Saguaro: Efficient Processing of Transactions in Wide Area Networks using a Hierarchical Permissioned Blockchain

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Abstract

The next frontier for the Internet leading by innovations in mobile computing, in particular, 5G, together with blockchains’ transparency, immutability, provenance, and authenticity, indicates the potentials of running a new generation of applications on the mobile internet. A 5G-enabled blockchain system is structured as a hierarchy and needs to deal with different challenges such as maintaining blockchain ledger at different spatial domains and various levels of the networks, efficient processing of cross-domain transactions, establishing consensus among heterogeneous nodes, and supporting delay-tolerant mobile transactions.

In this paper, we present Saguaro, a hierarchical permissioned blockchain designed specifically for Internet-scale mobile networks. Saguaro benefits from the hierarchical structure of mobile network infrastructure to address the aforementioned challenges. Our extensive experimental results demonstrate the high potential of Saguaro being the first 5G-enabled permissioned blockchain system in the community.

1 Introduction

Blockchain, originally devised for Bitcoin \(^{47}\), is a distributed data structure for recording transactions maintained by nodes without a central authority \(^{15}\). Permissioned blockchains, which target for commercial uses among a set of known but untrusted enterprises, are getting increasing traction across a wide spectrum of applications, e.g., cross-border payments \(^{29}\), patient data exchange \(^{51}\), and supply chain assurance \(^{66}\), in recent years.

The unique features of permissioned blockchains such as transparency, provenance, fault tolerance, and authenticity, are appealing to various distributed applications, however, their scalability remains a major challenge. Partitioning the data into multiple shards that are maintained by different subsets (i.e., clusters) of nodes is a proven approach to improve the scalability of distributed databases, e.g., Spanner \(^{18}\), and has been used in permissioned blockchain systems. Nevertheless, processing cross-shard transactions especially in wide area networks is challenging. Sharding techniques follow either a decentralized flattened approach, e.g., SharPer \(^{5}\) \(^{3}\), or a centralized coordinator-based approach, e.g., AHL \(^{19}\) to process cross-shard transactions. In the flattened approach, nodes of all involved shards participate in the consensus protocol, thus, if the involved shards are geographically far apart, the network distance results in high latency. Similarly, in the coordinator-based approach, since a single coordinator (a node or a cluster of nodes) processes all cross-shard transactions, the coordinator likely has a far network distance to either the shards or the clients, depending on where the shards are placed (close to the clients vs close to the coordinator). In either scenario, the performance of the system will be severely impacted. To reduce the latency of global communication, i.e., multiple rounds of cross-cluster message exchange, GeoBFT \(^{30}\) \(^{31}\) \(^{32}\), replicates the entire ledger on every node and establishes consensus on each transaction within only a single cluster. Clusters, however, communicate with each other to multicast their locally-replicated transactions and enable other clusters to
update their ledgers and execute transactions. Such cross-cluster communications for every single transaction results in high latency.

In the past few years, in the mobile computing world, there is an increasing trend towards infrastructures that are geared towards the edge and peer-to-peer computing. This is best epitomized by 5G, the fifth generation technology standard for cellular networks, that has attracted extensive research interest and industry adoption. 5G’s unique characteristics include very low latency, ultra-high reliability, device to device communication, and increased network capacity and connectivity. 5G networks are cellular networks, in which the service area is divided into small geographical areas (spatial domains). A typical 5G network infrastructure is hierarchical — from edge devices, edge servers, fog servers, to cloud servers.

The hierarchical infrastructure of wide area networks enables the efficient processing of transactions over wide area networks. First, since transactions are initiated and initially processed within lower-level domains, i.e., edge devices and edge servers, the load on the internal domains, e.g., cloud servers, is reduced, which is suitable for 5G and edge networks. Second, for each cross-domain transaction, the internal domain with the minimum total distance from the involved edge domains, i.e., the lowest common ancestor of all involved domains, can be chosen as the coordinator, using the coordinator-based approach. Finally, the hierarchical structure of the network enables optimistic ordering of transactions where each involved domain independently orders cross-domain transactions and higher-level domains validate the commitment of transactions.

While 5G suffers from trust and secure interoperability among sub-networks, immutable and decentralized blockchains enable distributed communication with high security and trustworthiness [59]. Building an Internet-scale hierarchical permissioned blockchain that can support mobile applications, however, is challenging. We highlight some of the challenges below:

**Maintaining Hierarchical Ledgers.** A blockchain ledger used to be a flat append-only data structure shared among all entities. A hierarchical blockchain in contrast requires maintaining ledgers from different domains at different levels of the hierarchy. However, maintaining the full ledger of different child nodes and preserving ordering dependency between transactions of different domains (resulting from cross-domain transactions) are challenging.

**Heterogeneous Nodes.** Nodes in different domains might follow different failure models, i.e., crash or Byzantine. Moreover, the system needs to process transactions even when the edge devices do not trust the edge servers (e.g., traveling abroad) or when the connection to the edge servers is unavailable (e.g., in rural areas).

**Edge Node Mobility.** Edge devices may transiently or persistently move across the spatial domains. Furthermore, a transaction may be started by a mobile node in one domain, buffered, and then committed by the same node once it reaches another domain.

In this paper, to address the above challenges, we present Saguaro, a hierarchical permissioned blockchain system designed specifically for wide area networks. In Saguaro, nodes are organized in a hierarchical structure following the wide area network infrastructure from edge devices to edge, fog, and cloud servers where nodes at each level are further clustered into fault-tolerant domains. Saguaro processes cross-domain transactions efficiently by either enabling an optimistic ordering of transactions or relying on the lowest common ancestor of the involved domains (i.e., a higher level domain with minimum total distance from the involved domains), resulting in lower latency. Saguaro is also able to process delay-tolerant transactions that are initiated by mobile devices. Specifically, Saguaro makes the following three key technical contributions:

- **DAG-Structured Summarized Views.** The hierarchical structure of Saguaro enables internal domains to not maintain the full information but just a summarized view (e.g., selected columns or aggregated values) resulting in higher performance and enhanced privacy. In addition, while ledgers at the lower-levels are formed as linear chains for consistency, maintaining cross-domain transactions result in ledgers structured as directed acyclic graph at the internal domains to capture dependencies.

- **Heterogeneous Consensus.** Saguaro provides a suite of consensus protocols to process transactions within and across domains with crash-only or Byzantine nodes. Saguaro benefits from the hierarchical structure of wide area networks to establish consensus on cross-domain transactions. The consensus protocols are hierarchy-aware and geographically optimized.

- **Delay-tolerant Mobile Consensus.** Saguaro supports mobility of nodes by providing delay-tolerant mobile consensus where edge devices can initiate transactions in different (spacial) domains.
We validated these technical innovations by developing a prototype of Saguaro, where our evaluation results across a wide range of workloads demonstrate the effectiveness of Saguaro in scalably support a range of cross-domain and delay-tolerant transactions.

The rest of this paper is organized as follows. Section 2 discussed the background and motivates Saguaro by several possible applications. The Saguaro model is introduced in Sections 3. Section 4 and Section 5 present transaction processing in Saguaro. Section 6 evaluates the performance of Saguaro. Section 7 discusses related work, and Section 8 concludes the paper.

2 Background

We motivate Saguaro, first through technology trends and opportunities enabled by 5G, followed by new applications that arise from these innovations.

2.1 Edge Computing and 5G

5G is the fifth generation of cellular network technologies developed in response to meet the growing demand for a variety of new services such as autonomous vehicles and massive IoT. Using different technologies such as the millimeter-wave spectrum, massive multiple-input and multiple-output, and network slicing, 5G aims to provide high data rates, coverage, connectivity, and bandwidth, with a massive reduction in latency and energy consumption. 5G, in addition, provides device-to-device (D2D) communication that enables edge devices to communicate directly with each other. The D2D communication accelerates the development of edge-centric applications [43] and also enables edge devices to establish consensus among themselves to process transactions. Processing transactions by edge devices and independent of edge servers is needed due to the lack of trust or connectivity between edge devices and edge servers or to offload traffic from edge servers.

5G networks are cellular networks, in which the service area is divided into small domains. In a 5G structure, machines (i.e., devices, servers) are organized in a hierarchical structure where at the leaf level, edge devices, e.g., smart cars, smartphones, within a local area (i.e., a spatial domain) are connected to each other and to an edge server (as the parent vertex). Nearby edge servers (e.g., campus area) are then connected to a fog server (e.g., metropolitan area) and finally, at the root level, cloud servers are placed. The network might include different layers of edge, fog, or cloud servers, i.e., the hierarchy might have more than four layers. Furthermore, to provide fault tolerance, each vertex of the hierarchy, e.g., edge, fog, or cloud servers, consist of a set of nodes, called a domain.

2.2 Blockchain and 5G: Applications

We envision permissioned blockchain as a promising technology to realize the full potential of 5G. Permissioned blockchains over the 5G network can enable many new applications. We show how different distributed applications benefit from a hierarchical blockchain system and discuss the aforementioned challenges in each application.

Accountable ride-sharing and 5G-enabled gig economy. In the ridesharing applications, drivers give rides to travelers through platforms, e.g., Uber, Lyft, and Curb. Participants in ridesharing environments, however, require to satisfy global regulations, e.g., the total work hours of a driver, who might work for multiple platforms, may not exceed 40 hours per week to follow the Fair Labor Standards Act [6]. As another example, California Proposition 22 challenges Assembly Bill 5 (AB5) by imposing its own set of regulations, e.g., if a driver works at least 25 hours per week, platforms are required to provide healthcare subsidies. The transparency of blockchains helps in verifiability of global regulations [6]. Ride-sharing applications also deal with the mobility of edge devices (i.e., cars) across spatial domains (e.g., a ride from JFK to Manhattan involves multiple edge servers). A 5G-enabled hierarchical permissioned blockchain system can exactly fill the bill by supporting cross-domain transactions. Moreover, while lower-level domains

1. https://www.dol.gov/agencies/whd/flsa
2. https://ballotpedia.org/California_Proposition_22,_App-Based_Drivers_as_Contractors_and_Labor_Policies_Initiative_(2020)
3. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB5
maintain the full record of transactions, an abstract version of records, e.g., the travel time (i.e., working hour) attribute, of each transaction is sufficient to be maintained by internal domains resulting in improved performance and enhanced privacy. Furthermore, nodes within a leaf domain are able to establish consensus on the ridesharing tasks using 5G’s D2D communication in order to assign drivers to tasks. Beyond ridesharing, the ability to add accountability and verifiable global statistics collection at Internet-scale can be generally applied to any other mobile 5G-enabled gig economy jobs.

**Mobile delay-tolerant micropayments.** Most popular micropayment infrastructures do not allow users to do cross-application payments, e.g., an Apple Pay sender cannot send money to a PayPal receiver. However, a 5G-enabled permissioned blockchain system can enable so. For micropayments under the same spatial domain and the same application domain (e.g., Alice pays Bob at a coffee shop, both using Apple Pay), transactions can be committed efficiently and securely by offloading most part of the transactions (e.g., consensus) to 5G’s D2D communications framework and propagating the consensus results (possibly an abstract version) to the ledger at a higher level. For micropayments under the same spatial but different application domains (e.g., Alice pays Bob in the same coffee shop, but Alice is using Apple Pay while Bob is using PayPal), transactions can be executed efficiently if each edge server hosts ledgers from different payment companies and executes the cross-domain transactions at the edge. For micropayments that cross spatial and application domains (e.g., Alice in the West pays Bob in the East), transactions can also be executed efficiently when ledgers are deployed in the entire wide-network hierarchy but (cross-domain) consensus is established only among the involved domains. The system needs to support the mobility of nodes as well.

**Resource management and provisioning.** As mobile devices and Internet-of-Things (IoT) devices scale to permeate the Internet, security concerns will become increasingly important as IoT devices can be easily compromised if software updates are not done. An example of a security attack is denial-of-service (DoS) attacks. One promising application for blockchain technology is doing resource provisioning over the Internet. This can come in the form of provisioning network resources for quality-of-service (QoS) traffic or provisioning against over usage of networks that lead to DoS attacks. Given that network resources are shared across multiple entities, one can use blockchain as a tamper-evident logging mechanism to track and enforce network resource utilization of edge devices and service providers in a hierarchical manner.

**Secure network slicing.** Within the core of the 5G network, network services can be broken into several private slices, one for each tenant. Network services are deployed as virtualized network functions that are replicated across nodes for fault tolerance. These network functions can leverage blockchains to provide tamper-evident communication and cross-domain transactions in the cloud [74].

3 System Model

Saguaro is a permissioned blockchain system designed specifically to achieve high performance in wide area networks. In this section, we present the infrastructure and the blockchain ledger of Saguaro.

3.1 Saguaro Infrastructure

Saguaro is a distributed system consisting of edge devices, edge servers, fog servers, and cloud servers, organized in a hierarchical tree structure. Each vertex of the tree, called a domain, further consists of a
sufficient number of nodes to guarantee fault tolerance. Nodes within each domain follow either the crash or Byzantine failure model. In the crash failure model, nodes may fail by stopping, and may restart, whereas, in the Byzantine failure model, faulty nodes may exhibit arbitrary, potentially malicious, behavior. Crash fault-tolerant protocols, e.g., Paxos [40], guarantee safety in an asynchronous network using \(2f + 1\) crash-only nodes to overcome \(f\) simultaneous crash failures while in Byzantine fault-tolerant protocols, e.g., PBFT [16], \(3f + 1\) nodes are usually needed to guarantee safety in the presence of \(f\) malicious nodes [11]. Figure 1 presents a sample 4-layer Saguaro infrastructure consisting of 11 domains where domains have heterogeneous failure models. For example, \(D_{31}\) includes 4 Byzantine nodes \((3f + 1\text{ where } f = 1)\) while \(D_{14}\) consists of 5 crash-only nodes \((2f + 1\text{ where } f = 2)\).

The hierarchy is globally known by all nodes and the network as well domains are reconfigurable, e.g., nodes can be added, as long as the domains are still fault-tolerant. Edge devices are also authenticated by corresponding edge servers (height-1 domains) using their unique device ids. The system uses point-to-point bi-directional communication channels to connect nodes. Messages across domains have to be relayed via high-level parent/child links. Network channels are pairwise authenticated to guarantee that a malicious node cannot forge a message from a correct node. Furthermore, messages contain public-key signatures and message digests [16]. A message digest is a fixed-length numeric representation of the contents of a message produced by collision-resistant hash functions. Message digests are used to protect the integrity of a message and detect changes and alterations to any part of the message. We denote a message \(m\) signed by node \(r\) as \(\langle m \rangle_{\sigma_r}\) and the digest of a message \(m\) by \(\Delta(m)\). Saguaro also uses threshold signatures [61] [14] in domains consisting of Byzantine nodes to reduce the quadratic communication cost of consensus among Byzantine nodes. In a \((k,n)\)-threshold signature scheme, a single public key is maintained by all nodes within a domain and each of the \(n\) nodes holds a distinct private key. In this paper, we use a threshold of \(k = 2f + 1\) (since each Byzantine domain includes \(n = 3f + 1\) nodes). For signature verification, we assume that all nodes have access to the public keys of all other nodes. We also assume that a strong adversary can coordinate malicious nodes and delay communication to compromise the service. However, the adversary cannot subvert standard cryptographic assumptions.

In most situations, edge servers (height-1 domains) process transactions that are initiated by edge devices. Depending on the infrastructure and due to the lack of trust or connectivity between edge devices and edge servers or to offload traffic from edge servers, consensus among edge devices within a leaf domain and independent of edge servers might also be needed. This is also consistent with the D2D feature of 5G networks. We call the lowest domain, i.e., either the height-1 or the leaf domain, that processes transactions and establishes consensus, the edge domain.

### 3.2 Blockchain Ledger

Transactions in a blockchain system are recorded in an append-only data structure, called the blockchain ledger. In Saguaro, each domain processes a different set of transactions, hence, each domain maintains its own blockchain ledger where the ledger is replicated on every node within the domain.

Leaf domains (i.e., edge devices) maintain blockchain ledger in rare cases either due to lack of trust or connectivity between the leaf domain and the corresponding height-1 domain or in order to offload traffic from the height-1 domain. When there is no trust, connectivity, or traffic issue, edge devices within a leaf domain send their requests to the corresponding height-1 domain. Edge servers within a height-1
domain receive transactions from the nodes of a single leaf domain, i.e., each leaf (edge devices) domain is connected to a single height−1 (edge servers) domain. In the height-1 domain, due to data dependency among transactions of the same domain, transactions are totally ordered to ensure data consistency. The total order of transactions is captured by chaining transaction blocks together, i.e., each block has a sequence number or includes the cryptographic hash of the previous transaction block.

A domain in height−2 or above receives transactions from possibly multiple child domains and establishes an ordering between all received transactions. If there is no dependency between transactions of different child domains, any unique order of transactions is acceptable. However, cross-domain transactions, which are appended to the ledger of multiple child domains, must be appended to the ledger of the parent domain only once. The resulting ledger is a directed acyclic graph to capture the ordering dependencies.

If a leaf domain maintains the ledger (i.e., is an edge domain), the ledger of the leaf domain and the corresponding height−1 domain have a similar structure (i.e., linear chain). Figure 2 demonstrates the ledger of different domains for the same network as Figure 1. The presented ledger of each domain is indeed replicated on all nodes of that domain. In this network, we assume that only leaf domain $D_{04}$ is an edge domain (i.e., maintains the ledger). As shown, the ledgers of leaf and height−1 domains are linear chains consisting of internal transactions, e.g., $11$, $13$, and $14$, and cross-domain transactions, e.g., $12$−$22$−$31$ where domains $D_{11}$, $D_{12}$, and $D_{13}$ are involved in. However, in height−2 and above, because of the cross-domain transactions, e.g., $33$−$42$, the ledger is formed as a DAG.

In Saguaro, nodes proceed through a succession of rounds where at the end of each round (i.e., after some predefined time interval), each domain sends a block message including all transaction records that it has received from its child domain(s) in that round (i.e., a chunk of its blockchain ledger) to its parent domain. The predefined time interval for the domains at the same level is the same, however, domains at higher levels have larger time intervals. If a domain has not received any transaction in that round, it sends an empty block message. Depending on the application, the domain might send an abstract version of the records where some attributes of a transaction record might not be sent. For example, in the ridesharing use case, it might be sufficient to send only the working hour attribute of each record to the higher-level nodes. The abstraction strategy is deterministic, predefined, and known by all nodes.

Figure 3 presents a snapshot of Saguaro for the same network as Figure 1 assuming all leaf domains are edge domains. Each height−1 domain has appended two blocks to its ledger, e.g., $D_{11}$, has received blocks $B110$ and $B110$ from leaf domain $D_{01}$. Each height−2 domain, e.g., $D_{22}$, has created a block of transactions including transaction blocks received from its child domain, and finally, the root domain $D_{31}$ has appended block $B31−1$ to its ledger including transaction blocks $B21−1$, $B21−2$, $B22−1$, and $B22−2$ received from $D_{21}$ and $D_{22}$. In this example, the time interval of height−2 domains is twice the height−1 domains and 6 times the leaf domains.

4 Transaction Processing in Saguaro

Processing transactions requires establishing consensus on a unique ordering of incoming requests. Consensus protocols use the State Machine Replication (SMR) algorithm [39]. The algorithm has to satisfy four main properties [13]: (1) agreement: all non-faulty nodes must agree on the same value, (2) Validity (integrity): a committed value must have been proposed by some (non-faulty) node, (3) Consistency (total order): all non-faulty nodes commit the same values in the same order, and (4) termination: eventually every node commits some value. The first three properties are known as safety and termination is known as liveness.
As shown by Fischer et al. [23], in an asynchronous system, where nodes can fail, consensus has no solution that is both safe and live. Based on that impossibility (FLP) result, in Saguaro, safety is guaranteed in an asynchronous network that can drop, delay, corrupt, duplicate, or reorder messages. However, a synchrony assumption is needed to ensure liveness. Transactions of the system are either internal, i.e., access records within a single domain, or cross-domain, i.e., access records across different domains. We first present the internal consensus protocol to process internal transactions followed by the cross-domain consensus protocol to process cross-domain transactions.

4.1 Internal Consensus

The internal consensus is needed among the nodes within a single domain. While nodes within edge (i.e., leaf or height−1) domains establish consensus on the order of every single request that they receive from edge devices, nodes in higher-level domains agree on block messages that they receive from their child domains.

Edge devices (i.e., clients) initiate transactions by sending request messages to the primary node (a pre-elected node that initiates consensus) of the corresponding edge domain. The block messages, however, are sent by the primary node of a domain to all nodes of its parent domain upon completion of a round (i.e., after a predefined time interval). Depending on the failure model of the child domain, the block message is signed by either the primary (if nodes are crash-only) or at least 2f+1 nodes (if nodes are Byzantine). If the primary node of the parent domain has not received the block message from a child domain after a predefined time (e.g., the primary of the child domain might be faulty), it sends a block-query message to all nodes of the child domain. To ensure that the completion of each round is deterministic on all nodes of a domain, the primary puts a "cut" symbol (parameter) into the propose message of the last request informing other nodes the completion of a round. Since nodes establish consensus on the received messages, if a malicious primary sends the "cut" symbol maliciously it will be easily detected.

The internal consensus protocol of Saguaro is pluggable and depending on the failure model of nodes, a crash fault-tolerant protocol, e.g., Paxos [40] or a Byzantine fault-tolerant protocol, e.g., HotStuff [71], can be used. Upon receiving a request message, the primary node of the edge domain assigns a sequence number to the transaction and initiates the consensus protocol by multicasting a propose message including the transaction and its digest (cryptographic hash) to the nodes of its domain. The primary node of each higher-level domain, however, waits for the block messages of every child domain (completion of a round), provides a unique ordering among them (as mentioned in Section 3), and multicasts a propose message including a sequence number and a transaction block (i.e., including all transactions of received ledgers) to the nodes of its domain. Since nodes have already received the block messages, they can validate the order of transactions within the transaction block. Once consensus is achieved, nodes append the transactions block and the corresponding commit messages to their ledgers. The commit messages are appended to the ledger to guarantee immutability. Indeed, commit messages include the digest of the transaction block and by appending them to the ledger, any attempt to alter the block data can easily be detected.

4.2 Cross-Domain Transactions

Cross-domain transaction access records across different edge domains, e.g., a micropayment transaction where the sender and receiver belong to two different domains. To ensure data consistency, such transactions are required to be appended to the blockchain ledgers of all involved domains in the same order. To establish consensus on cross-domain transactions, the decentralized flattened, e.g., SharPer [5], and centralized coordinator-based, e.g., AHL [19], approaches have been proposed. However, as discussed earlier, both approaches suffer from high latency especially in wide area networks. In the flattened approach, e.g., SharPer [5], a consensus protocol is run among the nodes of all involved domains. The flattened approach does not require a centralized coordinator and can order cross-domain transactions with non-overlapping domains in parallel. However, in a wide area network where the involved domains might be far apart, the overall performance will severely be impacted due to the network latency. The coordinator-based approach, e.g., AHL [19], on the other hand, is more centralized by relying on a single coordinator domain (called reference committee in AHL) to order cross-domain transactions. However, the coordinator-based approach, similar to the flattened approach, suffers from network latency especially in a wide area network because depending on where the domains are placed (close to the clients or close to the coordinator), the coordinator has a far network distance from either the involved domains or the clients. In this section, we show how the hierarchical structure of Saguaro enables the efficient processing of cross-domain transactions using coordinator-based and optimistic approaches.
Once the primary node of an involved domain receives a valid cross-domain transaction, every sent and received message is logged by nodes. As indicated in lines 1-5 of the algorithm, \( d_c \) is the coordinator domain, \( \pi(d) \) represents the primary node of domain \( d \), and \( D \) and \( \pi(D) \) are the set of involved domains in the transaction and their primary nodes.

4.2.1 Coordinator-based Cross-Domain Consensus

The coordinator-based approach in Saguaro is inspired by the traditional coordinator-based sharding techniques in distributed databases as well as the shard permissioned blockchain AAIL, where the two-phase commit protocol is used for communication between the coordinator and all involved participant domains.

Saguaro operates on the Lowest Common Ancestor (LCA) domain of all involved edge domains (participants) to play the coordinator role and process cross-domain transactions initiated by edge devices. Since the hierarchy is structured based on the geographical distance of nodes, the lowest common ancestor domain has the optimal location to minimize the total distance (i.e., latency). In comparison to existing coordinator-based approaches, Saguaro, however, deals with several new challenges. First, in Saguaro, in contrast to sharded databases where all nodes follow crash failure model, the coordinator and the involved domains (participants) might follow different possibly Byzantine failure model. As a result, messages from a Byzantine coordinator or Byzantine participant domain must be certified by at least \( 2f + 1 \) nodes of the domain (since the primary node of the domain might be malicious). Second, in Saguaro, in contrast to the coordinator-based approaches where a single coordinator (node or domain) sequentially orders all cross-domain transactions, there are multiple independent coordinator domains in the network, i.e., any domains in height \( -2 \) and above could be a coordinator (an LCA domain). As a result, a participant domain in addition to its internal transactions might be involved in several concurrent independent cross-domain transactions ordered by separate coordinator domains at the same time. Finally, while Saguaro processes cross-domain transactions in parallel, ensuring consistency between concurrent order-dependent transactions is challenging. For example, if two concurrent cross-domain transactions \( m \) (between \( d_i, d_j \), and \( d_k \)) and \( m' \) (between \( d_l, d_j \), and \( d_l \)) are initiated, Saguaro must guarantee that \( m \) and \( m' \) are appended to the ledger of both \( d_i \) and \( d_j \) domains in the same order, i.e., either \( m \rightarrow m' \) or \( m' \rightarrow m \). Since the LCA of \( d_i, d_j \), and \( d_k \) might be different from the LCA of \( d_l, d_j \), and \( d_l \), Saguaro can not rely on the LCA domain to guarantee consistency.

The normal case operation of the coordinator-based approach is presented in Algorithm 1 [1]. Although not explicitly mentioned, every sent and received message is logged by nodes. As indicated in lines 1-5 of the algorithm, \( d_c \) is the coordinator domain, \( \pi(d) \) represents the primary node of domain \( d \), and \( D \) and \( \pi(D) \) are the set of involved domains in the transaction and their primary nodes.

Once the primary node of an involved domain receives a valid cross-domain transaction \( m \), as shown in lines 6-7, the primary forwards it to the LCA of the involved domains. Upon receiving a cross-domain transaction, as presented in lines 8-11, the primary node of the LCA domain validates the message. If the primary node \( \pi(d_c) \) is currently processing another cross-domain transaction \( m' \) (i.e., has not sent commit message for \( m' \) where the involved domains of two requests \( m \) and \( m' \) intersect in at least two domains, the node does not process the new request \( m \) before the earlier request \( m' \) gets committed. This is needed
to ensure cross-domain requests are committed in the same order on overlapping domains (i.e., consistency property). Otherwise, node $\pi(d_c)$ assigns a sequence number $n_c$ to $m$ and initiates consensus on request $m$ in the coordinator domain. Once consensus is established, the primary node sends a signed $\text{prepare}$ message including the sequence number $n_c$, request $m$ and its digest $\delta = \Delta(m)$ to the nodes of all involved domains. Note that if the nodes of the LCA domain are Byzantine, as explained earlier, a threshold signature is used where $2f+1$ (out of $3f+1$) nodes of the LCA domain sign the $\text{prepare}$ message.

Upon receiving a valid $\text{prepare}$ message, as shown in lines 12–15, if the primary node of an involved domain $d_i$ is not processing another cross-domain transaction $m'$ where the involved domains of two requests $m$ and $m'$ intersect in at least two domains, the primary assigns a sequence number $n_i$ to request $m$ and initiates consensus in $d_i$ on the order of the message. Once consensus is achieved, the primary node of each involved domain $d_i$ sends a signed $\text{prepare}$ message to $d_c$ (as before, for Byzantine nodes, a threshold signature is used). As shown in lines 16–18, when primary node $\pi(d_c)$ receives valid $\text{prepare}$ messages from every involved domain, the coordinator domain establishes consensus and sends a signed $\text{commit}$ message to every node of all involved domains. Otherwise (if some involved domain does not agree with the transaction), the domain sends a signed $\text{abort}$ message. The sequence number of the $\text{commit}$ messages is indeed a concatenation of the received sequence numbers from all involved domains. The nodes of the LCA domain do not append the transaction to their ledgers in this step and update their ledgers only after receiving $\text{block}$ messages.

Upon receiving a valid $\text{commit}$ message, as shown in lines 19–21, each node considers the transaction as committed and sends an $\text{ack}$ message to the coordinator domain. If all transactions with lower sequence numbers have been committed, the node appends the transaction and the corresponding $\text{commit}$ message to the ledger and executes it. This ensures that all nodes execute requests in the same order as required to ensure safety. Depending on the application, a $\text{reply}$ message including the execution results might also be sent to the edge device (requester) by either the primary (if nodes are crash only) or all nodes (if nodes are Byzantine) of the domain that has received the request.

It should be noted that in an unlikely situation where cross-domain transactions (1) are concurrent, (2) overlap on at least two domains, and (3) are received by overlapping domains in a different order, ensuring consistency (total order) might result in a deadlock situation. In such a situation, each domain waits for the $\text{commit}$ message of one transaction before processing another one. This happens when the LCA of two transactions are different, i.e., if the LCA is the same, the LCA never initiates the second transaction, as shown in Algorithm 1, lines 8–11. Therefore, once the timer of an LCA domain for its cross-domain transaction is expired, the LCA aborts the transaction (i.e., resolves the deadlock) by sending a new $\text{prepare}$ message to the involved domains. Saguaro assigns different timers to different domains to prevent parallel and also consecutive aborting of transactions in case of deadlock situations.

**Primary Failure Handling.** The primary failure handling routine improves liveness by allowing the system to make progress when a primary node fails. If the primary of either the LCA or a participant domain is faulty, the primary failure handling routine of the internal consensus protocol, e.g., view change in PBFT [16], is triggered by timeouts to elect a new primary. In particular, for cross-domain transactions, if node $r$ of an involved domain does not receive a $\text{commit}$ message from the LCA domain for a prepared request and its timer expires, the node sends a $\langle \text{commit-query}, n_c, n_i, \delta, r \rangle_{\pi}$ message to all nodes of the LCA domain where $n_c$ and $n_i$ are the sequence numbers assigned by the primary nodes of LCA and $d_i$ and $\delta$ is the digest of the request. Similarly, if node $r$ in the LCA domain has not received $\text{prepare}$ message from an involved domain soon enough, it sends a $\langle \text{prepare-query}, n_c, \delta, r \rangle_{\pi}$ to all nodes of the involved domain. In either case, if the message has already been processed, the nodes simply re-send the corresponding response. Nodes also log the query messages to detect denial-of-service attacks initiated by malicious nodes. If the query message is received from a majority of a domain (i.e., $f + 1$ crash-only or $2f + 1$ Byzantine nodes), the primary will be suspected to be faulty resulting in running the failure handling routine. Note that since in all communications between a participant and an LCA domain, the primary node of the sender domain multicasts messages, e.g., $\text{request}$, $\text{prepare}$, or $\text{prepared}$, to all nodes of the receiver domain, if the primary of the receiver domain does not initiate consensus on the message among the nodes of its domain, it will eventually be suspected to be faulty by the nodes. Finally, if an edge device does not receive $\text{reply}$ soon enough, it multicasts the request to all nodes of the domain that it has already sent its request. If the request has already been processed, the nodes simply send the execution result back to the edge device. Otherwise, if the node is not the primary, it relays the request to the primary. If the nodes do not receive $\text{prepare}$ messages, the primary will be suspected to be faulty; i.e., it has not multicast request to the LCA domain.

**Correctness.** Consensus protocols have to satisfy safety and liveness. We briefly analyze the safety (agreement, validity, and consistency) and liveness (termination) properties of Saguaro.
Lemma 4.1 (Agreement) If node $r$ commits request $m$ with sequence number $h$, no other non-faulty node commits request $m'$ ($m \neq m'$) with the same sequence number $h$.

Proof: We assume that the internal consensus protocol of both coordinator and participants domains ensures agreement. Let $m$ and $m'$ ($m \neq m'$) be two committed cross-domain requests with sequence numbers $h = [h_i, h_j, h_k, ...]$ and $h' = [h'_i, h'_j, h'_k, ...]$ respectively. Committing a request requires matching prepared messages from $n-f$ different nodes of every involved domain. Therefore, given an involved domain $d_k$ in the intersection of $m$ and $m'$, at least a quorum of $n-f$ nodes of $d_k$ have sent matching prepared messages for $m$ and at least a quorum of $n-f$ nodes of $d_k$ have sent matching prepared messages for $m'$. Since any 2 quorums intersect on at least one non-faulty node, $h_k \neq h'_k$, hence, $h \neq h'$.

Lemma 4.2 (Validity) If a non-faulty node $r$ commits $m$, then $m$ must have been proposed by some node $\pi$.

Proof: If nodes follow the crash failure model, since crash-only nodes do not send fictitious messages, validity is ensured. With byzantine nodes, validity is guaranteed based on standard cryptographic assumptions about collision-resistant hashes, encryption, and signatures which the adversary cannot subvert them (as explained in Section 3). Since all messages are signed (by $2f+1$ nodes) and either the request or its digest is included in each message (to prevent changes and alterations to any part of the message), if request $m$ is committed by a non-faulty node $r$, the same request must have been proposed earlier by some node $\pi$.

Lemma 4.3 (Consistency) Let $D_\mu$ denote the set of involved domains (participants) for a request $\mu$. For any two committed requests $m$ and $m'$ and any two nodes $r_1$ and $r_2$ such that $r_1 \in d_i$, $r_2 \in d_j$, and \{d_i, d_j\} $\in D_m \cap D_{m'}$, if $m$ is committed before $m'$ in $r_1$, then $m$ is committed before $m'$ in $r_2$.

Proof: As shown in lines 12–15 of Algorithm 1 when node $r_1$ of a participant domain $d_i$ receives a prepare message for some cross-domain transaction $m$, if the node is involved in another uncommitted cross-domain transaction $m'$ where $|D_m \cap D_{m'}| > 1$, i.e., some other domain $d_j$ is also involved in both transactions, node $r_1$ does not send a prepared message for transaction $m$ before $m'$ gets committed. Since committing request $m$ requires a quorum of prepared messages from every involved domains, $m$ cannot be committed until $m'$ is committed. As a result, the order of committing messages is the same in all involved domains. As shown in Algorithm 1 lines 8–11 the coordinator domain $d_c$ also checks the same condition before sending prepare messages.

Property 4.4 (Termination) A request $m$ issued by a correct client eventually completes.

Due to the FLP result [23], Saguaro guarantees liveness only during periods of synchrony. Saguaro addresses liveness in primary failure and deadlock situations. First, if the primary of either the LCA or a participant domain is faulty, e.g., does not multicast valid request, prepare, prepared, or commit messages, as explained earlier, its failure will be detected and using the primary failure handling routine of the internal consensus protocol, a new primary will be elected. Second, Saguaro, as explained earlier, addresses deadlock situations resulting from concurrent cross-domain transactions that overlap on at least two domains and are received by overlapping domains in a different order to ensure liveness.

4.2.2 Optimistic Cross-Domain Consensus

The coordinator-based consensus protocol of Saguaro is more efficient than the existing coordinator-based protocols because Saguaro first, relies on the lowest common ancestor domain to minimize the distance between the coordinator and involved (participant) domains, and second, processes cross-domain transactions in parallel. However, it still requires multiple rounds of intra- and cross-domain communication. To reduce the latency of coordinator-based protocol, Saguaro can leverage the hierarchical structure of the network to enable the optimistic processing of cross-domain transactions. In the optimistic protocol, each involved domain optimistically processes and commits a cross-domain transaction independent of other involved domains assuming that all other involved domains commit the transaction as well. Since the transactions will propagate up, nodes in higher levels and eventually the LCA of all involved domains can check the commitment of the transaction.

In the optimistic approach, upon receiving a valid cross-domain request from an authorized edge device, the request is multicast to the nodes of all other involved domains. Since the primary might be malicious and not send the request to some involved domains, all nodes multicast the request to ensure that other domains receive the request. Each involved domain (including the initiator domain) then, uses its internal consensus
protocol to optimistically establish agreement on the order of the transaction, append the transaction to its ledger (assuming all other involved domains also append the transaction), and execute it. For each executed cross-domain transaction $t$, nodes of a domain maintain a list of transactions (both internal and cross-domain) that are executed after $t$ and have direct or indirect data (i.e., read-write) dependency to transaction $t$. If transaction $t$ gets aborted, e.g., some other involved domain does not commit the transaction, all data-dependent committed transactions need to be aborted as well. When the domain is informed (by the LCA domain) about the commitment or abortion of transaction $t$, the domain no longer maintains the list.

Figure 4 presents ledgers of different domains using the optimistic cross-domain consensus protocol for the same network as Figure 1 assuming all edge domains are in height $-1$. In this figure, $m_b$ is a cross-domain transaction between $D_{11}$, $D_{12}$, and $D_{13}$ and $m_i$ and $m_j$ are between $D_{13}$ and $D_{14}$. Each domain maintains a list of data-dependent transactions for each cross-domain transaction, e.g., in $D_{12}$, $m_g$ has data dependency to $m_b$.

Each edge domain processes all internal and cross-domain requests and upon completion of a round (i.e., the predefined time interval) sends a block message including the committed transactions, non-committed (aborted) cross-domain transactions (to inform other domains), and the dependency lists for cross-domain transactions (within this block and the previous blocks) that have not yet been decided by all their involved domains to its parent domain.

Each parent domain and eventually the LCA of all involved domains in a cross-domain transaction first, ensures that concurrent cross-domain transactions (if any) have been appended to the ledger of the intersection domains in the same order (i.e., consistency). Otherwise, one of the transactions will be aborted. For example, in Figure 4 $m_i$ and $m_j$ are appended to the ledger of $D_{13}$ and $D_{14}$ in an inconsistent order, hence, domain $D_{22}$ aborts $m_j$. Saguaro guarantees that aborting transactions is deterministic, i.e., all higher-level domains reach the same decision on choosing transactions to be aborted, e.g., abort the transaction with the lowest id.

Note that intermediate domains between involved domains and the LCA domain might receive the transaction from a subset (more than one) of involved domains and be able to partially check the consistency and early abort in case of inconsistency. For example, in Figure 4 domain $D_{21}$ receives $m_b$ from $D_{11}$ and $D_{12}$. Upon finding an inconsistency, the primary node of the domain marks one of the transactions and all its data-dependent transactions as aborted, e.g., in Figure 4 $m_j$ is marked as aborted. The primary also sends an abort message (signed by a crash-only primary or $2f + 1$ Byzantine nodes) including the digest of the request to the nodes of the involved domains. Involved domains need to roll back the aborted cross-domain transaction and all its data-dependent ones. Since transactions have not been already appended to the ledger, the domains append compensating transactions to the ledgers to cancel the effect of those transactions.

Each intermediate and eventually the LCA domain then checks whether the cross-domain transaction is committed by involved domains. The intermediate domains can check the commitment of the transaction by a subset of the involved domains. For example, in Figure 4 domain $D_{21}$ can check whether $m_b$ is committed by $D_{11}$ and $D_{12}$ while the LCA domain $D_{31}$ can also check the commitment of $m_b$ by $D_{13}$ as well. If the transaction is committed by all involved domains, the transaction will be appended to the ledger and upon the completion of the round sent to the parent domain. Once the primary of the LCA domain receives the transaction from all involved domains, it sends a signed commit message to all domains informing them that the transaction is committed.

If the transaction has not been appended to the blockchain ledger (block message) of an involved domain (due to the asynchronous nature of the network), the intermediate or the LCA domain does not append the
transaction and waits for the next block messages. The domain does not append the following transactions within the block message to its ledger as well. This is needed because there might be an inconsistency issue and the domain might need to mark the transactions as aborted (as explained earlier).

If a node of an involved domain does not receive the commit message for cross-domain transaction m after a predefined time, it sends a signed commit-query including the digest of m to its parent domain. If the parent domain has already been informed about the decision, it sends the commit (or abort) message to the node. Otherwise, it forwards the commit-query to its parent domain. If the LCA domain receives the commit-query and the transaction has been processed, the domain sends the commit (or abort) message to the node, otherwise, it sends a commit-query to the involved domain(s) that has not sent their transactions. Upon receiving a valid commit-query message, if the domain has not processed the transaction, it immediately starts processing the transaction. If the request is not committed in some predefined number of rounds by all involved domains it is considered to be aborted. It should be noted that in the optimistic approach, the predefined time interval for completion of rounds, i.e., sending block messages to the parent domains, is considered to be very small to avoid aborting a large number of transactions in case of aborting cross-domain transactions.

**Correctness.** We now briefly show the safety and liveness of the optimistic approach.

**Lemma 4.5 (Agreement)** If node r commits request m with sequence number h, no other non-faulty node commits request m′ (m ≠ m′) with the same sequence number h.

**Proof:** Assuming the internal consensus protocols guarantee agreement, the agreement property of the cross-domain protocol is ensured. In addition, if the transaction is not committed in an involved domain, the LCA domain detects it resulting in aborting the transaction.

**Lemma 4.6 (Validity)** If a non-faulty node r commits m, then m must have been proposed by some node π.

**Proof:** Validity is guaranteed in the same way as cross-domain consensus (lemma 4.2).

**Lemma 4.7 (Consistency)** For any two committed requests m and m′ and any two nodes r1 and r2 such that r1 ∈ d_i, r2 ∈ d_j, and {d_i, d_j} ∈ D_m ∩ D_m′, if m is committed before m′ in r1, then m is committed before m′ in r2.

**Proof:** Upon receiving a cross-domain transaction, each intermediate and eventually the LCA domain(s) of both m and m′ checks consistency and resolves any inconsistencies by aborting either m or m′. The aborting strategy is deterministic resulting in aborting the same transaction independent of the domain that checks. While transactions might be initially optimistically committed in an inconsistent order, eventually inconsistency will be resolved, i.e., the protocol guarantees eventual consistency.

**Property 4.8 (Termination)** A request m issued by a correct client eventually completes.

The liveness of the algorithm is guaranteed in periods of synchrony based on the assumption that both LCA and involved (participants) domains ensure liveness for all transactions. Furthermore, if a node does not receive commit (or abort) message from the LCA domain for some cross-domain request and its timer expires, as discussed earlier, it sends a commit-query message to the parent domain, resulting in sending a commit-query message to the nodes of the involved domain(s) that have not committed the message. If the request is not committed in some predefined number of rounds by all involved domains it is considered to be aborted.

## 5 Delay-Tolerant Mobile Consensus

Edge devices (i.e., leaf-level nodes) over wide-area networks might be mobile, e.g., smart cars or smartphones. The mobility of edge devices is either permanent or transient. If the mobility is permanent, the node will be authenticated by the edge servers of the new domain and is able to initiate transactions. If consensus at the leaf level is needed, the node also obtains the blockchain ledger of the new domain and participates in the consensus routine. However, if an edge device temporary moves from its leaf domain (local) to another leaf domain (remote), reaching consensus on transactions that are initiated by the mobile device is challenging. In fact, nodes of the remote domain do not access to the history of the mobile node, hence, are not able to process its requests. Moreover, any communication across domains is costly.
The normal case operation of delay-tolerant mobile consensus is presented in Algorithm 2. As indicated in this, however, requires several rounds of communications across domains for every single request. A more coordinator-based or the optimistic approach, consensus among both local and remote domains is established. Once a mobile device sends a request to a remote edge (either leaf or height $S_2$) the primary node of the local domain receives a valid history-query message, and $i$ is $\pi(d_l)$. Upon receiving a valid request $r$ from a remote node $n$ and $i$ is $\pi(d_r)$, the remote domain, sends a signed message for its edge node history-query message including the request $r$. Upon receiving valid $\langle$history-query, $m, \delta_m \rangle_{\sigma_i(d_r)}$ to $d_l$ and $\langle$history-query, $m, \delta_m \rangle_{\sigma_i(d_l)}$ and $i$ is $\pi(d_l)$. If $lock(n) = false$ then $\pi(d_l).\text{GENERATEHISTORY}(n, d_l, d_r) \quad \triangleright lock(n) is true and remote(n) = d_r$. The primary of $d_r$, $\pi(d_l).\text{GETHISTORY}(n, d_l, d_r)$, if $lock(n) = true$, remote($n$) = $d_r$. Establish consensus on history $H(n)$ among nodes in $d$. $lock(n) = true$, $remote(n) = d_r'$ (signed by $\pi(d)$ or $2f + 1$ nodes of $d$). $\pi(d_r').\text{GENERATEHISTORY}(n, d_r', d)$. Upon receiving valid $\langle$history, $H(n), \delta_h, \delta_m \rangle_{\pi(d_r')}$ message from $\pi(d_r')$. $lock(n) = false$. Establish consensus on transactions of history message among nodes in $d$. Append the transactions and commit message(s) to the ledger.

Saguaro can deal with transactions initiated by mobile devices in the same way as cross-domain transactions. Once a mobile device sends a request to a remote edge (either leaf or height−1) domain, the remote domain, similar to cross-domain transactions, sends the request to the local edge domain and then using either the coordinator-based or the optimistic approach, consensus among both local and remote domains is established. This, however, requires several rounds of communications across domains for every single request. A more efficient way to address consensus with mobile devices is to provide access to the history of the mobile node in one round of communication across domains.

The normal case operation of delay-tolerant mobile consensus is presented in Algorithm 2. As indicated in lines 1–4 of the algorithm, $d_l$ and $d_r$ are the local and remote edge domains. Upon receiving a valid request $m$ from an unauthorized edge device, as shown in lines 5–6, the primary of the remote domain, sends a signed history-query message including the request $m$ and its digest $\delta_m$ to the local domain to obtain the history of the node. Each domain maintains a lock bit for each edge device to keep track of its mobility. When an edge device initiates a transaction in a remote domain, the lock is set to true representing that the history of the edge device in the local domain is out-of-date. The domain also defines a variable remote for each edge device to maintain the id of the remote domain that has the most recent transaction records of the node. Once the primary node of the local domain receives a valid history-query message for its edge node $n$, as presented in lines 7–13, if lock($n$) is false (i.e., the history of node $n$ in the local domain is complete and up-to-date), the GENERATEHISTORY function is called. As shown in lines 14–19, the primary node of the local domain, $\pi(d_l)$, first generates an abstract history of mobile node $n$. The abstract history is application-dependent and includes the information that is needed to process transactions. For example, in the micropayment application, the abstract history might include only the balance of node or in the ridesharing application, the abstract history might include only the work hours of the driver. The primary then initiates consensus among nodes of the local domain on the generated history by sending a message including both history-query message received from the remote domain as well as the generated abstract history $H(n)$. Once consensus is achieved, the primary sends a signed history message including the generated history $H(n)$, the digest $\delta_h$ of the corresponding history-query message, and the digest $\delta_m$ of request $m$ to the remote domain. Nodes in the local domain also set lock($n$) to be true and remote($n$) to $d_r$. 

Algorithm 2 Delay-Tolerant Mobile Consensus

1: $i := node_id$
2: $d_l := local\ domain$
3: $d_r := remote\ domain$
4: upon receiving valid request $m$ from a remote node $n$ and $i$ is $\pi(d_r)$
5: send $\langle$history-query, $m, \delta_m \rangle_{\sigma_i(d_r)}$ to $d_l$
6: upon receiving valid $\langle$history-query, $m, \delta_m \rangle_{\sigma_i(d_l)}$ and $i$ is $\pi(d_l)$
7: if $lock(n) = false$ then
8: $\pi(d_l).\text{GENERATEHISTORY}(n, d_l, d_r)$
9: else
10: $\pi(d_l).\text{GETHISTORY}(n, d_l, d_r)$
11: $\pi(d_l).\text{GENERATEHISTORY}(n, d_l, d_r)$
12: end if
13: function GENERATEHISTORY(node $n$, domain $d$, domain $d'$)
14: generate (abstract) history $H(n)$
15: establish consensus on history $H(n)$ among nodes in $d$
16: $lock(n) = true$, remote($n$) = $d_r'$ (signed by $\pi(d)$ or $2f + 1$ nodes of $d$)
17: send $\langle$history, $H(n), \delta_h, \delta_m \rangle_{\sigma_i(d_r')}$ to $d_r'$
18: end function
19: function GETHISTORY(node $n$, domain $d$, domain $d'$)
20: send $\langle$history-query, $m, \delta_m \rangle_{\sigma_i(d_r')}$ to $\pi(d_r')$
21: $\pi(d_r').\text{GENERATEHISTORY}(n, d_r', d)$
22: upon receiving valid $\langle$history, $H(n), \delta_h, \delta_m \rangle_{\pi(d_r')}$ message from $\pi(d_r')$
23: $lock(n) = false$
24: establish consensus on transactions of history message among nodes in $d$
25: append the transactions and commit message(s) to the ledger
26: end function
If lock(n) is true and remote(n) = d′, i.e., some other remote domain d′ has the most recent transaction records, the local domain gets the recent transactions from d′ by calling the GetHistory function, and then calls the GenerateHistory function to update its history and send an abstract history of n to the remote domain d′. This situation happens when an edge device moves to a remote domain d′, initiates some transactions and then moves to another remote domain d′. The GetHistory function, as shown in lines 20–27, sends a history-query to remote(n) to obtain the most recent transaction records. Upon receiving the history-query message, the remote domain generates a complete history of the transactions that node n has been involved in them. Note that, in contrast to the local domain, the history of the remote domain is complete because these transactions need to be appended to the blockchain ledger of the local domain. Once the history message is received, the local domain appends transactions to its ledger and set lock(n) to be false. If the mobile node returns to its local domain and initiates a transaction, the local domain calls GetHistory, updates the ledger and then processes the transaction locally.

Correctness. The correctness of delay-tolerant mobile consensus protocol is mainly ensured based on the correctness of internal consensus protocols in both local and remote domains. Since edge devices are mobile and might move from a leaf domain to another domain, we need to ensure safety in unlikely situations where consensus at the leaf-level is required, i.e., the edge domain is the leaf domain. First, mobile devices (in case of transient mobility) do not participate in the consensus protocol of remote domains, hence, they can not violate the safety condition of remote domains. Furthermore, nodes in a leaf domain can establish consensus only if the safety condition holds, e.g., excluding mobile nodes, more than two-thirds of the existing nodes are non-malicious. Assuming the internal consensus protocols are safe and live, we just need to show that communications across domains do not violate safety or liveness. Safety is guaranteed because to send a history message consensus among nodes of a domain is needed and history messages are signed by a crash-only primary or 2f + 1 Byzantine nodes.

To guarantee liveness, if node r of a domain does not receive a history message after sending a history-query message and its timer expires, the node sends the history-query message to all nodes of the other domain. If the message has already been processed, the nodes simply re-send the corresponding response. Nodes also log the query messages to detect denial-of-service attacks initiated by malicious nodes. If the query message is received from a majority of a domain (i.e., f + 1 crash-only or 2f + 1 Byzantine nodes), the primary will be suspected to be faulty resulting in running the failure handling routine. If nodes of domain d′ receive history-query from domain d, however, the primary of d′ does not initiate consensus on history message, nodes of d′ suspect that their primary is faulty. Similarly, upon receiving history messages, nodes of domain d wait for the primary node of d to initiate consensus. Otherwise, the primary will be suspected to be faulty.

6 Experimental Evaluation

In this section, we conduct several experiments to evaluate Saguaro. We have implemented a micropayment application (as a representative and the most demanding application) using Saguaro and emulated a four-level 5G network (following the structure in Figure 1) where the leaf domains do not maintain the blockchain ledger (i.e., height−1 domains are edge domains). Nodes follow either crash or Byzantine failure model.
consider three workloads with different degrees of contention between transactions of each domain, i.e., such transactions in the optimistic approach results in aborting all their data-dependent transactions. We cross-domain transactions have been appended to the ledger of two domains in a different order. Aborting earlier, a committed cross-domain transaction might be aborted due to inconsistency, i.e., two concurrent cross-domain transactions are not committed (aborted) by some involved domain. Furthermore, as discussed to process more than

When all nodes are crash-only and all transactions are internal, as shown in Figure 5(a), Saguaro is able to process more than 31000 transaction with less than 100 ms latency before the end-to-end throughput is saturated. Since, each domain process its transactions independently, the throughput of the entire system will increase linearly by increasing the number of domains. Adding 20% cross-domain transactions, the optimistic approach with 10% contention shows the best performance by processing 22800 transactions with 80 ms latency. This is expected because the optimistic approach, does not require any communication across domains, and transactions are optimistically committed. In this scenario, only 0.03% of transactions were appended to the ledgers in an inconsistent order, hence, increasing the percentage of contention in the workload to 50% and 90% (Opt-50% C and Opt-90% C graphs) does not significantly impact the performance of the optimistic protocol. Similarly, since only 20% of transactions are cross-domain, failure of 10% of cross-domain transactions (2% of all transactions) with 10% contention in the workload does not significantly reduce throughput (Opt-10% F graph). The coordinator-based approach also processes 21150 transactions with 95 ms latency which is 23% more than AHL (17300 transactions with the same latency).

Increasing the percentage of cross-shard transactions to 80% and 100% results in a larger performance gap between the coordinator-based approach and existing approaches (SharPer and AHL). This is expected because in AHL, the single coordinator becomes overloaded by cross-domain transactions and in SharPer consensus across domains becomes a bottleneck. However, Saguaro, by relying on multiple coordinator
domain, is still able to process transactions efficiently, e.g., in the workload with 100% cross-domain transaction, the coordinator-based approach processes 10400 transactions, which is 67% more than the AHL with the same latency.

In the optimistic approach, and with 80% cross-domain transactions, 1.35% of transactions are appended to the ledgers in an inconsistent order. Hence, increasing the percentage of contention in the workload to 50% and 90% results in 5% and 11% reduction in the throughput (respectively). With 100% cross-domain transaction and with 50% and 90% contention in the workload, we measure 6% and 14% reduction in the throughput. Similarly, the failure of 10% of cross-domain transactions decreases 24% and 29% of the throughput with 80% and 100% cross-domain transactions respectively. Note that since both inconsistencies and failures are detected by higher-level domains, the latency of processing transactions by edge domains is not affected.

In the presence of Byzantine nodes, as shown in Fig 6(b), Saguaro shows similar behavior, however, with lower throughput and higher latency. This is expected because Byzantine fault-tolerant protocols are in general more expensive than crash fault-tolerant protocols.

6.2 Transactions Initiated by Mobile Devices

In the second set of experiments, we measure the performance of the delay-tolerant mobile consensus protocol to process remotely initiated transactions. We consider four workloads with different percentages (i.e., 0, 20, 80, and 100) of remotely initiated (called mobile) transactions where a local and a remote domain are involved in each mobile transaction. Figure 7(a) and Figure 7(b) show the results with crash and Byzantine nodes.

When nodes are crash-only and all transactions are local, as shown in Figure 7(a), Saguaro processes more than 31000 transaction with less than 100 ms latency (same scenario as Figure 5(a)). Adding 20% mobile transactions, Saguaro still processes 30000 transactions (only ~3% reduction) with 107 ms latency before the end-to-end throughput is saturated. Similarly, with 80% and 100% mobile transactions, Saguaro processes 26000 (with 129 ms latency) and 23800 (with 144 ms latency) transactions respectively. This indeed shows the effectiveness of Saguaro in handling mobile devices: when the percentage of mobile transactions increases from 0% to 100%, Saguaro incurs only a 23% reduction in its throughput.

With Byzantine nodes, as shown in Figure 7(b), Saguaro demonstrates similar behavior and is able to process 15400 transactions even when all transactions are mobile (overall throughput of Saguaro reduces only 25% compared to when there is no mobile transaction).

6.3 Scalability Over Wide Area Domains

In the third set of experiments, the impact of network distance on the performance of Saguaro is measured. We compare the setting where all nodes are placed in a single AWS region with the setting where domains are distributed over seven different AWS regions, i.e., California (CA), Oregon (OR), Virginia (VA), Ohio (OH), Tokyo (TY), Seoul (SU), and Hong Kong (HK).4 In this scenario, each leaf and its corresponding height−1 domain are placed in one of the TY, HK, VA, and OH data-centers, the height−2 domains are in SU and OR and the root domain is in the CA region. We consider workloads with 90%-internal 10%-cross-

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4 The average measured Round-Trip Time (RTT) between every pair of Amazon datacenters can be found at https://www.cloudping.co/grid
domain transactions (typical settings in partitioned databases [64]), where two randomly chosen domains are involved in each cross-domain transaction. Since the workload includes only 10% cross-domain transactions, we do not perform experiments on optimistic protocol with different percentages of contention as well as injected failures (when the percentage of cross-domain transactions is low, as shown in Section 6.1, these parameters do not impact the performance). The results are demonstrated in Figures 8 and 9 for crash-only and Byzantine nodes.

As shown in Figure 8(a), when domains are close to each other, the optimistic approach processes 26000 transactions with 100 ms latency. Similarly, the coordinator-based approach, SharPer, and AHL process 23500, 20200, and 18400 transactions with the same latency (respectively). Placing nodes in far apart domains, as shown in Figure 8(b), however, results in lower throughput and higher latency, e.g., the throughput of the optimistic approach is decreased by 40% and its latency is increased by 61%. Interestingly, AHL demonstrates better performance than SharPer which is expected due to the flattened consensus protocol of SharPer that needs rounds of communication among domains over a wide area. Furthermore, increasing the gap between the performance of the coordinator-based approach and AHL (single coordinator) from 23% to 47% higher performance demonstrates the effectiveness of the coordinator-based approach over wide area networks. In the presence of Byzantine nodes, as shown in Figure 9, all protocols demonstrate similar behavior to the previous case.
We then use the same settings to measure the impact of network distance on mobile transactions where edge nodes move one, two, and three hubs away from their local domain and initiate transactions. The workloads include 90% internal and 10% mobile transactions. As shown in Figure 10(a), in the presence of crash-only node and when mobile nodes are one hub away, e.g., the local domain in Tokyo and the remote domain in Hong Kong, the throughput is decreased only by 4% (20% higher latency). Similarly, for two hubs away and three hubs away scenarios, the throughput reduces only 10% and 14% (in comparison to no mobile devices) which demonstrates the efficiency of the mobile consensus protocol. In the presence of Byzantine nodes, as shown in Figure 10(b), processing transactions of mobile nodes incurs even less overhead due to the cost of Byzantine consensus protocols which makes the overhead less notable.

6.4 Fault Tolerance Scalability

Finally, we evaluate the performance of Saguaro with a different number of nodes (i.e., maximum possible failures (f)). We consider two scenarios with f = 2 and f = 4, i.e., each crash-only domain includes 5 and 9 nodes, and each Byzantine domain includes 7 and 13 nodes respectively. All nodes are placed within an AWS region and the workload includes 90%-internal 10%-cross-domain transactions. As shown in Figure 11 and Figure 12, increasing the number of nodes, reduces the performance of all protocols (insignificantly), e.g., the end-to-end throughput of the coordinator-based protocol is reduced by 6% and 11% (with the same latency) when the number of nodes within each domain increases from 3 to 5 and 7. This is expected because once the number of nodes increased, achieving consensus requires larger quorums.

7 Related Work

Despite several years of intensive research, existing blockchain solutions do not adequately address the performance and scalability requirement of wide area networks, which is characterized by possibly mobile nodes communicating over the wide-area transacting across domains. In general, the ordering and execution of transactions are the two main phases of processing transactions. Early blockchains, e.g., Tendermint [37] and Quorum [17] follow the sequential order-execute paradigm resulting in high latency. Hyperledger Fabric [7], as a permissioned blockchain, introduces the execute-order-validate (XOV) architecture and leverages parallelism by executing the transactions of different applications simultaneously. Several recent permissioned blockchains, e.g., blockchain relational Database [48], ParBlockchain [4], Fast Fabric [27], XOX Fabric [26],
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Fabric++ [60], and FabricSharp [57] also, execute transactions in parallel and try to address the shortcomings of Hyperledger Fabric, e.g., dealing with contentious workloads.

Parallel ordering of transactions is addressed in blockchains using both off-chain, e.g., Lightning Networks [45] [53] and sidechains [8] [21] [38] [41] [68], and on-chain, sharding techniques. Off-chain techniques increase the system throughput by moving a portion of the transactions off the chain. However, such techniques do not scale more than two levels, thus, they are not compatible with the hierarchical structure of wide area networks.

Sharding is a proven technique to improve databases scalability [18] [55] [72]. Data sharding is commonly used in globally distributed databases such as H-store [34], Calvin [65], Spanner [18], Scatter [25], Google’s Megastore [9], Amazon’s Dynamo [20], Facebook’s Tao [12], and E-store [64] where the nodes are assumed to be crash-only and a coordinator processes transactions across shards. To achieve better performance in sharding protocols, consensus protocol and transaction management have been combined [46] [70] [73] (in contrast to to layering one on top of another). The sharding technique has been used in both permissionless (e.g., Elastico [44], OmniLedger [36] and Ethereum 2 [1]) and permissioned blockchains (e.g., AHL [19], Blockplane [49], and SharPer [5]). However, sharding has several shortcomings that make it inappropriate to be used in wide area networks. First, sharding approaches maintain data shards mainly on cloud servers (far from edge devices) and do not benefit from the hierarchical structure of wide area networks, resulting in increased latency. Second, sharding approaches either use a flattened approach, e.g., SharPer [5], or a coordinator-based approach, e.g., AHL [19] to process cross-shard transactions where in both approaches, as explained earlier, the far network distance either between the involved shards (in the flattened approach) or between the coordinator and involved shards (in the coordinator-based approach) results in high latency. Third, while many edge devices in wide area networks are mobile, mobility has not been addressed in sharding solutions.

GeoBFT [31], as another scalability solution, maintains the entire ledger on every node and orders each transaction within only a single cluster to reduce the latency of cross-cluster transactions. After ordering every transaction, however, all clusters need to communicate with each other to enable other clusters to update their ledgers and execute transactions, resulting in high latency.

The hierarchical permissioned blockchain model presented in [58] focuses only on the data abstraction across different levels of the hierarchy and does not address cross-domain transactions, consensus, and the mobility of nodes. Plasma [52] also uses hierarchical chains to improve transaction throughput of Ethereum blockchain using a series of smart contracts to create hierarchical trees of sidechains, however, processing cross-domain transactions and mobility of nodes have not been addressed in Plasma.

Our work is also related to blockchain systems with DAG-structured ledgers, e.g., Iota [54], Vegvisir [35], Phantom [63], Spectre [62], and Caper [2]. In particular, in Caper, the DAG structure is the result of the simultaneous appending of local and global transactions to the ledger whereas in Saguaro, the DAG structure is used to support cross-domain transactions in internal levels. Moreover, Caper neither follows the hierarchical structure of wide area networks nor supports the mobility of nodes.

Blockchain brings the capability of managing wide area networks data through its secure distributed ledger and provide immutability, decentralization, and transparency, all of which promise to tackle security issues of current 5G networks [50]. A permissionless blockchain-based architecture for IoT has been introduced in [22] where each cluster of nodes, e.g., a smart home, maintains a blockchain ledger. Blockchain is also utilized to build an authentication system for reliable authentication and information sharing among different edge-based IoT platforms [28]. In [24] [67], a trusted access control scheme for energy sharing and distribution is designed using blockchains. Vehicular network [42], resource management [50], and resource allocation [69] are some of the other applications that use blockchain to achieve performance and trustworthiness. Nonetheless, the challenges of maintaining hierarchical ledgers, processing cross-domain transactions, and establishing consensus in presence of mobile devices are not addressed in these studies.

Finally, in comparison to mobile databases [33] [10], while Saguaro has a similar architecture, the trust model (e.g., Byzantine nodes), the level of mobility (only edge vs every node), and how Saguaro establishes consensus and tracks mobility are different.

8 Conclusion

In this paper, we proposed Saguaro, a hierarchical permissioned blockchain system designed specifically for wide area networks. Saguaro leverages the hierarchical structure of wide area networks to enable effi-
cient processing of cross-domain transactions using coordinator-based and optimistic consensus protocols. Moreover, Saguaro addresses the mobility of edge devices in wide area networks by introducing a delay-tolerant mobile consensus protocol. Eminent applications of Saguaro include cross-companies micropayment and global regulation over the gig economy. The experimental results reveal the efficiency of Saguaro in processing cross-domain transactions and transactions initiated by mobile devices especially in wide area networks where the involved nodes are far apart.

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