology-save-the-credit-scoring-system/



Transactions Hashed in a Merkle Tree

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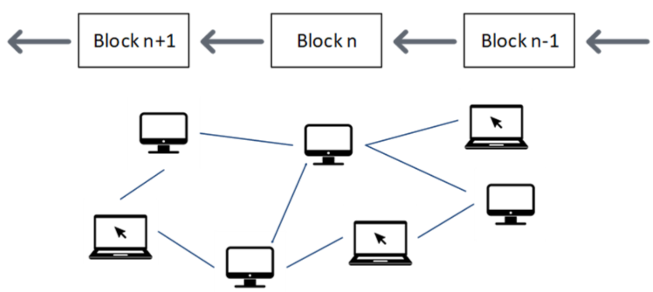
Blockchain – Hosted by a Distributed Network



A peer-to-peer network with each node storing a copy (or a part of a copy) of the blockchain data

Data consistency: consensus algorithm

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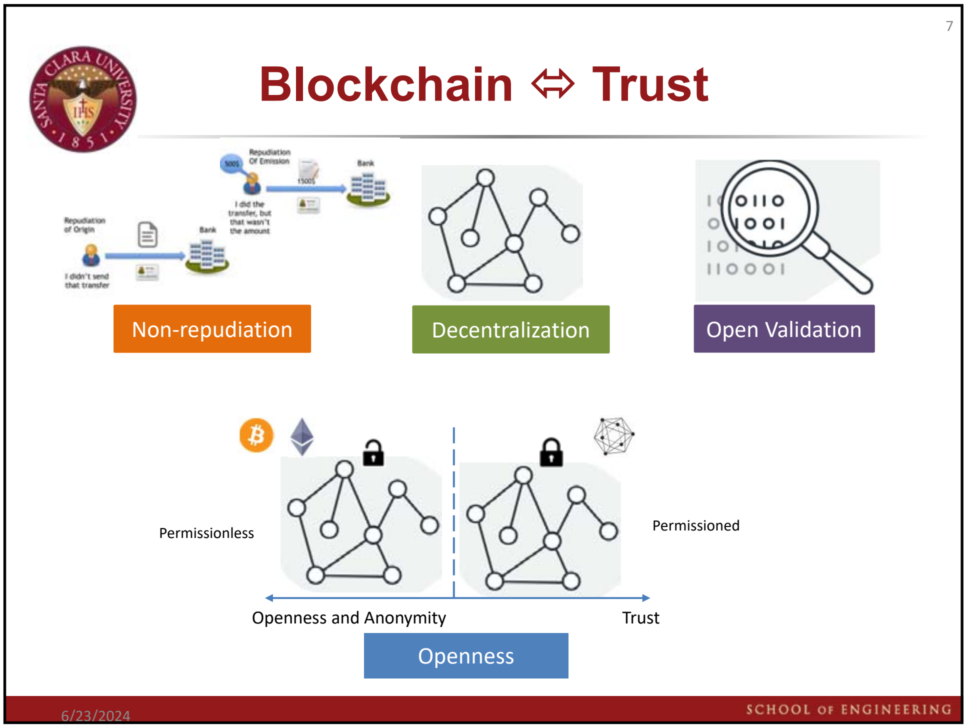
7
Blockchain ⇔ Trust
Non-repudiation
Decentralization
Open Validation
Permissionless
Permissioned
Openness and Anonymity
Trust
Openness
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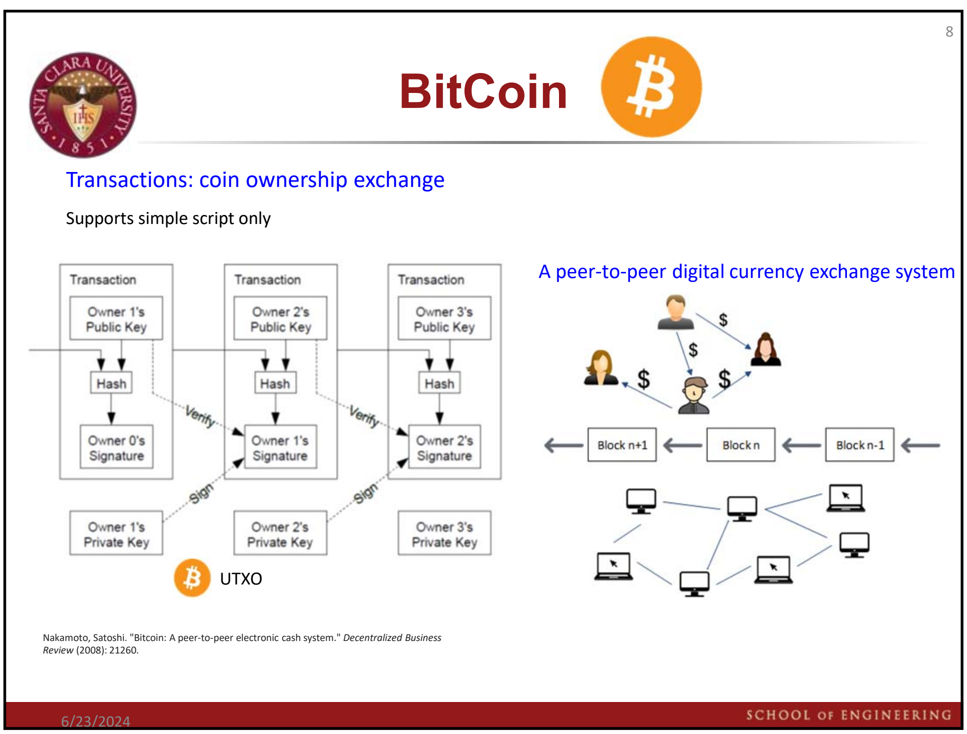
8
BitCoin
Transactions: coin ownership exchange
Supports simple script only
Transaction
Owner 1's Public Key
Hash
Owner 0's Signature
Owner 1's Private Key
Transaction
Owner 2's Public Key
Hash
Owner 1's Signature
Owner 2's Private Key
Transaction
Owner 3's Public Key
Hash
Owner 2's Signature
Owner 3's Private Key
Verify
Sign
UTXO
A peer-to-peer digital currency exchange system
Block n+1
Block n
Block n-1
Nakamoto, Satoshi. "Bitcoin: A peer-to-peer electronic cash system." Decentralized Business Review (2008): 21260.
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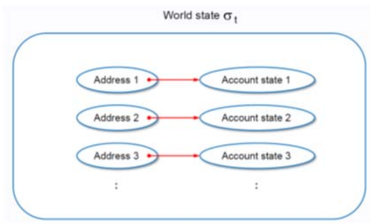
9

Ethereum

blockchain system is generalized as a state machine.



The world state is a mapping between address and account state.

A transaction represents a valid arc between two states.

Smart contracts allow complex logic => Turing complete

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Fabric

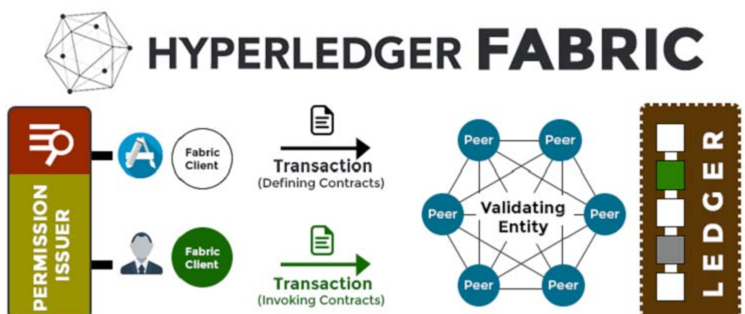

Image from Internet

- Strong identity management
- Enabled endorsement functions
- Adopt cryptographic digital signatures (ECDSA).

10

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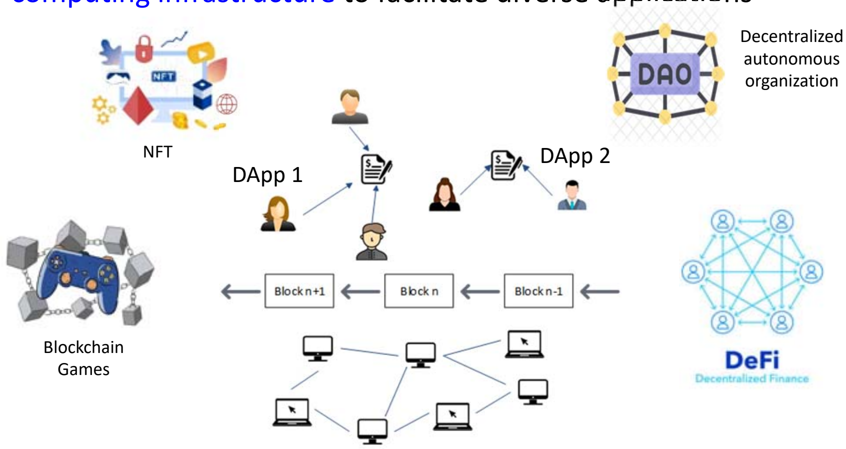
Blockchain as a Computing Infrastructure

Generalized blockchain system can potentially serve as a computing infrastructure to facilitate diverse applications



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Challenge: Digital Signature Efficiency

- Endorsement process based on digital signature is
  - **Inefficient:** signature collected from each endorser
  - **Resource consuming**: verification & storage of multiple signatures; significant broadcasting overhead
  - **Lack of scalability**: 100- 2000 tps.

12

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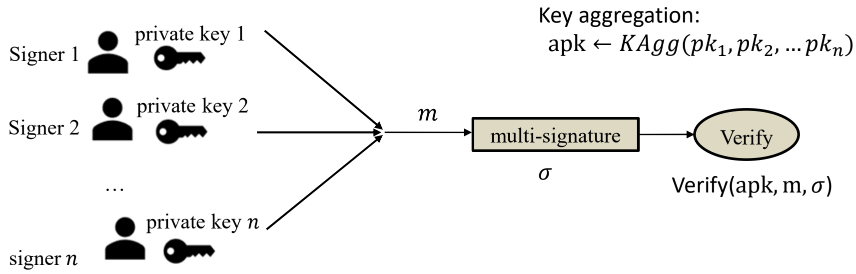
A Promising Solution: Multi-Signature

Multi-signature allows a group of signers to jointly produce a single signature on the same message.



Advantage:

- One single signature saves storage space;
- One-time verification improves efficiency.

13

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Existing Multi-Signature Basis

Basic Scheme	Modulus	Signature length	Computation Operations
RSA	2048 bits	2048 bits	Multiplications
Schnorr	2048 bits	448 bits	Multiplications
BLS	2048 bits	224 bits	Bilinear parings

```
Multiplication time consuming: 0.0415ms
pairing time consuming: 232.7998ms
```

- Bilinear pairing operation takes much more time than multiplication operation.
- Considering the signature length and computational cost, we study the Schnorr-based multi-signature schemes.

14

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Schnorr Signatures

$pk = g^{sk}$

$r \leftarrow_R Z_q$

$t \leftarrow g^r$

$c \leftarrow H(t, m)$

$s \leftarrow r + c * sk \bmod q$

$\sigma \leftarrow (c, s)$

Verification:

$c = H(g^s * pk^{-c}, m)$

15

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"Plain" Schnorr multi-signatures

Signing:

$pk_1 = g^{sk_1}$	$pk_2 = g^{sk_2}$	$pk_3 = g^{sk_3}$
$r_1 \leftarrow_R Z_q$	$r_2 \leftarrow_R Z_q$	$r_3 \leftarrow_R Z_q$
$t_1 \leftarrow g^{r_1}$	$t_2 \leftarrow g^{r_2}$	$t_3 \leftarrow g^{r_3}$
$t \leftarrow t_1 t_2 t_3$	$t \leftarrow t_1 t_2 t_3$	$t \leftarrow t_1 t_2 t_3$
$c \leftarrow H(t, m)$	$c \leftarrow H(t, m)$	$c \leftarrow H(t, m)$
$s_1 \leftarrow r_1 + c * sk_1 \bmod q$	$s_2 \leftarrow r_2 + c * sk_2 \bmod q$	$s_3 \leftarrow r_3 + c * sk_3 \bmod q$
$s \leftarrow s_1 + s_2 + s_3 \bmod q$	$s \leftarrow s_1 + s_2 + s_3 \bmod q$	$s \leftarrow s_1 + s_2 + s_3 \bmod q$
$\sigma \leftarrow (c, s)$	$\sigma \leftarrow (c, s)$	$\sigma \leftarrow (c, s)$

Verification:

$apk \leftarrow pk_1 * pk_2 * pk_3$

$c = H(g^s * apk^{-c}, m)$

16

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Problem 1: Rogue-key Attacks

- *a malicious endorser arbitrarily claims his/her public key so that he/she can independently forge a joint signature*

$pk_1 = g^{sk_1}$

$pk_2 = g^{sk_2}/pk_1$

$apk = pk_1 * pk_2 = g^{sk_2}$

  - *The malicious endorser can control apk by claiming his/her public key based on the other parties public keys*
  - *Hence, he/she can compute signatures under apk by him/herself*

17

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Problem 2: k-sum Attacks

- *An attack can succeed if a malicious endorser can simultaneously open k-1 signature oracle queries with honest signers on a message m as s_i, where $i \in \{1, .. k-1\}$, and get a valid signature $\sigma \leftarrow (c^*, s^*)$ on a target message $m^* \neq m$, meaning that*

$$c^* = \sum_{i=1}^{k-1} c_i \qquad s^* = \sum_{i=1}^{k-1} s_i + c^* * sk \quad \Rightarrow \quad c^* = H(g^s * apk^{-c}, m^*) = H(g^{\sum_{i=1}^{k-1} r_i}, m^*)$$

- *Since $c_i \leftarrow H(t_i, m)$, where t_i can be controlled by the attacker, an attack can succeed if the attacker is able to construct*

$$c^* = \sum_{i=1}^{k-1} c_i = \sum_{i=1}^{k-1} H(t_i, m) \quad \Rightarrow \quad \sum_{i=1}^{k-1} H(t_i, m) = H(g^{\sum_{i=1}^{k-1} r_i}, m^*)$$

- *The last signer of the endorsement, with excessive power, can forge a joint signature on a new message.*

18

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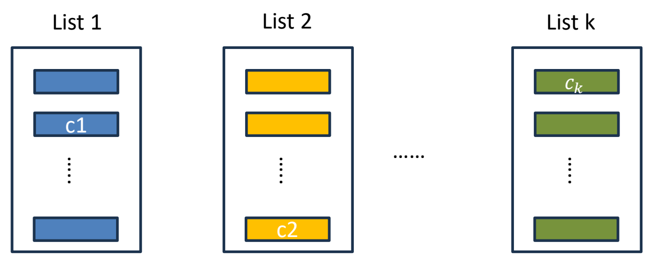
K-Sum Problem

- Wagner's generalized birthday attack (K-sum problem)
  - Given k lists of random elements in Z_q, find $(c_1, \dots c_k)$ in lists such that $c_1 + \cdots + c_k = 0 \ mod \ q$



19

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Multi-Signature for Blockchain

*Xiao Yue, Peng Zhang, **Yuhong Liu**, "Secure and Efficient Multi-Signature Schemes for Fabric: An Enterprise Blockchain Platform", IEEE Transactions on Information Forensics and Security, 16 (2020): 1782-1794.*

20

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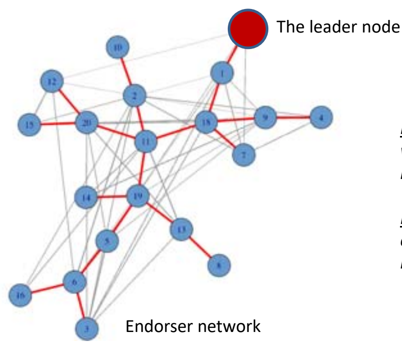
CoSi: Multi-signature Scheme

- A very popular Schnorr-based scheme
- High scalability due to the spanning tree structure
  - a loop-free logical topology
  - a single active path between any two network nodes.



K-sum problem attacks: the leader of the endorsement, with excessive power, can forge a joint signature on a new message.

Rogue-key attacks: a malicious endorser arbitrarily claims his/her public key so that he/she can independently forge a joint signature

21

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Proposed Schemes

- A Gamma Multi-Signature (GMS) – security
  - Spanning tree structure (high scalability)
  - Proof of possession against rogue-key attacks
  - Improved signing process - against k-sum attacks
- An Advanced Gamma Multi-Signature (AGMS) - efficiency
  - Improved online efficiency by reordering the signing process

22

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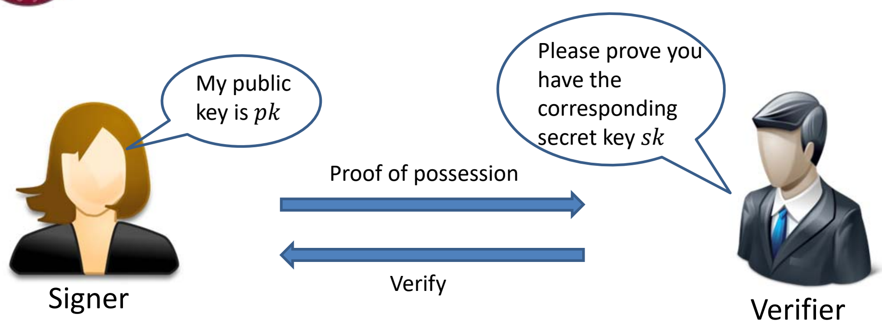
Proof of Possession



Proof of possession $\pi = (a, d) \begin{cases} a = H_1(g_1, g_1^r) \\ d = r * a - H_2(pk) * sk \bmod q \end{cases}$

verification $a = H_1(g_1, (g_1^d y^{H_2(y)})^{a^{-1}})$?

23

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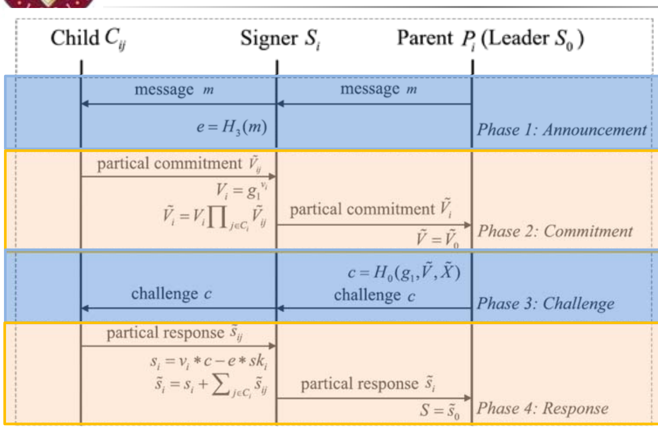
Proposed GMS – Signing Process



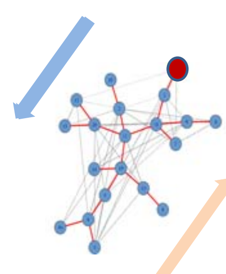


Fig. 1. The signing algorithm of our GMS scheme (We suppose that signer S_i holds the key pair (pk_i, sk_i), where $pk_i = (y_i, \pi_i)$, and parent P_i works as a leader S_0. If parent P_i is not a leader, it just works as signer S_i. Finally, the leader S_0 outputs (c, S) as the joint signature.).

24

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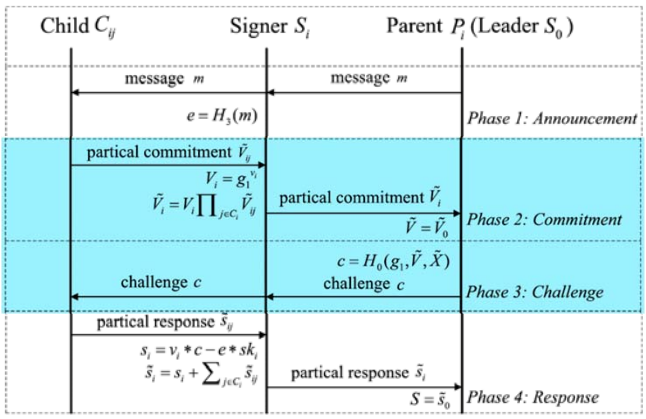
Proposed GMS – Signing Process



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25

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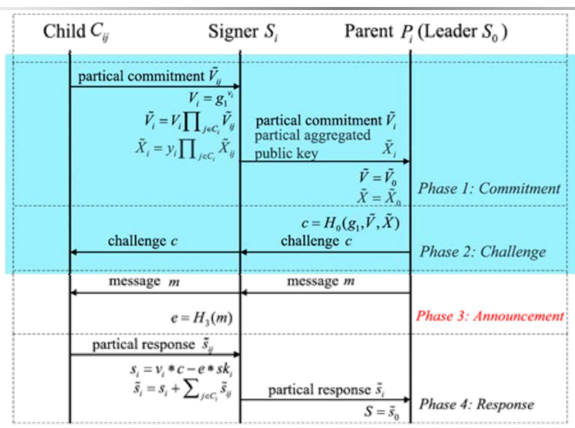
Advanced GMS (AGMS)



Reorder phase 1, 2, 3

Fig. 2. The signing algorithm of the proposed AGMS scheme (Text in red indicates changes from Fig. 1. We suppose that signer S_i holds the key pair (pk_i, sk_i), where $pk_i = (y_i, \pi_i)$, and parent P_i works as a leader S_0. If parent P_i is not a leader, it just works as signer S_i. The key aggregation algorithm also runs together with the signing algorithm. Finally, the leader S_0 outputs (c, S) as the joint signature.)

26

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Running Time on the Leader node

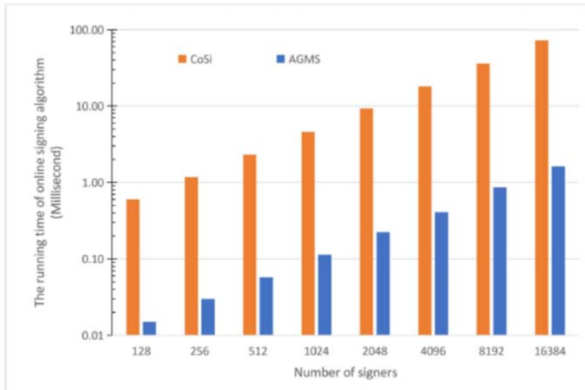

Fig. 7. The CPU running time on a leader node of CoSi and AGMS in online signing phase (y-axis has logarithmic scale.).

27

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Applying on Fabric

Key revision: replace the original ECDSA by the proposed AGMS.

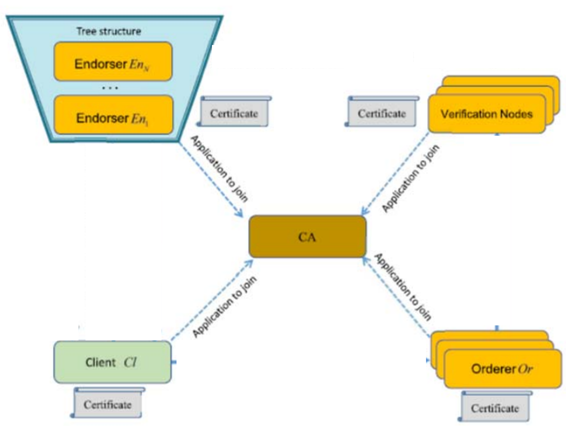

Fig. 9. The revised Fabric transaction process.

28

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Performance Testing on Fabric

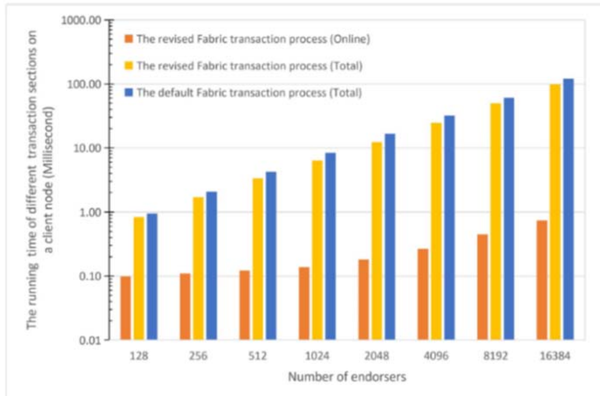

Fig. 13. The total CPU running time on a client node between the default Fabric transaction process and the revised Fabric transaction process (y-axis has logarithmic scale.).

29

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Another Problem – Flexible Endorsement

- Endorsement policy in Fabric can be expressed as:

EXPR(E[, E...]),

where *EXPR* is "*AND*", "*OR*" or "*OutOf*"; and *E* is either an endorser or another nested call to *EXPR*.

- Typical endorsement policies are monotonic and group-based:

AND('Org1.member',' Org2.member', ...),

where "*OR*" expression is used to check if any member from Org1 (and Org2) has endorsed.

- Not supported by existing Multi-signature schemes: Existing multi-signature schemes mainly focus on "AND" relationship among multiple singers, they can only support individual-based endorsement policies like

"AND('member1','member2',...)".

30

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*Peng Zhang, Yongwen Huang, Fa Ge, **Yuhong Liu,** "Group-Oriented Multi-Signature Supporting Monotonic Endorse Policies in Hyperledger Fabric", IEEE Blockchain 2023, Hainan, China, Dec. 17-23, 2023*

31

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The Proposed Scheme

- We propose a Group-oriented Multi-Signature scheme, which supports secure and more flexible endorsement policy
- Based on the proposed scheme, the transaction protocol in Fabric is optimized, so that the block size and verification time are reduced.

32

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The Proposed Scheme

Group-oriented multi-signature scheme with smart contract

- Smart contract on blockchains is distributed on peer-to-peer networks, publicly verifiable, and executed automatically.
- By introducing public and trustworthy smart contracts to be the last signer responsible for commitment operations, *k*-sum problem attacks are prevented.

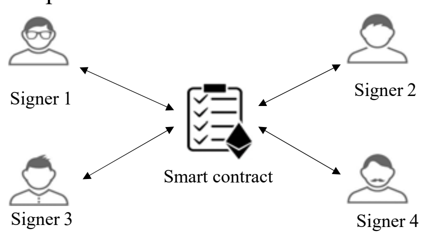

Fig. 3 The network structure of our scheme

It is responsible for:

1. Collecting commitments $R_{i,j}$ from all signers;
2. Recording the timestamp t and computing the last commitment $W = g^{H(t)}$;
3. Computing and Distributing the joint commitments.

$$R = W^{\theta} \prod_{i=1}^{\theta} R_{i,j}$$

33

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The Proposed Scheme

- By introducing **Chinese Remainder Theorem** to combine all public keys of members in a group into one group public key, the public key of each member is unknown to all others except the group administrator, so that only the group public key is involved in verification.

$$\begin{cases} k_i = X_{i,1} (mod\ p_{i,1}) \\ \vdots \\ k_i = X_{i,\eta} (mod\ p_{i,\eta}) \end{cases}$$

34

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Security Analysis

We conduct a security analysis on the proposed scheme. Based on the difficulty problem assumption, our scheme satisfies the unforgeability, anonymity, revocability and traceability.

- Unforgeability: The signature cannot be forged by an attacker.
- Anonymity: The identity of the signer will not be revealed.
- Revocability: Signers who exit the group cannot be regenerated into legal signatures.
- Traceability: Only the group administrator knows the identities of the members participating in the multi-signature.

35

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Comparison

Table1 The comparisons of key and signature length (θ represents the number of groups)

Scheme	Public key	Private key	Signature
Musig2	$\lvert\mathbb{G}\rvert$	$\lvert\mathbb{Z}_\alpha\rvert$	$\lvert\mathbb{G}\rvert + \lvert\mathbb{Z}_\alpha\rvert$
GMS	$\lvert\mathbb{G}\rvert$	$\lvert\mathbb{Z}_\alpha\rvert$	$\lvert\mathbb{G}\rvert + (\theta + 1)\lvert\mathbb{Z}_\alpha\rvert$

Table2 The comparisons of computational cost and security assumptions
(*Exp* represents the calculation cost of an exponential operation in the group)

Scheme	Sign	Verify	Join	Revoke	Assumptions
Musig2	$7EXP$	$2EXP$	–	–	AOMDL
GMS	$2EXP$	$2EXP$	$1EXP$	$0EXP$	DL

36

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Experiment Results

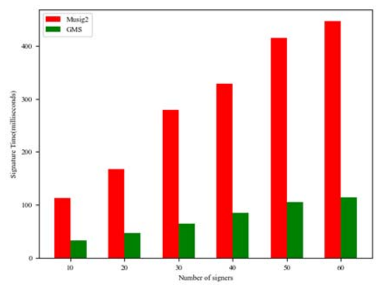

Fig. 4 Signature time comparisons of Musig2 and GMS.

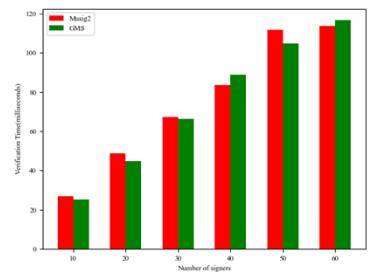

Fig. 5 Verification time comparisons of Musig2 and GMS

37

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Application on Fabric

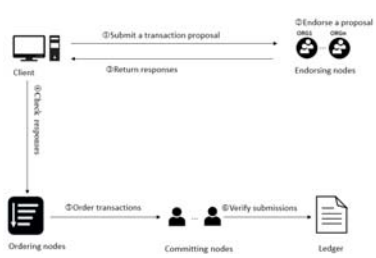

Fig. 6 Original transaction protocol in Fabric

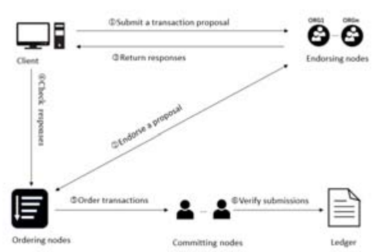

Fig. 7 Improved transaction protocol in Fabric

Since the proposed scheme introduces smart contracts, we install them on the ordering nodes, and endorsing nodes need to interact with the ordering nodes.

38

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Endorsement Policy

$AND(OR(org1.member1, org1.member2), \ldots, OR(org10.member1, .., org10.member2))$

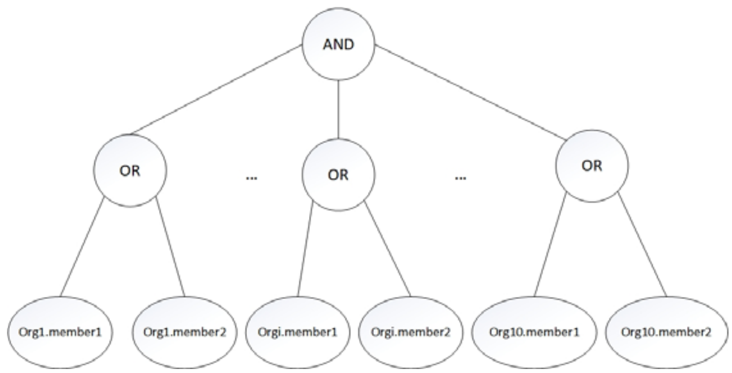

Fig. 8 The endorsement policy used in this experiment

39

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Experiment Results

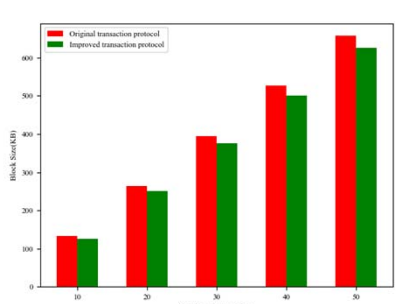

Fig. 9 The block size in original and improved transaction protocols

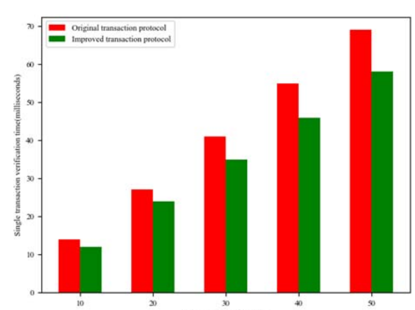

Fig. 10 The verification time for each transaction in original and improved transaction protocols

40

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41

Other Relevant Studies

- Autonomous vehicle networks,
- Transactive Energy trading,
- Internet of Things,

…

More to come …

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42

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Thank You !

Questions ?

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