Soteria: A Provably Compliant User Right Manager Using a Novel Two-Layer Blockchain Technology (Extended Version)

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Abstract—**Soteria is a user right management system designed to safeguard user-data privacy in a transparent and provable manner in compliance to regulations such as GDPR and CCPA. Soteria represents user data rights as formal executable sharing agreements, which can automatically be translated into a human readable form and enforced as data are queried. To support revocation and to prove compliance, an indelible, audited trail of the hash of data access and sharing agreements are stored on a two-layer distributed ledger. The main chain ensures partition tolerance and availability (PA) properties while side chains ensure consistency and availability (CA), thus providing the three properties of the CAP (consistency, availability, and partition tolerance) theorem. Besides depicting the two-layer architecture of Soteria, this paper evaluates representative consensus protocols and recommends side-chain and inter-chain management strategies for improving latency and throughput.**

Index Terms—**blockchain, privacy, ccpa, gdpr**

I. INTRODUCTION

Artificial intelligence (AI) has the potential to improve the quality of many application domains. In order to effectively train AI models, an application typically requires large quantities of personal information (PI) from users. To address data privacy issues, regulations such as GDPR [1] and CCPA [4] in the general domain and HIPAA [2] in the medical domain need to be upheld. Businesses are required to comply with the *consumer rights* in a *provable* way. The eight consumer rights of GDPR and the six of CCPA can be summarized into three categories: 1) right to *consent*, rectify, and delete; 2) right to be *informed*; and 3) right to *access* and transfer.

- Consent: users must explicitly opt-in and always have the ability to opt-out of PI collection.
- Informed: users have the right to know how their PI is collected, used, and shared.
- Access: users have the right to access his/her own data, transfer data to another person or entity, and erase data.

To protect privacy rights in a provable manner, we propose Soteria, a user-right management system with a distributed ledger platform. Soteria provides a formal end-to-end solution that automatically maps user agreements to share data in natural language into formal compliance code. Our *executable sharing agreements* (ESA) are a formal representation of sharing agreements that can specify a superset of the rights protected under GDPR and CCPA. These agreements are translated into formal Satisfiability Modulo Theory (SMT) formulas for enforcement. Agreements can be translated back into natural language automatically so users can review and audit. (Most users may not be able to understand an ESA written in SMT formulas.) For provable compliance to privacy regulations, Soteria uses a distributed ledger to support auditability and revocability. We create an indelible trail of records by first logging every agreement signed and every query made, and putting a hash of the log on a distributed ledger. Soteria ensures all transactions (including permission, revocation, data access, and deletion) on PI leave indelible and consistent records for public audit. Provability is essential in the court of law to resolve disputes.

Soteria's ledger system employs a two-layer blockchain architecture to allow all three CAP (consistency, availability, and partition tolerance) properties [12] to be simultaneously satisfied. The base-layer blockchain guarantees PA (partition tolerance and availability) properties to ensure transparency, whereas the side chains guarantee CA (consistency and availability) properties to ensures provability. Soteria ensures performance scalability in both latency and throughput. To this end, Soteria uses permissioned side chains to achieve low latency, and replicates side chains when necessary to achieve high throughput. At the same time, the main chain uses a decentralized and permissionless blockchain to ensure transparency for public auditing. We detail our protocol selections for the base blockchain and side chains, and inter-chain management policies in Section III.

The rest of this paper is organized into four sections. Section II depicts Soteria's architecture and its user right management system. Section III presents and evaluates consensus protocols for both the main chain and side chains qualitatively. In Section IV, we report our quantitative performance evaluation on readily deployable protocols and suggest main-chain, side-chain, and inter-chain management strategies. We offer our concluding remarks and discuss future work in Section V.

IEEE Infrastructure Conference, San Francisco, October, 2020.

II. ARCHITECTURE OF SOTERIA

We use the terms *user* and *consumer* interchangeably to refer to the owner of data. (Data consumer is the term defined in CCPA to refer to an application user whose data the regulation aims to protect.) We use *business* and *company* to refer to the collector and custodian of user/consumer data. A user, and a business with that user's consent, can access the data collected from the user stored at the business.

A. Components and Design Goals

Figure 1 presents the components of Soteria. Soteria consists of three modules: in additional to its distributed ledger (DLT) that employs a two-layer blockchain, URM is user-right management for and ATS is for audit trail service .

- *User right management* (URM): URM stores descriptions of user data and metadata that are collected and stored by a company.
- *Distributed ledger* (DTL): DTL is our two-layer blockchain that satisfies Soteria's requirements including privacy, throughput and latency.
- *Audit trail service* (ATS): ATS stores incurred transactions on data items for transparent auditing.

Soteria is designed to address the following challenges:

1) Today users are asked to consent to long hard-to-read agreements. How can we write agreements that can be understandable to users?
2) How do we ensure that the agreements users sign translate into a faithful implementation?
3) How can a company prove that it is compliant? In particular, how do consumers ensure that no accesses to revoked data are performed?

While Section III depicts the ledger design in DTL for addressing the provability requirement, the remainder of this section presents how URM complies with regulations of consent, informed, and access described in Section I.

B. ESA: Executable Sharing Agreement

In existing systems, users are required to agree to long documents that are not understandable. Furthermore, because these agreements are expressed in natural language, which can be ambiguous, it is not clear what the effect of the agreements, or whether a certain company is truly in compliance. Instead, we propose *executable sharing agreement* (ESA), which have a well-defined unambiguous semantics; that is, whether a specific transaction complies with the agreement can be verified automatically. Furthermore, ESAs can automatically be converted into natural language unambiguously. This ensures that the contract is understandable to users and auditors.

Our ESA notation is inspired by the previously proposed ThingTalk language [16], designed originally for personal data sharing [18]. The syntax of an ESA is as follows:

$$\gamma, \pi(r,p) : [f_1, f_2, \dots] \;\; \texttt{of} \;\; d, \pi(f_1, f_2, \dots)$$

This statement reads as follows: "for consumer γ, the fields $f_1, f_2, \dots$ from domain d can be shared with any *requester* r for purpose p, provided that the predicates $\pi(r,p)$ and $\pi(f_1, f_2, \dots)$ are satisfied.

So, for example, to express that they are willing to share their abnormal PSA (a protein called prostate-specific antigen) with Stanford Medical Center, including their age and ethnicity but not their name, and only for research purposes, a patient named "Bob" would issue an ESA agreement of the form:

$$\begin{aligned}\gamma = \text{“Bob”}, r = \text{“Stanford Medical Center”} \wedge p = \text{research} :\\ [age, ethnicity, PSA] \;\; \texttt{of} \;\; \text{EHR}, PSA \geq 2\end{aligned}$$

1) Translating to and from Natural Language: As consumers are not expected to understand formal languages, the ESA notation is designed to provide a natural language interface. The sharing agreements can be translated from formal to natural language using a rule-based translation. The previous example can be expressed in natural language as:

> "Stanford Medical Center can read the age, ethnicity and PSA of Bob's EHR for research and if the PSA is greater than or equal to 2."

While the automatically generated sentences can be verbose and clunky due to the rule-based translation, they are understandable, and they are guaranteed to correspond exactly to the code of the agreement. Furthermore, the ESA notation is designed so that a user can define their own sharing agreement in natural language. Previous work [16] has shown that it is possible to automatically translate natural language access controls into attribute-based policies for personal data sharing [17], [18], and the same semantic parsing technology is used here.

C. ESA Enforcement

All writes to and reads from the database containing user data must go through the Soteria interface to ensure compliance to all the sharing agreements, which represent user consent. Soteria automatically includes an *owner* field for each row of the database. Every database access is rewritten to include the sharing agreements constraints; it is timestamped and logged for later auditing.

1) Verification of SQL Queries for Auditing: To prove compliance to an external auditor, Soteria stores the requester, the purpose and the final query, right before it is issued to the database, including all the clauses related to the sharing agreements. Using the set of the sharing agreements in force at the time, the auditor can then formally verify that the query was compliant. Given a query from requester r for purpose p in the audit logs of the form:

$$\texttt{SELECT}\ \bar{f}\ \texttt{FROM}\ t\ \texttt{WHERE}\ \pi$$

and sharing agreements of the form:

$$\begin{aligned}\gamma_1, \pi_1(r,p) : [f_1, f_2, \dots] \;\; \texttt{of} \;\; t, \pi_1(f_1, f_2, \dots)\\ \gamma_2, \pi_2(r,p) : [f_1, f_2, \dots] \;\; \texttt{of} \;\; t, \pi_2(f_1, f_2, \dots)\\ \dots\end{aligned}$$

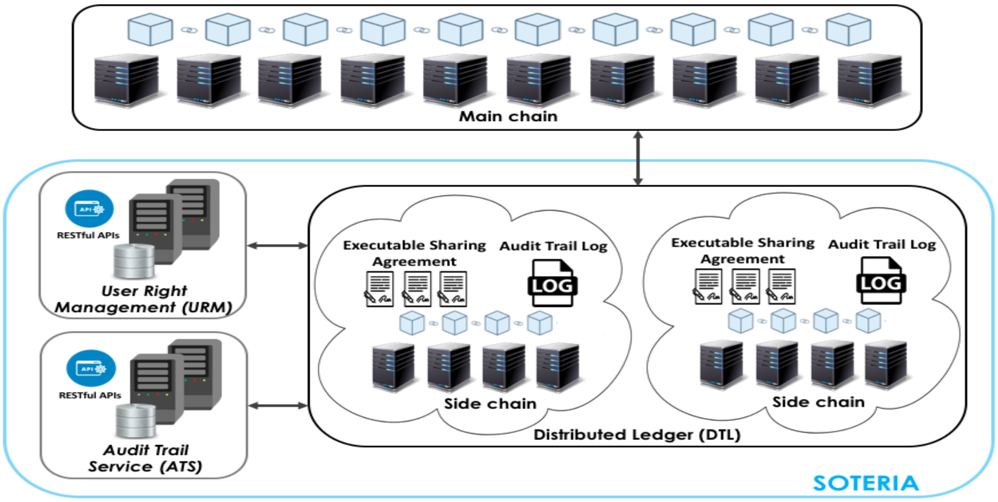

Fig. 1: Soteria Components: URM, DTL, and ATS.

the query is compliant if and only if

$$\begin{aligned}\pi \models\ & (\gamma = \gamma_1 \wedge \pi_1(r,p) \wedge \pi_1(f_1,f_2,\ldots)) \vee \\ & (\gamma = \gamma_2 \wedge \pi_2(r,p) \wedge \pi_2(f_1,f_2,\ldots)) \vee \ldots\end{aligned}$$

where γ is the consumer who owns a specific row in the database. This logical formula can be verified efficiently using a satisfiability modulo theory (SMT) solver [10].

2) Formally Verified SQL Query: To ensure that all queries are compliant, Soteria uses the following algorithm to construct a query that is guaranteed by construction to satisfy the sharing agreements. Given a SQL query from requester r for purpose p of the form:

$$\texttt{SELECT}\ \bar{f}\ \texttt{FROM}\ t\ \texttt{WHERE}\ \pi$$

and sharing agreements of the form:

$$\begin{aligned}&\gamma_1, \pi_1(r,p) : [f_1, f_2, \ldots] \ \ \texttt{of}\ \ t, \pi_1(f_1, f_2, \ldots)\\ &\gamma_2, \pi_2(r,p) : [f_1, f_2, \ldots] \ \ \texttt{of}\ \ t, \pi_2(f_1, f_2, \ldots)\\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad \cdots\end{aligned}$$

Soteria constructs a query of the form:

$$\begin{aligned}&\texttt{SELECT}\ \bar{f} \cap \{f_1, f_2, \ldots\}\ \texttt{FROM}\ t\ \texttt{WHERE}\ \pi\ \texttt{AND}\\ &\quad (\gamma = \gamma_1\ \texttt{AND}\ \pi_1(r,p)\ \texttt{AND}\ \pi_1(f_1, f_2, \ldots))\,\texttt{OR}\\ &\quad (\gamma = \gamma_2\ \texttt{AND}\ \pi_2(r,p)\ \texttt{AND}\pi_2(f_1, f_2, \ldots))\,\texttt{OR}\ldots,\end{aligned}$$

where γ in the table contains the owner of that row.

It is possible to prove that the result set of this query is consistent with the sharing agreement. Only the fields allowed by the agreement are returned, and a row is included only if the predicates in the sharing agreement in force for the row owner are satisfied.

3) Enforcing Requester and Purpose: A data requester can be an app user defined in CCPA or a company that stores user data. The URM component of Soteria assumes that the identity of the data requester has been verified by the data transport protocol. Soteria does not mandate any specific transport protocol; meaningful protocols could be REST, messaging-based [18], or could even be through physical media.

Furthermore, Soteria does not verify the purpose of the data access. The design assumes that at identification time, the data transport protocol will also compute the allowed purpose of data access. For example, using REST data transport, a medical data requester could be issued two different access tokens, one for clinical purposes and the other for research purposes. The correct purpose can be established through an existing business agreement between the data provider and data requester. If the data requester then uses the data in a manner inconsistent with the agreed purpose, the provider can use Soteria to establish that the fault lies with the requester.

4) Enforcing Access on Write: To limit the data stored by a business entity such as AWS, queries that manipulate data (insert, update, delete) are also intercepted by Soteria, and modified to match the ESA governing the storage of data. Write queries not allowed by any ESA are not executed and not logged.

To support permanent deletion of the data upon request by the consumer, the data itself (included in the `VALUES` and `SET` clauses of the insert and update queries) is masked in the audit log, as the audit log is immutable and append-only. For this reason, an ESA limiting writes that depend on the specific values cannot be audited after the fact. Soteria disallows such ESA: only the set of fields to write can be controlled.

Deletions are a special case of write, because they reduce the data that is stored about a specific customer rather than store new data. Hence, deletion is always allowed regardless of the current ESA. All deletions are logged, to prove that they were executed properly.

Additionally, upon revoking an ESA that limits the allowed writes to the database, some columns that were previously allowed might becomes disallowed. In that case, Soteria overwrites the data to set those columns to `NULL`. In case all columns are now disallowed, such as when all ESAs for a customer are revoked, Soteria deletes the row entirely. Both the database write (update or delete) and the ESA revocation are logged for later auditing.

D. ESA Storage and Audit

To support long-term auditability, as well as revocation of contracts, Soteria makes use of a distributed ledger (blockchain) to track which sharing agreements are in force. The use of the blockchain provides a global ordering of all the events across all parties in the system; the events include issuing a sharing agreement, accessing the data, and revoking a sharing agreement. This global ordering ensures it is always possible to verify whether a sharing agreement was in force when a data transaction occurred, without disputes.

Sharing agreements can potentially be privacy-sensitive themselves; for example, the sharing agreement in the previous section can reveal that the patient is likely to be male. For this reason, Soteria only stores the hash of the sharing agreement code, and the hash of each transaction, in the public blockchain. Upon request by a competent authority (e.g. under subpoena in a civil dispute), a data provider using Soteria can reveal the full audit logs, including the full code of the sharing agreements, and the exact transactions performed. These logs can then be matched to the hashes stored in the public blockchain to verify that they were not tampered with.

Soteria includes three types of events in the blockchain:

1) *Sharing Agreement Deployment* (ESAD). An ESAD event occurs when a new sharing agreement is created between a user and a business. An ESAD transaction on the blockchain (ESAD-TX) includes both user and business addresses, the hash of the agreement code, ESA deployment date, and ESA validity status (set to *true*).
2) *Data Transaction* (DATA-TX). A data transaction indicates the transfer of data between a data provider and a data requester. DATA-TX records in the blockchain include the address of the data provider, the address of the data requester, and the hash of the exact query executed against the database. Note that, as described in the previous section, the exact query will include a reference to the consumers and their sharing constraints. Hence, given the raw audit logs, paired with the hash in the blockchain, it is possible to verify that the query was valid when executed.
3) *Sharing Agreement Revocation* (ESAR). A sharing agreement can be revoked by a user, making it invalid. Since the ledger is append-only, a revocation is implemented by creating a new sharing agreement transaction with the validity status set to *false*. Note that a rectification request issued by a user is executed in two consecutive transactions, an ESAR to revoke an existing consent and then an ESAD to create a new consent.

III. DLT CONSENSUS PROTOCOLS

Soteria adopts blockchain technology to maintain its distributed ledger among several institutions and users. To achieve high throughput and low latency, Soteria uses a two-layer blockchain (we previously proposed in [30]). The base layer is decentralized similar to Ethereum, and its side chains are entrusted by a group of selected validators, known as *juries*. Soteria may spawn multiple independently operated side chains for improving overall throughput. An ESA'a agreement, access, and revocation are all logged on the same side chain to ensure a local consistent order on that side chain.

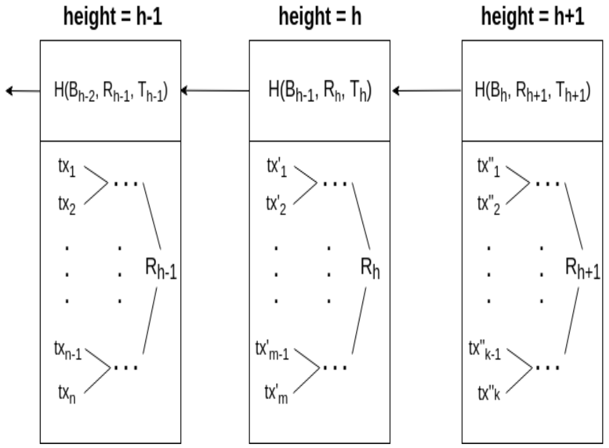

Fig. 2: Blocks with Hash Pointers

This two-layer approach does not compromise consistency between the data maintained by Soteria and the data on the providers' servers, as consistency can always be verified by users on the base-layer public blockchain. Recall that the CAP theorem [12] states that a distributed database system can only satisfy two of the three properties: consistency, availability, and partition tolerance. While the base-layer chain ensures availability and partition tolerance, the side chains ensure consistency and availability. Using a permissioned side chain with a jury pool, Soteria can improve both throughput and latency by limiting the number of juries. Note that public audit is performed on the permissionless main chain. There is a delay between when a transaction is committed on a side chain and when the hash of the side-chain block containing the transaction is written onto the main chain. A user can be informed that her ESA signed with the business has been recorded on a side chain. However, only after the main chain has been updated, the user (or through the user's agent) can verify that the contract has indeed been signed and was not altered. (Inter-chain latency will be discussed in greater details shortly.)

Soteria's ledger requires a consensus protocol since it supports contract revocation. A consensus protocol ensures that all validators agree on a unique order of transactions on the ledger. Note that without this strict access permission and access revocation order requirement, an append-only log suffices to support the decentralized auditability requirement.

There are several types of consensus protocols, each of which enjoys some pros and suffers some cons. An application selects a particular consensus protocol for its desired performance objectives (e.g., latency, throughput, and consistency).

For instance, a protocol that guarantees immediate consistency may trade latency and throughput for achieving the consistency objective. A protocol that requires just weak consistency or eventual consistency can achieve shorter latency and higher throughput[1].

Specifically, the PoX (proof-of-something) family protocols [3], [15], [26], [35] such as Proof-of-Work (PoW), Proof-of-Stake (PoS), and Proof-of-Importance (PoI) offer timely consistency with good network scalability but suffer from high latency and low transaction throughput. On the contrary, the BFT (Byzantine Fault Tolerance) family protocols offer good performance with limited scalability with respect to the number of validators. PoX is thus more suitable for permissionless blockchains (Soteria 's main chain), whereas BFT is more suitable for permissioned blockchains (side chains).

In the remainder of this section, we survey representative BFT consensus protocols including Tendermint [14], Hashgraph [9], HotStuff [41], and Stellar[32]. We summarize in Section III-C a qualitative comparison before presenting our empirical study in Section IV.

A. Blockchain Overview and Terminologies

A blockchain of height H is composed of a sequence of H blocks. Each block h, where $h = 0, \dots, H-1$, in a blockchain contains various numbers of transactions organized into a Merkle tree. The Merkle tree root of the h^{th} block, denoted as R_h, summarizes the information in that block. The h^{th} block, where $h \in [1, \dots, H-1]$ points to its previous block with pointer B_h. (The first block, or $h = 0$ is the genesis block.) $B_h$is the hash of three components: previous block hash B_{h-1}, the Merkle tree root of current block R_h, and some information from the h^{th} block T_h such as timestamp.

B. Base Chain Protocols

Proof-of-something (PoX) protocols aim to support decentralized permissionless blockchains. As mentioned in Section I, Soteria uses a PoX blockchain as its base chain. The choice of a PoX protocol depends on the factors of cost and *inter-chain consistency latency*, which is defined as the time between when a transaction commits on a side chain and when the root of the transaction's Merkle tree is hashed onto the main chain. Inter-chain consistency is different from transaction consistency. The former ensures a consistent public view of transactions for the purpose of decentralized audits, whereas the latter ensures the validity of individual transactions. Transactions committed on a side chain guarantees a consistent local order on that chain. The main chain, however, does not guarantee total order on all the transactions across all side chains. Once Soteria enforces that a contract revocation must take place on the same side chain where the contract was agreed upon and validated, side chain consistency guarantee suffices.

Access revocation transactions take effect within seconds, as a side chain of Soteria can ensure transaction-commit latency to be within seconds. In other words, once a user revokes a prior permission to access her data, her data will be inaccessible within seconds. For the purpose of auditing, Soteria can only guarantee inter-chain consistency within minutes (inter-chain latency), this suffices for the auditing purpose required by regulations[2]. A PoS (proof-of-stake) protocol such as Ethereum satisfies latency in minutes at a relatively low cost (compared to e.g., Bitcoin). Therefore, Soteria uses Ethereum as its main chain.

C. Side Chain Protocols

Byzantine Fault Tolerance (BFT) has a long history with distributed systems [40]. In 1999, [19] implemented "practical" Byzantine Fault Tolerance (PBFT) protocol. PBFT can work in an asynchronous environment, such as the Internet.

PBFT executes in two modes, normal mode and view-change mode. In the normal mode, a leader proposes a candidate value to the other replicas in the pre-prepare phase. PBFT then goes through two successive voting phrases: prepare and commit. If the candidate value is accepted by a replica p_i, as known as a validator, p_i enters the prepare phase and broadcasts a prepare message to others consisting the candidate value. Once p_i collects enough messages, i.e., $2f+1$ messages over $3f+1$ replicas (f denotes the number of Byzantine nodes) and agree on the same value, it enters into the commit phase. In the commit phase, replicas conduct an election similar to the one in the prepare phase to agree that more than $2f$ replicas will write the candidate value into their respective databases. To prevent indefinitely waiting, p_i transitions to view-change if a timeout is triggered. In the view-change mode, replicas start a new view to elect a new leader by sending view-change messages.

The message complexity of BFT/PBFT protocols is between $\mathcal{O}\left(N^2\right)$ and $\mathcal{O}\left(N^3\right)$. Since N, the size of a jury is typically a small set of trusted validators, latency can be managed[3] to be under 10 seconds.

Of late, there are a large number of BFT/PBFT protocols proposed for prioritizing various performance objectives, e.g., safety, fault tolerance, latency, and throughput (e.g., [5], [22], [23], [24], [28], [29], [21], [34], [36], [39].) A comprehensive survey is beyond the scope of this paper.

For the Soteria' side-chain design, we prioritize reliability under different attacks [33] and preservation of CA properties. We select and evaluate four widely deployed and battle-tested BFT protocols known for their reliability: *Tendermint*, *Stellar*,

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[1] All consensus protocols discussed in this paper, in either the family of PoX or BFT/PBFT, observe properties including consistency, safety, liveness, and fault tolerance to an extent. A protocol may prioritize e.g., liveness over consistency (accepting eventual consistency instead of enforcing strong consistency). Which properties enjoy higher priorities and the choice of a protocol may boil down to performance and cost consideration. We assume each protocol works correctly as it specifies and claims. Detailed discussion on the properties observed by individual protocols is beyond the scope of this paper.

[2] E.g., the CCPA announced in January 2020 requires a data holder to respond to an audit request in 45 days.

[3] Unlike that a decentralized protocols must deal with a potentially massive number of nodes, the administrator of a side chain can adjust N to cap its latency.

	Tendermint	**Stellar**	**HotStuff**	**Hashgraph**
Timing Model	Partial Synchronous	Partial Synchronous	Partial Synchronous	Asynchronous
Key Design Goals	Single mode mechanism	Flexible trust	1. Linearity 2. Optimistic responsiveness	High throughput
Fault Tolerance	$\leq \frac{2}{3}$ Voting Power	not available (na)	$\leq \frac{2}{3}$ Voting Power	$\leq \frac{2}{3}$ Voting Power
Message Complexity	$\mathscr{O}\left(N^2\right)$ NA $\mathscr{O}\left(N^3\right)$	na	$\mathscr{O}\left(N\right)$ NA $\mathscr{O}\left(N^2\right)$	$\mathscr{O}\left(N^2\right)$
Scalability	100-$1,000$	na	≥ 100	$\geq 1,000$
Validator Bound	64	43	128	128
Throughput (tx/s)	$4k$	na	$10k$	$\geq 50k$
Latency (s)	5	1.3	10	≥ 10
Hardware Config.	AWS t2.medium	AWS c5d.9xlarge	AWS c5.4xlarge	AWS m4.4xlarge

TABLE I: Consensus Protocols Comparative Analysis. Data Sources: [9], [13], [31], [41]. N denotes # of validators.

HotStuff, and *Hashgraph*. The detailed specifications of these protocols are documented in the appendix. Table I presents a qualitative comparison between these four protocols in eight properties:

1) Timing model: timing assumptions of different models including synchronous, asynchronous, and partial synchronous.
2) Design goals: the primary performance goals that a consensus algorithm was designed to achieve. This provides the contextual information for evaluating a protocol. (A protocol designed for achieving low latency should not be derided for its weaknesses in other performance metrics.)
3) Fault tolerance: the upper bound of faulty nodes (or weighted votes) that can cause system failure.
4) Message complexity: the overall message complexity to commit a block. N denotes the number of validators.
5) Scalability: the number of validators that the consensus protocol claims to allow in the consensus process.
6) Validator bound: the largest number of validators that can participate in a consensus protocol.
7) Throughput: the number of transactions per second that can be committed by the majority of validators under the largest number of validators.
8) Latency: the average delay before a transaction is committed under the largest number of validators.

Table I shows only the performance data under the largest number of validators that a protocol can support given its own hardware configuration and assumptions, documented in their own white papers [9], [13], [31], [41]. In Section IV, we presents our own experiments attempting to do a relatively fair comparison.

Note that Stellar is absent in most of the fields in Table I for two reasons. First, fault tolerance and message complexity are highly correlated with the configuration of each validator on the Stellar network. This flexible configuration makes it difficult to analyze Stellar without knowing its network structure. Second, the work of [31] focuses only on reducing latency and assumes that throughput can be improved by adding hardware. Also note that though Table I does not provide an apple-to-apple comparison, it provides a birds-eye view on representative protocols' characteristics.

IV. EXPERIMENTS

Our experiments were designed to evaluate tradeoffs between latency and throughput under different hardware and software configurations and then devise strategies to improve performance. More specifically, we would like the following questions to be answered:

1) Which protocol(s) can achieve the best performance?
2) What is a cost-effective configuration to support a target throughput and latency performance?
3) Given a required latency, what is the maximum number of validators allowed?
4) What are the side-chain and inter-chain parameters that can be adjusted to achieve desired performance?

Since there is no stable implementation of Hashgraph or Hotstuff[4] to date, we evaluated only the latest versions of Tendermint and Stellar. Note that though we attempt to perform "fair" evaluation on the protocols, it is impossible to achieve absolute fairness due to the fact that engineering quality, parameter settings, and network configurations all can affect experiment results. Therefore, when evaluating the results, we focus on observing trends and patterns to recommend strategies to improve the target performance.

We adopted Tendermint v0.32.1 and Stellar v12.0.0 and deployed them on Google Cloud Platform (GCP). For Tendermint and Stellar, respectively, we created up to 64 validators, and assigned an 8-core Intel(R) Xeon(R) 2.20 GHz CPU with 7.2 GB memory to each validator. Validators were configured into a fully connected topology. To measure realistic network latency, we deployed validators on Google servers in different geographical locations (Taiwan, Singapore, Belgium, and Columbia). Validators were distributed equally to these locations. For example, in the 64-validator implementation, 16 validators were allocated to each of the four geographic locations.

A. Metrics

We define throughput and latency based on an end-user's perspective. Given a set of N validators $V = \{p_1, p_2, \ldots, p_N\}$,

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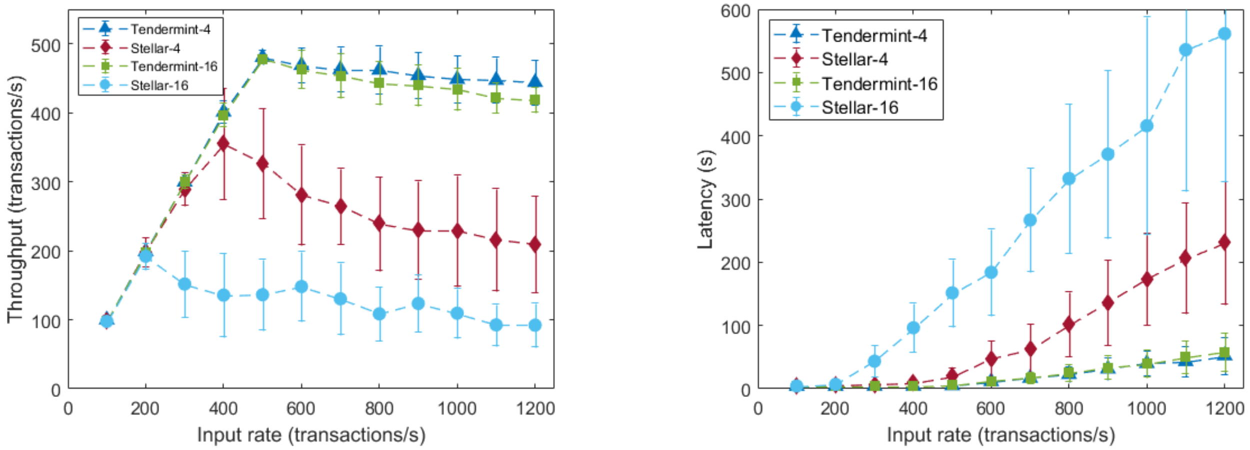
[4] Hashgraph does not provide open-source release. Hotstuff's open-source code is not free of bugs as of Q4 2019 to put into production.



(a) Throughput vs. Input Rate.

(b) Latency vs. Input Rate.

Fig. 3: Performance of Tendermint and Stellar with 4 and 16 Nodes (Validators).

throughput denoted as TPS_{avg} is written as

$$\text{TPS}_{\text{avg}} = \frac{\Sigma_{i=1}^{N} \text{TPS}_{\text{avg}}^{i}}{N}, \tag{1}$$

where $\text{TPS}_{\text{avg}}^{i}$ denotes the average throughput of validator p_i, who owns a sequence of blocks $B^i = \{b_0^i, b_1^i, \ldots, b_H^i\}$. In turn, TPS_h^i (throughput of the $h+1^{th}$ block of validator p_i) is the average throughput of all transactions in that block, which is obtained by the number of transactions in the block divided by the commit interval between b_{h-1}^i and b_h^i, which is denoted as Δt_h^i, or

$$\text{TPS}_{\text{avg}}^{i} = \frac{\Sigma_{h=0}^{H_i} \text{TPS}_h^i}{H_i}, \text{ where } \text{TPS}_h^i = \frac{|T_h^i|}{\Delta t_h^i}.$$

The latency of a transaction is the time between when the transaction is submitted by a client and when the transaction is committed in a block on a side chain, running either Tendermint or Stellar. Each transaction j may encounter different latency measures in V validators' databases, Latency_i^j, $\forall p_i \in V$. We thus denote $\text{Latency}_{\text{med}}^j$ as the median latency of transaction j among all V validators. The average latency of all the T transactions denoted as $\text{Latency}_{\text{avg}}$ can then be written as

$$\text{Latency}_{\text{avg}} = \frac{\Sigma_{j=1}^{T} \text{Latency}_{\text{med}}^{j}}{T}. \tag{2}$$

B. Parameter Settings

Several parameters affect the block commit time, including maximum block size, transaction size, commit interval, transaction weight, and quorum-slice size [13], [41].

- *Maximum block size*. The maximum number of transactions that can be included in a block.
- *Transaction size*. The capacity of a transaction in bytes.
- *Minimal commit interval*. The minimum time increment between consecutive blocks. A minimum commit interval may prolong block commit time if an implementation intends to produce a block whose latency is smaller than the commit interval. However, we assume that a block's latency, which will be no longer than the commit interval, is an acceptable delay.

Max block size	Trans. size	Commit interval
3,000 transactions/ block	212 bytes	5 seconds

TABLE II: Parameter Settings for Tendermint and Stellar.

- *Transaction weight*. The probability of a transaction being committed in a block. All transaction types are given the same frequency in our experiments.
- *Quorum slice*. In Stellar, each validator has its quorum slice [32]. To have a fully connected network for our side-chain experiments, each validator's quorum slice is comprised of the rest of the validators so that all validators join the quorum.

We used the parameter settings listed in Table II to evaluate Tendermint and Stellar.

Both implementations were issued the same workload of a large number of synthetic transactions. To simulate realistic client behavior, we used a separate node to submit transactions to validators continuously. This node sent transactions in different input rates up to 1,200 transactions/s in a round-robin fashion.

C. Side Chain Evaluation

Figure 3 presents the performance of both implementations with 4 and 16 validators (or CPU nodes). (Later in the scalability study, we present performance with a larger number of nodes.) With 4 validators (or nodes), Tendermint and Stellar have nearly the same performance when the input rate is under 300 transactions/s (tps). However, when input rates exceed 400 tps, Tendermint achieves higher throughput and lower latency. The gap between the two protocols widens as the input rate is further increased.

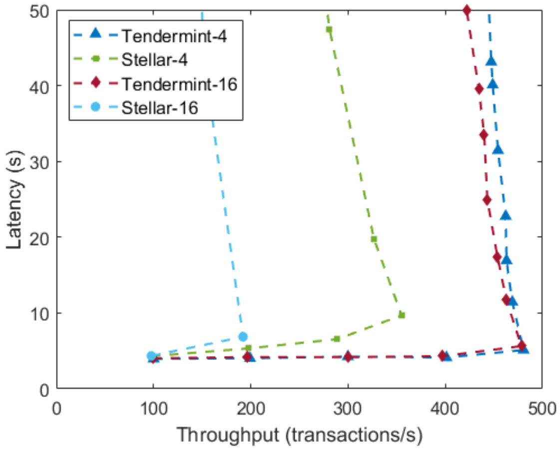
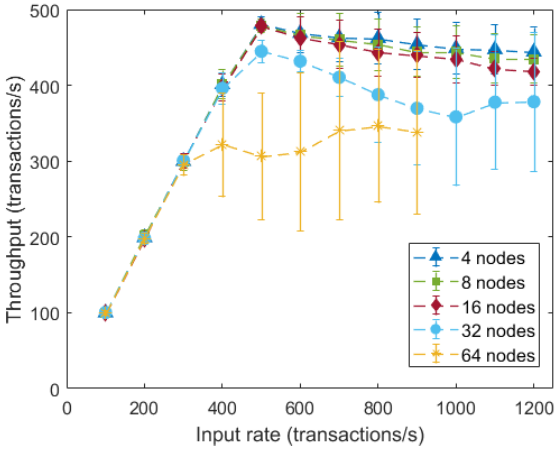
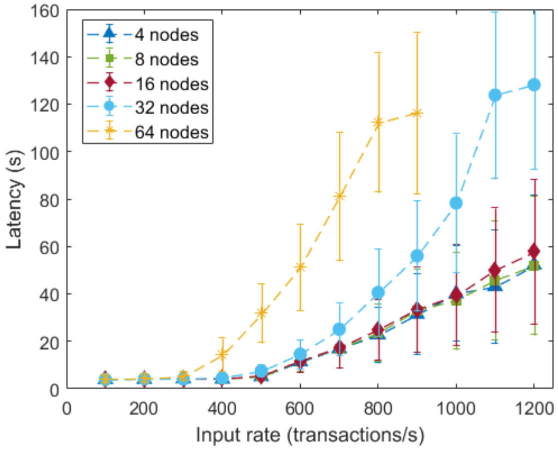


Fig. 4: Throughput vs. latency of Tendermint and Stellar with 4 and 16 nodes. In each dashed line, the consecutive vertices represent the input rate increases, starting from 100 tps and increasing by 100 tps each time.



(a) Throughput vs. Input Rate.



(b) Latency vs. Input Rate.

Fig. 5: Tendermint Performance with 4 to 64 Nodes.

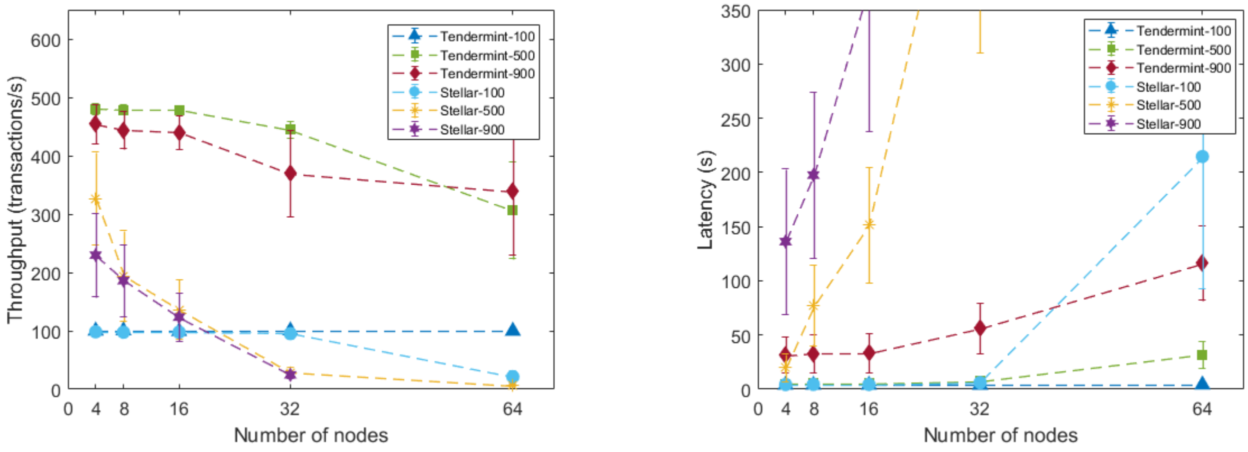
Furthermore, we examine peak performance, which is defined as the highest throughput with the lowest latency. In Figure 4, we plot throughput (x-axis) and latency (y-axis) tradeoff for 4 and 16 validators of Tendermint and Stellar, respectively. The nodes on each line represent the input rates from 100 tps onward by increments of 100 tps. As an example, for Stellar-4 (Stellar with 4 validators), its throughput initially steadily increases from an input rate of 100 to 400 tps, but then begins to degrade as the input rate increases beyond 400 tps. (Throughput starts to degrade when the curve(s) in the figure bends leftward as the input rate continues to increase.) Meanwhile, latency grows rapidly (beyond the upper bound of the figure after input rate is larger than 600 tps) when throughput starts to degrade due to saturation of system resources.

Having confirmed the latency and throughput tradeoff, we further stress Soteria with heavier workload and increase the number of validators to investigate problems and devising remedies. Figure 5 depicts Tendermint's through and latency at input rates increased from 200 to $1,200$ tps. Stellar's performance exhibits the same patterns as Tendermint's, and we do not separately present its data. We report Tendermint vs. Stellar comparison in Figure 6.

From Figure 5[a], we observe that the throughput of Tendermint eventually saturates after the input rate has reached the capacity of the system. Throughput degradation occurs at a lower input rate when the number of validators are larger. The degradation point of 16-node Tendermint is at input rate 450 tps, while the degradation point of 64-node configuration starts at 250. Figure 5[b] depicts latency versus input rate. At the same input rate when throughput starts to degrade, the latency of Tendermint also increases drastically. For smaller configurations from 4 to 16 nodes latency reaches 50 seconds at input rate $1,200$, whereas for larger configurations 32 and 64 latency reaches two minutes.

It is expected that system capacity eventually limits throughput and latency. To improve overall Soteria throughout at a guaranteed level of latency, we can configure an up to 32-node side chain with an admission control that limits the input rate to be under 450 tps. This configuration can support throughput up to 450 tps with 10-second latency. As we mentioned in Section III-C, Soteria can spawn multiple independent side-chain instances to improve throughput, while maintaining the same latency. When the overall throughput requirement is higher than 450, Soteria can configure another 32-node side chain to satisfy throughput scalability at the same latency.

Another avenue to simultaneously improve both latency and throughput is to use a small set of validators. This small jury approach is safe only if all validators are trusted and their systems highly secured and independently operated (in terms of system failure and security breach). One example scenario is in patient-data sharing. If a jury pool consists of the NIH, a small number of reputable hospitals and non-profit organizations, the jury pool can be trusted though small.



(a) Throughput vs. # of Nodes.

(b) Latency vs. # of Nodes.

Fig. 6: Performance of Tendermint vs. Stellar at Input Rates 100, 500, and 900.

D. Two-Layer End-to-End Evaluation

We have this far evaluated side-chain performance with two consensus protocols. We next examine Soteria's end-to-end performance with the main chain running the Ethereum protocol and one side chain running the Tendermint protocol.

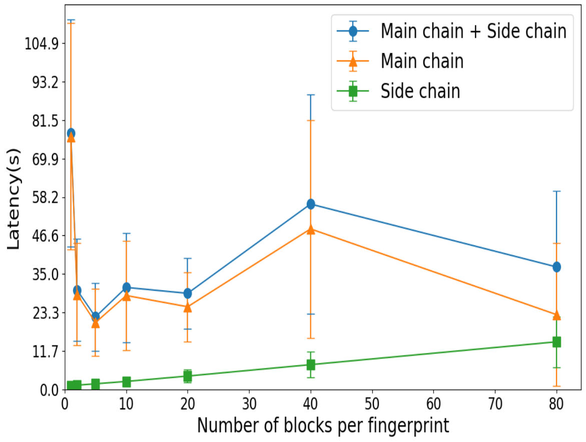


Fig. 7: Latency vs. Blocks per Fingerprint.

Soteria collects on the side chain a number of blocks, each consists of a number of executed transactions, and then writes the fingerprint (or hash) of the blocks onto the main chain. The question is how many blocks on the side chain should be bundled to hash onto the main chain?

At first glance, higher frequency of inter-chain updates lowers the transaction latency. Our experiment, however, shows otherwise, as the bottleneck is on the main chain, not side chains. We will explain why the latency incurred on the main chain does not practically affect the design goals of Soteria after the experimental results are presented.

Figure 7 depicts that when the number of blocks per fingerprint is small (on the x-axis) or the inter-chain update rate is high, the end-to-end latency of Soteria can be as long as two minutes. The figure shows that this long latency is caused by the main chain, not by the side chains. The reason is that a public chain such as Ethereum is shared by many third parties, and the main chain's policy cannot be adjusted by Soteria. With high inter-chain update frequencies, Soteria can overload the main chain and cause lengthened delay.

When we reduce the inter-chain update rate to be once every 10 blocks or more, the latency is much reduced and stable (with a low variance). High update rates increase not only latency, but also cost, because the public main chain collects fees based on the number of updates. Soteria thus should set an update rate that can balance latency and cost.

E. Key Takeaways

From the results, we make the following observations:

- The Main chain must be decentralized for transparency to satisfy the provability of compliance with privacy regulations. Side chains can each independently run its own selected BFT/PBFT protocol and inter-operate with the main chain.
- The main chain's latency could be a performance bottleneck. Nevertheless, the purpose of the main chain is for public auditing, and a latency of minutes and even hours is acceptable by CCPA and GDPR user-privacy regulations. Moreover, the ATS module of Soteria can cache pending main-chain requests to perform first a fast audit and then later a confirmation once the main chain has hardened the side-chain's block hash.
- Side chains are permissioned and private, they can deploy BFT/PBFT protocols with a small jury pool to reduce latency. Transaction latency on side chains can thus be kept below ten seconds with an admission control. Throughput can be improved by spawning additional side-chain instances.

- Inter-chain update frequency can be dynamically adjusted depending on the workloads on both the main chain and side chains to balance between latency and cost.

V. CONCLUSION

This paper presented Soteria, consisting of a user right management system (URM), a distributed ledger (DLT), and a auditing service (ATS) to support provable, auditable and scalable data governance. To protect consumer rights of privacy and to comply with data-privacy regulations, we design Soteria to fulfill the functional requirements of consent, record keeping, and transparency (for auditing). We presented the architecture of Soteria, its functional specifications, and protocol choices for its base chain and side chains. On protocol selection, we qualitatively evaluated four algorithms and experimented with two readily deployable protocols Tendermint and Stellar. From studying the experimental results, we recommend side-chain and inter-chain configuration strategies to improve both latency and throughput.

Soteria cannot prevent a business from unlawfully distributing user data to a third party. However, when suspicion arises, Soteria can help validate data ownership, prove absence of user consent, and provide a list of potential unlawful distributors to facilitate an investigation. IP and data privacy protection involves substantial legal knowledge. Soteria shows that it is technically feasible to develop a scalable and public auditable distributed ledger. For additional challenges in judicial procedures to prove data rights please consult [27], [38].

Our future work will address various performance optimization issues that will arise with URM and DLT. Three specific topics are:

- SQL optimization. In Section II-C, we note that the SQL query, while correct, might not be very efficient, as it includes at least one clause for each owner of the data in the database. In our experience, this is sufficient, as in practice the same sharing agreement is used by many different consumers, so clauses can be unified when the query is constructed. As consumers' preferences become more fine-grained, this might not be the case. Future work should investigate an optimization algorithm or an index structure suitable to queries of this form, so that both performance and formal correctness can be maintained.
- Inter-chain protocol optimization. How often side chains should hash a block onto the main chain affects Soteria's latency and throughput. While Soteria may have full control on the parameters of its side chains, the main, public chain (such as Ethereum classic) can be shared with other applications. Soteria should look into dynamic adjustment policies on its side-chain block size and hash (to the main chain) frequency.
- Interoperability with native access control policies. Most companies have had their own access control policies and/or tools. For instance, Zelkova [8] developed by AWS is an SMT-based (Satisfiability Modulo Theories) reasoning tool for analyzing security/privacy policies and their risks. We will investigate how Soteria can complement existing tools.

VI. ACKNOWLEDGEMENT

We would like to thank professor David Mazières (Department of Computer Science, Stanford University) for his insights on Stellar consensus protocol and valuable comments and suggestions to this work.

APPENDIX A — PROTOCOL SURVEY

Since BFT/PBFT family protocols meet CA properties and performance requirements of Soteria's side chains, we survey four representative protocols belonging to this family.

1) Tendermint: Tendermint is a leader-based BFT approach that does not conduct leader selection, aiming to reduce the number of communication IOs. Unlike PBFT which is composed of two modes, normal mode and view-change mode, Tendermint can frequently change leaders (proposers) and make consensus progress under a single mode by using a predefined leader selection function. In a nutshell, the idea of Tendermint to embed view-change mode into normal mode in PBFT. With this idea, Tendermint reduces the communication complexity by an order of magnitude compared to PBFT: from $\mathscr{O}\left(N^3\right)$ in PBFT to $\mathscr{O}\left(N^2\right)$, where N denotes the number of validators.

For a new block, validators go through several *rounds* utill they reach a consensus on that block. Each round consists of four phases, *propose*, *prevote*, *precommit*, and *commit*. Tendermint's voting process is the same as PBFT's, in which each validator collects votes from the others between *propose* and *prevote* phases and between *precommit* and *commit* phases. Let f denote the number of Byzantine fault nodes. When over $N-f$ of the same vote have been collected by a validator, the validator switches from the first phase to the second phase. Furthermore, Tendermint implements the following three functions to ensure safety and liveness properties.

1) *Predefined leader selection function*. At the beginning of a new round (propose phase), validators choose a new leader with this function, which is weighted round-robin against these validators' voting power.
2) *Timeout function*.
   As a partially synchronous model, Tendermint triggers a timeout in between every two phases if a validator cannot receive enough votes within a specified duration. This timeout prevents a validator from waiting forever. To adapt to network delay, Tendermint uses a timeout function $timeout\left(r\right) = timeout\left(r-1\right) + r * \Delta$, where r is the round number and Δ is a configurable constant. The initial timeout value ($r = 0$) is set by a configurable constant. When a timeout occurs, a new round starts with a longer timeout value.
3) *Voting lock mechanism*. To validate a block, each validator maintains two values, a *locked value* and a *valid value*. If a validator p_i sends a *precommit* message with a valid v value ($v \neq nil$), it locks v as its locked value. If a validator p_i receives $N-f$ *prevote* messages with

the same valid value v, it updates its valid value with v. Also, if the proposer already has had a valid value, it proposes only this value to other validators. That valid value is regarded as the most recent possible value. Once a locked value $v_{locked,i}$ is updated by p_i in round r_l, it can only vote for $v_{locked,i}$ in the following rounds unless validator p_i receives a valid value $v_{valid,j}$ from the new proposer p_j and satisfies $r_k > r_l$, where r_k is the round where p_j updated its valid value to $v_{valid,j}$. Validator p_i can unlock $v_{locked,i}$ and vote for $v_{valid,j}$ in the *prevote* phase.

The intuition of Tendermint is that at block h at least one correct validator p_i proposed $v_{valid,i}$ in round rl is acceptable by $N-f-1$ correct validators. In addition, given any of these $N-f-1$ correct validators p_j and its locked value $v_{locked,j}$ in round r_k, one of the following two conditions is always satisfied, $v_{valid,i} = v_{locked,j}$ or $r_l > r_k$. This means that every correct validator can always send *precommit* message with $v_{valid,i}$ in the same round and commit a block on block h. Therefore, correct validators can always commit the same valid value, and hence guarantees the safety property [14]. Besides, contrary to PBFT, adapting these mechanisms does not require forwarding additional information (e.g., sending $N-f$ valid check point messages) to the new proposer.

Tendermint also can be improved by using threshold signatures [41] for reducing message complexity to improve the scalability. In addition, the protocol has been proven to achieve fairness under certain conditions [6]. However, since each change of leader requires waiting for a known upper bound of the network delay, which may exceed the maximum actual network delay, Tendermint does not enjoy *optimistic responsiveness* defined in [37].

The pros and cons of Tendermint are:

- Pros: With a small jury of trusted validators, Tendermint achieves low latency with safety.
- Cons: Its number of communications is larger than the other protocols, and therefore, the size of a jury cannot be too large. This makes Tendermint a good protocol for DataXchange's side chains, but not desirable to be its main chain.

2) Stellar: The Stellar consensus protocol (SCP) is composed of two protocols, the *nomination* protocol and *ballot* protocol. These protocols reach a consensus by using federated voting, which supports flexible trust. With flexible trust, users can choose any parties they trust to join the consensus process without a central authority.

More formally, every validator can select a set of validators to establish a quorum slice. For example, validator p_i selects a set of validators denoted as L to form quorum slice $QS_{(i,L)}$. Validator p_i can create multiple quorum slices, or $S_i = \{Q_{(i,L_1)}, QS_{(i,L_2)}, \dots, QS_{(i,L_n)}\}$. A quorum slice is defined as a set of validators sufficient to reach an agreement.

SCP assumes *quorum intersection* in that two quorum slices share at least one well-behaved node. SCP is a leaderless PBFT protocol, and it does not have the *pre-prepare* phase. However, SCP adds an *accept* phase to PPBFT to design its *federated voting* scheme to reach global consensus. Thus, federated voting includes three phases following the order of *prepare*, *accept*, and *confirm*.

1) *Prepare*. Once a new instance v has been created, p_i sends a message with value v to whomever trusts p_i. Once p_i votes for v, it will not vote for other values.
2) *Accept*. Validator p_i receives messages from the validators in its quorum slices QS_i. Validator p_i can change its voted value in the *prepare* phase if the majority of p_i's *blocking set* vote for another value v' in the *prepare* phase. Otherwise, p_i still stands for the value v it voted in the *accept* phase. The *blocking set* of p_i, B_i, is defined as: for each quorum slice of p_i, $QS_{(i,n)} \in QS_i$, such that $\forall QS_{(i,n)} \cap B_i \neq \emptyset$, which means B_i contains at least one node in every quorum slice of p_i.
3) *Confirm*. p_i broadcasts the value that it voted in the *accept* phase, thereby committing to that value.

The reason for the *accept* phase is that if the value voted by a validator in the *prepare* phase is different from the value voted by the majority of its neighbors, the neighbors can convince the validator to accept the other value. Therefore, although the SCP network structure can be configured the same as that of PBFT, SCP does not request a validator to commit a block with $N-f$ of the same votes in any phases. Instead, validator p_i only conveys messages to those who list p_i in their quorum slices.

In summary, SCP provides users with the flexibility to make their own quorums, and its use of federated voting can lead to consensus and enjoy the safety property based on the assumptions listed in the white paper [32]. These assumptions may limit the freedom of network extension, since validators require adequate settings of quorum slices.

The pros and cons of SCP are:

- Pros: First, users have the privilege of selecting quorum slices composed of parties that they can trust. Second, based on the BFT-based protocol, SCP achieves low latency with safety.
- Cons: Setting up quorum slices may introduce network structure errors.

3) HotStuff: HotStuff is a leader-based BFT protocol in partial synchronous settings for reaching consensus. HotStuff is a four-phase consensus protocol including *prepare*, *pre-commit*, *commit*, and *decide*. (For details of these phases please refer to [41].) HotSuff fulfills two properties: linearity and optimistic responsiveness:

- *Linearity*. The consensus algorithm has a linear communication complexity for committing a block in one round. Two scenarios must be considered. First, if a designated proposer (leader) is correct, the proposed block only takes $\mathcal{O}(N)$ messages (N was defined as the number of validators) to be committed by the majority. Otherwise, a new proposer must be elected, known as view-change as defined in Section III-C, in the limit of $\mathcal{O}(N)$ messages as well. In the worst case, the total communication cost

is $\mathscr{O}\left(N^2\right)$ for at least f ($f \propto N$) times proposer selection. We will shortly explain how this linearity is achieved by HotStuff.
- *Optimistic responsiveness.* Any correct proposer p_i only has to wait for a delay of $N-f$ messages to ensure that the candidate value v that p_i proposed can be committed (in view change mode). This message delay is independent of the known set upper bound δ on the network's delay [37].

HotStuff uses two techniques to achieve the *linearity* property. First, it adopts a simpler message transmission pattern. Instead of letting each validator broadcast messages to the others in any consensus phases, HotStuff makes all validators send signed messages to a designated leader. Then the leader integrates messages into an agreement. If $N-f$ validator agree on the same content, the result is broadcast to the other validators to be voted on in the next phase.

Second, HotStuff employs the *threshold signature* scheme to reduce the message complexity. To verify whether an agreement broadcasted by the leader is actually signed by validators, the message should contain $N-f$ valid messages signed by validators. These $N-f$ attached signatures incur $\mathscr{O}\left(N^2\right)$ communication complexity in the consensus process. However, with the threshold signature technique, an agreement which only carries one signature can be verified by validators. With these two schemes, HotStuff can satisfy linearity.

In the threshold signature scheme, all validators hold a common public key PUB, but each validator denoted as p_i owns a distinct private key PRI_i. A threshold signature ρ can be defined as: $\rho \leftarrow combine(m,S)$, where $S = \{\rho_i \mid p_i \in V\}$, V is the set of validators where $|V| = N$, and $|S| \geq N-f \wedge \rho_i \leftarrow sign(m,PRI_i)$ where $sign(m,PRI_i)$ means validator p_i signs the message m with its private key PRI_i to create the partial signature p_i.

Two trade-offs are made in order to achieve linearity. First, compared to three-phase protocols, HotStuff adds an additional phase to each view, which causes a small amount of latency [41]. Second, the threshold signature can cost more computational resources. Taking Rivest–Shamir–Adleman (RSA) based implementations of threshold signature schemes as an example, given a (t,n) threshold signature scheme, at lease t or more participants in a group of size is n can generate a valid signature collaboratively. According to the work of [25], the computation complexity can range from $t \times T_{RSA}$ to $3t \times T_{RSA}$ for an individual signature generation and verification, depending on the feature design choices. (T_{RSA} represents the time for computing exponent in an RSA-type scheme.) Also, in Elliptic curve based implementations, generating an individual signature still requires t times of T_{EC}, the time for computing a Elliptic curve [20]. In HotStuff, (t,n) is (f,N), which means that the threshold signature scheme could cost f times of RSA-type schemes or Elliptic-curve-type schemes.

The pros and cons of HotStuff are:

- Pros: HotStuff optimizes the message complexity. Chained HotStuff also simplifies the algorithm and allows for more frequent leader rotation.
- Cons: HotStuff adopts a more sophisticated cryptography mechanism, which takes longer time to reach a consensus, compared to RSA-type schemes or Elliptic-curve-type schemes.

4) Hashgraph: The Hashgraph consensus protocol (HCP) is a BFT solution in a completely asynchronous model. HCP consists of a hashgraph data structure, a *gossip about gossip* data-transfer algorithm, and a *virtual voting* mechanism. We describe these components as follows.

- *Hashgraph.* A hashgraph is a directed acyclic graph (DAG). Each validator maintains a local copy of the hashgraph. A graph node is known as an *event*, which records a timestamp, transactions, and two pointers, one pointing to *self-parent* event and the other to *other-parent* event. Creating a new event can be regarded as proposing a new candidate value.
- *Gossip about gossip.* Gossip about gossip is a process of synchronizing two validators' local hashgraph. Validator p_i randomly selects a peer p_j to transfer events that p_j does not known yet. Validator p_j only accepts events with valid signatures and places those events on its hashgraph. Finally, p_j creates a new event e whose pointers link to both p_i and p_j. Event e also indicates the fact that p_i has shaken hands with p_j.
- *Virtual voting.*
  The virtual voting process is similar to the process of PBFT in the normal mode. If validator p_i verifies the transactions wrapped in event e_{t-1} to be valid, validator p_i creates a new event e_t and points e_t to e_{t-1}. Event e_t will be transferred when the next round of gossip about gossip process starts. Otherwise, p_i drops e_{t-1}. From validator p_j's view, if e_t has been sent to $N-f$ validators, HCP defines that p_j can strongly see e_{t-1}. The concept of 'strongly seeing' is similar to 'going to the next phase' in PBFT. Moreover, there are two voting rounds, just like prepare and commit, to confirm events. Therefore, every validator has to send each voting message to other validators directly or indirectly, which means the message complexity is still $\mathscr{O}\left(N^2\right)$
- *Coin flip.* According to the FLP impossibility, it is impossible for a consensus algorithm running on an asynchronous network to achieve both safety and liveness under node failure [23]. Therefore, to avoid the impossibility in an asynchronous model, Hashgraph consensus protocol adopts randomized algorithm by allowing validators to flip coins. That is, a validator periodically votes pseudorandomly depending on the middle bit of signatures of events. Furthermore, validators do not broadcast coin-flip results since they can tally votes based on their local copies.

In HCP's white paper [9], the safety property is proofed. For liveness, HCP guarantees only termination of all non-faulty processes with probability one in its asynchronous model. However, there is no upper bound of time to reach a consensus. In addition, a local coin-flip protocol such as Ben-Or [11] requires exponential expected time to converge in the worst case [7]. Therefore, if Byzantine nodes manipulate the gossip protocol and it takes validators numerous rounds to reach consensus, the transaction latency can suffer a great deal.

The pros and cons of Hashgraph are:

- Pros: The message complexity is reduced by an order compared to PBFT. With a small-scale network, HCP can achieve low latency.
- Cons: Latency can be long in a large-scale network.

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