# WedgeChain: A Trusted Edge-Cloud Store With Asynchronous (Lazy) Trust

Faisal Nawab University of California, Santa Cruz Santa Cruz, CA 95060 fnawab@ucsc.edu

#### Abstract—

We propose WedgeChain, a data store that spans both edge and cloud nodes (an edge-cloud system). WedgeChain consists of a logging layer and a data indexing layer. In this study, we encounter two challenges: (1) edge nodes are untrusted and potentially malicious, and (2) edge-cloud coordination is expensive. WedgeChain tackles these challenges by the following proposals: (1) Lazy (asynchronous) certification: where data is committed at the untrusted edge and then lazily certified at the cloud node. This lazy certification method takes advantage of the observation that an untrusted edge node is unlikely to act maliciously if it knows it will be detected (and punished) eventually. Our lazy certification method guarantees that malicious acts (i.e., lying) are eventually detected. (2) Data-free certification: our lazy certification method only needs to send digests of data to the cloud-instead of sending all data to the cloud—which enables saving network and cloud resources and reduce costs. (3) LSMerkle: we extend a trusted index (mLSM [32]) to enable indexing data at the edge while utilizing lazy and data-free certification.

#### I. INTRODUCTION

To support processing this huge volume of data in edge and IoT applications, the data management solution must be capable of fast data ingestion at the edge—closer to data sources. This is critical for two reasons: (1) many applications require real-time processing—such as interactive mobile applications and time-critical processing in Industry 4.0 and autonomous vehicles. (2) many applications—such as large-scale video analytics and smart city applications—produce huge amounts of data at a large number of locations that would lead to increased costs for cloud communication and computation.

However, processing data at the edge is complicated by the following challenges: (1) Edge nodes are untrusted. This is because the edge node might be operated by a third-party provider outside of the administrative domain of the data owner. This can also be due to inexpensive or unmanaged edge nodes being more susceptible to malicious breaches. (2) Edge-cloud coordination is expensive in terms of latency (round-trip times are in the order of 100s of milliseconds to seconds) and bandwidth (applications pay for data transfer costs between the data center and the Internet). This means that relying on trusted nodes—in a trusted cloud or private cloud in the administrative domain of the owner—to authenticate the data is expensive, and thus must be left out of the execution path of requests and only utilized for asynchronous tasks.

In this paper, we propose *WedgeChain*, an edge-cloud data store that provides both logging and indexing of data for edge and IoT applications. WedgeChain enables both an efficient

and trusted data storage and access. In WedgeChain, the system model consists of authenticated clients that produce data and send signed copies of the data to untrusted edge nodes. The edge nodes service data access requests in coordination with a trusted private cloud node that ensures that untrusted edge nodes are not acting maliciously by providing an inconsistent view of data<sup>1</sup> In WedgeChain, we propose the following three features:

(1) Lazy (asynchronous) certification enables committing directly at the untrusted edge node and then asynchronously verifying with the cloud node that an edge node did not act maliciously. Specifically, the role of the cloud node is to prevent edge nodes from giving inconsistent views of the system to different clients. If an edge node is caught giving inconsistent views, then it is punished. The way WedgeChain implements this feature is by making the untrusted edge node provide a signed message to the client that the data is committed. This signed message is used by the client to prove that the edge node lied in case the data was not actually committed. Our observation is that in edge-cloud environments, nodes identities are known (e.g., an edge node belongs to an IT department). Therefore, an untrusted edge node would not act maliciously if it knows that it will be caught and punished. The punishment should be severe enough to outweigh the benefit of the malicious act.

(2) Data-free certification allows the certification at the cloud to be performed using the data's digest which is smaller than the data being certified. This allows reducing the size of edge-cloud communication. This is possible because agreement on the digest of data translates to agreement on the data itself if the digest is a one-way hash function.

(3) LSMerkle implements a fast-ingestion trusted index at edge nodes that utilizes the lazy and data-free certification strategies of WedgeChain. We integrate a new kind of indexing structures—called mLSM [32]—that combines the design features of LSM trees [24], [29] (used for high-velocity ingestion) and Merkle trees [25] (used for trusted data storage and access.) LSMerkle uses mLSM as a data structure, replacing the memory component with a WedgeChain log/buffer and building the edge-cloud protocol around it to update and compact the mLSM structure in cooperation with the cloud node. (This integration is needed for key-value operations

<sup>&</sup>lt;sup>1</sup>In the remainder of the paper, the terms cloud and trusted cloud refer to a private cloud that is in the administrative domain of the application owner.

only; WedgeChain logging data operations do not require the integration of a Merkle tree structure.)

In the rest of this paper, we present background in Section II. Then, we present the model and design of WedgeChain and LSMerkle in Sections III to V. An experimental evaluation is presented in Section VI followed by a related work discussion in Section VII. The paper concludes in Section VIII.

# II. BACKGROUND

#### A. Target Use Cases

We target edge, IoT, and mobile applications where data is generated in huge volumes and/or have workloads with realtime requirements. Applications with real-time requirements, sending data to be processed to a potentially faraway cloud node is infeasible as it can take hundreds of milliseconds to seconds to receive a response (not counting the time to process the data). For example, interactive mobile applications—such as Virtual and Augmented Reality-based applications—require a latency of only tens of milliseconds, which gives enough time to process the frames and leave no time for widearea communication. This is also the case for mission-critical applications in Industry 4.0 and autonomous vehicles.

In this paper, we use the term edge to represent any type of resources that are close to users and sources of data. Edge devices range from the client's personal devices (*e.g.*, a router or cluster of nodes in a building or university campus) to third-party providers of edge data center technology, such as micro and mobile data centers. The range of these resources are sometimes referred to as mobile-edge computing, fog computing, and edge computing.

The challenge with leveraging edge infrastructure is that edge resources-in many cases-are not in the same control domain as the application owner and client and thus might be untrusted. For example, consider a smart traffic application where a state government is monitoring traffic to provide better routes and traffic signals to vehicles and traffic controls such as traffic lights and ramp meters. The data in this application includes information from sensors and cameras that are placed around the city as well as government-owned or contracted public transport. The state government (the owner of the application) has access to the government data center that is faraway from the city (it is typical for data centers to be placed in remote areas.) Therefore, the application utilize edge resources at the city to enable fast response to traffic conditions (e.g., reacting swiftly to a traffic accident to reroute and change the flow in ramps).

Although the application owner might have access to data sources and traffic sensors around the city, it does not have compute resources that are capable of data storage and processing at the scale of this application. Therefore, it utilizes edge machines that are operated by other entities outside of the owner's administrative domain. This includes one or more of the following: (1) third-party edge service providers that rent out compute resources close to the city. (2) Independent contractors such as private transportation companies that may integrate their vehicles with edge resources to act as mobile edge resources. Both these types of edge resources (edge service providers and independent contractors) are untrusted by the application owner. Therefore, there is a need to maintain the integrity of the data.

This direction of utilizing edge resource providers is now starting to manifest as services provided by various entities including public cloud providers. For example, Amazon AWS services such as Amazon Wavelength [3] are partnering with telecommunication providers such as Verizon, Vodafone, and SK telecom to allow Amazon AWS cloud compute to be hosted on their edge resources (e.g., cellular towers and 5G infrastructure). Similarly, Microsoft Azure partnered with AT&T for the same purpose [1]. (This corresponds to edge providers in the example above.) Similarly, other cloud services (such as Amazon AWS IoT Greengrass [2]) allow customers to deploy cloud functions on the customer's edge devices. In these types of applications, operations on user's edge devices must be performed in a trusted manner. (This corresponds to independent contractors in the example above.)

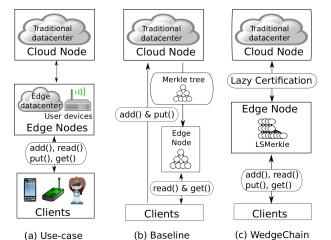
Figure 1(a) shows an example of an edge-cloud deployment. Clients access the data or generate data from their devices and send data to the WedgeChain data system that consists of edge nodes and a cloud node. There are two types of data requests. The first is for data logging and streaming requests, which consists of add() and read() operations. The other type of data access is for key-value requests, which consists of put() and get() key-value operations.

Each *edge node* handles the storage and processing for a subset of the clients (*i.e.*, a partition of the data). Specifically, each client is associated with a single partition/edge node. Thus, finding the data that pertains to a client is done by directing the request to its corresponding client. Due to the spatial locality of edge applications, we focus on single-partition operations in this work. Edge nodes can be edge and micro datacenters or user devices. The *cloud node* maintains the rest of the application's data (and potentially a backup of a subset of the data on edge nodes). It also helps edge nodes in certifying data and running maintenance tasks.

# B. Relevant Technologies

1) LSM Trees: Log-Structured Merge (LSM) Trees are designed to support fast ingestion of data. LSM trees batch updates in pages and merge them with the rest of the data later. This moves merging the data out of the execution path of updates, hence making ingestion more efficient. There are many LSM tree variants [24], [29]. In general, the tree is structured into L levels. Level 0 is where new pages are appended and is maintained in main memory. Once the number of pages in Level 0 exceeds a threshold, then the pages are merged with the next level, Level 1. Levels 1 and higher are persisted in storage. Each level has a threshold, when exceeded, pages are merged with the next level. The details of these operations and structure vary across designs [24].

2) *Merkle Trees:* Merkle trees [25] allow an untrusted node to serve data in a trusted way. Specifically, it allows the untrusted node to provide a proof of the authenticity of the data that are originally generated and signed by a trusted node. The



(a) Use-case (b) Baseline (c) WedgeChain Fig. 1: An overview of the use-case, edge-cloud baseline, and architecture of WedgeChain.

way Merkle trees are usually designed is by dividing the data into pages. Then, Each page is hashed with a cryptographic hashing function. The hashes of the pages represent the leaves of the Merkle tree. Then, each pair of leaf nodes are hashed to construct a node at the next level of the Merkle tree. This is continued until there is only a single node in a level. This node is called the *Merkle root*. A trusted entity (*e.g.*, the trusted cloud node in our case) signs the Merkle root to certify the authenticity of the data. The untrusted node uses this signed Merkle root to provide a proof to clients that the data is authentic. In this work, we leverage Authenticated Data Structures such as Merkle Trees to enable key-value access to data from untrusted edge nodes. However, these structures are not needed for logging data operations which utilize lazy (asynchronous) trust directly.

#### C. Baseline Solutions and Their Drawbacks

Given the use case and relevant technologies introduced in this section, it is possible to come up with a straight-forward solution for edge-cloud data management with untrusted edge nodes. We call this *edge-baseline* and show it in Figure 1(b). Specifically, clients send their add() and put() requests to the (trusted) cloud node. Then, the cloud node regenerates the Merkle tree to account for the new updates, sign the Merkle root, and send the Merkle tree to the untrusted edge node. This enables the edge node to serve data access requests by using the signed Merkle root as proof of the data's authenticity.

However, this straight-forward solution has a drawback. Whenever data needs to be logged (using add) or inserted into the data structure (using put), the cloud node is in the path of execution. Our proposal WedgeChain overcomes these limitation by employing a lazy (asynchronous) certification strategy that takes the cloud node out of the execution path of add and put operations—see Figure 1(c). In WedgeChain, data access requests are served immediately from the edge nodes without having to wait for the cloud node to certify the data. To make sure that the edge node does not lie, the edge node provides a temporary proof in its response. This temporary

proof can be used later by the client to detect if the edge node lied. If the edge node lied to the client, then the client can use the temporary proof it received to prove that the edge node is malicious and thus is able to punish the malicious node.

#### D. Security Model Assumptions

Our lazy certification method is enabled by observing that some security model characteristics of existing systems can be relaxed in applications of edge-cloud systems with a hybrid trust model. Specifically, we make the following assumptions about the security model (and how they are reflected in the smart traffic application we presented above):

1. The application owner can enforce a punishment that would deter untrusted edge nodes from committing malicious acts. In the smart traffic application, for example, this assumption can hold by enforcing a monetary and/or legal punishment. For both edge service providers and independent contractors, since they are known entities, the application owner can enforce the punishment.

2. The application can prevent an untrusted node that acted maliciously before from reentering as an edge node. In the smart traffic application, because the real identities of both edge providers and independent contractors are knows, and they cannot fabricate new identities, the application owner can prevent their reentry.

3. Malicious acts cannot lead to catastrophic consequences. This condition can be trivially satisfied by handling critical operation that can be catastrophic at the cloud. The definition of catastrophic depends on the application. In our smart traffic application, for instance, destroying the data at an edge location might not be deemed catastrophic as the application state depends on the collective information of a large number of sensors/cameras and the small potential of nodes acting maliciously (due to assumption 1 above) outweighs the inaccuracy and potential lost of information.

#### III. SYSTEM AND DATA MODEL

The system consists of three types of nodes: (1) cloud nodes that are trusted (non-byzantine). Each cloud node can be backed by a high-availability cluster for availability. For ease of exposition, however, we assume that there is one cloud node. The role of the cloud node is to ensure that edge nodes are not providing an inconsistent view of data to clients. (2) edge nodes that are not trusted. An edge node receives data from clients and stores it locally in the form of a log or index. It also receives requests to access stored data from clients. (3) clients are authenticated nodes that generate and consume data from edge nodes and devices. The generated data is signed and sent to edge nodes for processing.

Each edge node maintains a log that pertains to a subset of clients (edge devices). For example, in an application with IoT sensors, each edge node maintains the data generated by a set of the IoT sensors (*i.e.*, clients). Also, each client belong to a single partition on a single edge node. Each block is a batch of data entries. Clients may read a block by issuing a request with the block's id to the edge node. Block ids are unique monotonic numbers that are assigned by the edge node (the ids

are unique relative to an edge nodes, but are not unique across edge nodes.) In addition to the log, each node may maintain an index data structure. We present more details about the index data structure in Section V.

## IV. WEDGECHAIN LOGGING

In this section, we present WedgeChain and the detailed design of the logging component. In Section V, we present the indexing component.

## A. Logging Interface

The edge node's interface consists of the following calls (all message exchanges are signed by the sender):

- add(in: entry, out: bid, (optional) block): this call adds an entry to the next block at the edge. The edge node returns the block id (*bid*) that contains the entry. If requested, the edge node returns the newly formed block that contains the entry.
- read(in: bid, out: block, bid, proof): this function takes a block id number as input and returns the corresponding block in addition to a proof of the authenticity of the block. This proof might be either (1) *in-progress (Phase* I) or (2) *final (Phase II)*. More details about proofs and commit phases later in the section.

Each of these logging operations is performed on a single block, independent of prior blocks. The cloud node ensures that untrusted edge nodes are not giving an inconsistent view of the blocks. Because logging operations operate at the level of single blocks, the detection of malicious behavior by the cloud can operate at the level of single independent blocks as well. This limits the type of stateful operations running on the log. For this reason, we also present a key-value operations that maintain state across blocks in Section V.

#### B. WedgeChain Overview

**Guarantees.** The main goal of WedgeChain is to support adding to and reading from the edge node's log while guaranteeing *validity* and *agreement*. Validity is a guarantee that an entry in the log is one that has been proposed by a client. Agreement is a guarantee that any two nodes reading the same block will observe the same content.

Lazy (Asynchronous) Certification. Lazy certification distinguishes between two types of commitments: *initial commit* (*Phase I Commit*) and *final commit* (*Phase II Commit*). Initial commit is the commitment done without involving the trusted cloud node. Instead, the untrusted edge node provides a temporary proof to the client. This temporary proof can be used by the client later to prove that the edge node promised to add the entry to a specific block. Therefore, a malicious edge node can be detected and punished. The final commit phase is when the trusted cloud node authenticates the request either ensuring that the edge node did not lie in its response or proving that it lied and should be punished.

Initial (Phase I) Commit is Sufficient to Make Progress. The ability to detect malicious behavior allows a client to commit immediately and make progress after Phase I commit. This is because an untrusted edge node does not have an incentive to lie since it knows that it will eventually be detected. This assumes that the harm of the penalties/punishments that would be applied to a malicious edge node outweigh the benefit of the malicious activity.

**Coordination Pattern (Phase I Commit).** In the rest of this section, we cover how WedgeChain enables adding and reading from a single edge node's log. Consider a scenario with a client c, an edge node e, and a cloud node  $\mathcal{L}$ . The client c can be an IoT sensor or edge device that generates data continuously. Assume that c sends all its data to e for it to be stored in its log. Client c sends an add request to e to add entries. Upon receiving the add request, e batches the client's sent entry, m, with other requests to be committed as part of the next block. Once a block is ready, the block id and the block containing the entry m are returned to the client c. At this time, the entry and block are Phase I Committed.

**Coordination Pattern (Phase II Commit).** Concurrently, the edge node e sends the digest of the block (that contains both the content and the block id) to the cloud node  $\mathcal{L}$ . The digest must be constructed using a one-way hash function. Then,  $\mathcal{L}$  sends back a message that contains the signed digest of block *bid* if it is the first time it receives a digest for block *bid*. Otherwise, the cloud node detects a malicious activity and rejects the request. The signed message from  $\mathcal{L}$  acts as a certification that this is the block digest that is committed. The cloud node also maintains the digests of all committed blocks of edge nodes. At this time, the entry and the block are Phase II Committed.

**Data-Free Coordination.** Note that the edge node only needs to send the digest (constructed with a one-way hash function) to the cloud node during Phase II Commit. This is beneficial because it reduces the edge-cloud communication overhead. Data-free coordination is possible because the digest is used as a proxy of the actual content of the data. Therefore, if all clients agree on the committed digest d of a block B, then they also agree on the content of the block B.

**Certification.** A digest that is accepted and signed by the cloud node is called a *certified digest* and the corresponding block is called a *certified block*. A client can ensure that its entry is Phase II Committed by checking whether the block it received got certified by the cloud node. This can be done by contacting the cloud node directly or asking the edge node to forward the signed digest. This certification also guarantees agreement, since an edge node cannot certify two different blocks as Phase II committed with the same block id.

**Reads.** The signed digest is also used to certify reads. When a read request is sent to the edge node, the edge node responds with the block and the signed digest (denoted proof in the interface). The client can then verify the authenticity of the block by computing the digest and comparing it to the proof. For blocks that are not yet certified by the cloud node, the edge node may utilize lazy certification and send the block and an empty proof. The client will get the certification from the cloud node eventually and can detect whether the edge node was malicious, similar to the case of the add interface. If the edge node lied in its response, then the client can show the response to the read request as a proof and thus punish the edge node.

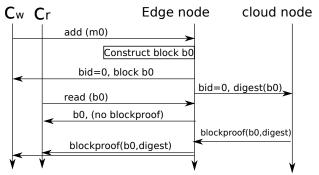


Fig. 2: An example of the coordination necessary to add and read blocks in WedgeChain.

Algorithm	1.	Client	algorithm	to	hhe	an	entry	
AIYOHUUUU		CHEHL	aigonunn	w	auu	an	CILLIV.	

- 1: on AddNewEntry (in: entry) {
- 2: Send add(\$entry) to edge node
- 3:  $\$block,\$bid \leftarrow edge node response$
- 4: Verify that the entry is in *\$block*
- 5: Mark *\$entry* as Phase I Committed
- 6: Wait until block-proof is received
- 7:  $\$blockProof \leftarrow block-proof$  message from cloud node
- 8: Verify that digest(\$block\$id) = \$blockProof
- 9: Mark add as Phase II Committed
- 10: }

This ability to prove maliciousness would deter malicious activity and enable clients to consider the add committed with high certainty even before Phase II Commitment.

#### C. Example

Consider a scenario (Figure 2) with two clients,  $c_w$  and  $c_r$ , an edge node, and a cloud node. Initially,  $c_w$  sends the data entry  $m_0$  to the edge node. The edge node creates a block  $b_0$  with  $m_0$  in its payload. Then, it sends the signed block and its id back to  $c_w$ . Client  $c_w$  uses this response to terminates its Phase I Commit and continues operation while lazy certification is performed in the background. Asynchronously, the edge node sends the digest of  $b_0$  to the cloud node to be certified (Note that only the digest need to be sent, not the whole block.) While the edge node is waiting for the cloud node, the other client,  $c_r$ , sends a request to read  $b_0$ . The edge node responds with the content of  $b_0$  but with no certification from the cloud (called *blockproof* in the figure). Client  $c_r$  uses this response to terminates its Phase I Commit and continues operation. Afterward, the certification is sent from the cloud node to the edge node for  $b_0$ . The edge node forwards the certification (called blockproof in the figure) to both  $c_w$  and  $c_r$ , which terminates their Phase II Commit.

## D. Algorithms

1) Adding to the log: The following are the algorithms to add a block to the edge node's log.

Client algorithm (Algorithm 1). The client constructs an add message that contains the data it wants to add to the log. In our model, the client—which represents an IoT sensor or edge device—is authenticated. To trust the add message,

the client includes a signature. The client sends the signed add message to the (untrusted) edge node. Then, it waits until it hears a response from the edge node that contains the contents and block id of the block that contains the added entry. This response is signed from the edge node (This is important since the client can use this signed response in the event of a dispute to punish the malicious node.) The client verifies that its entry—that corresponds to the add request—is part of the block.

After hearing the add-response message from the edge node and verifying its contents, the client marks the corresponding add request as a *Phase I Commit*. This Phase I Commit represents the following guarantee:

**Definition** 1: (Phase I Commit Guarantee) If an entry is Phase I Committed in block *bid*, then that implies that either (1) the entry is part of block *bid* or, otherwise, (2) the client can successfully prove that the edge node is malicious and thus the edge node would be punished.

Eventually, the client receives a block-proof message from the cloud node—that might be forwarded by the edge node. The block-proof message is signed by the cloud node to ensure its authenticity. It contains the block id, *bid*, and its corresponding digest. Upon receiving this message, the client marks the add request as a *Phase II Commit* which guarantees:

**Definition** 2: (Phase II Commit Guarantee) If an entry is Phase II Committed in block *bid*, then this means that the edge node cannot report another block for this block id as Phase II Committed. Therefore, it is impossible for two clients to disagree about the content of a block if their operations on it were both Phase II Committed.

Edge node algorithm. When an edge node receives an add request, it verifies the authenticity of the message by checking the signature and that it belongs to a certified client. Then, it adds it to a buffer. Once the buffer is full, a new block is constructed with the entries in the buffer and appended to the log. Then, the edge node constructs an add-response message for each entry in the block (the add-response messages can be aggregated and sent together if they belong to the same client.) The add-response message is signed by the edge node and includes the block and block id. These messages are then sent to the corresponding clients.

After adding the block to the log, the edge node sends a signed block-certify message to the cloud node that contains the block id and block digest. The cloud node sends back a signed block-proof message with the block id and digest. The edge node forwards the block-proof message to all clients that added entries in the corresponding block.

**Cloud node algorithm.** The cloud node receives a signed block-certify request from an edge node that contains the block id and digest. It verifies that it did not hear any prior requests to certify a block with the same block id. If it is the first, then it sends back the block-proof message with the block id and digest. Otherwise, it flags the edge node as malicious.

2) **Reading from the log**: The following are the algorithms to read a block.

**Client algorithm.** To read a block, a client sends a read request with the block id that it wishes to read to the edge node. There are three cases:

- 1. *The block is not available:* The edge node responds with a signed message saying that the block is not available. At this point, if the client is suspicious that the edge node is malicious and lying about the unavailability of the block, it can send a request to the cloud node asking whether the block was reported.
- 2. *Phase II Commit read:* A signed response that includes the block and a proof. The proof is a block-proof message that has been signed by the cloud node. The client verifies the block-proof and terminates the read.
- 3. *Phase I Commit read:* A signed response that includes the block but without a proof. In this case, the client waits for a block-proof to be sent from the cloud node. After receiving the response, but before receiving the block-proof, the read is considered Phase I Committed. The client can successfully dispute the read response in the case it turns out that the edge node lied in its initial response. Once the block-proof is received, the read is considered Phase II Committed.

Edge node algorithm. When an edge node receives a read request, it checks whether the requested block is available. If it is not, then the edge node responds negatively. Otherwise, the edge node responds with the block. If a block-proof is available, then it is sent with the block. Otherwise, an empty proof is sent. Eventually, when a block-proof is received from the cloud node, the edge node forwards it to the client.

## E. Security Threats

Replay attacks. A replay attack is performed by the malicious edge node repeating a valid client request more than once. To overcome this attack, existing techniques can be integrated without incurring extra communication overhead to the cloud. The choice depends on the what the application permits. Specifically, in many edge applications, requests are idempotent which means that applying the request more than once has the same effect as applying it once, e.g., a sensor indicating that the temperature reading is x at timestamp tshas the same effect when repeated. Generalization of this using timestamps, session ids, and prior state (*i.e.*, explicitly defining the prior state in the request) can all be integrated from the client-side without affecting WedgeChain. WedgeChain can also be extended to provide support to make any arbitrary request idempotent. This can be done by making each request signed by the client for a specific log position. Specifically, the client first reserves a log position via a round of messaging with the edge node. Then, the client signs the request with the reserved log position. Because the request is signed for a specific log position, any other client would not accept the request if it is in another log position. This design does not lead to extra edge-cloud communication. Also, the reservations can be mandatory (the block waits for all reserved requests) or best-effort (if some reserved requests are late, then they are discarded, and the client has to do another reservation.)

**Omission attacks.** A malicious edge node might respond negatively to a read request of a log position that is actually filled (either to delay the response or because data was maliciously destroyed). Minimizing the effect of this omission attack can be performed by asynchronous gossip propagation from the cloud node to clients (either through the edge node or directly from the cloud node). These gossip messages are signed by the cloud node with a timestamp and the log size as of that timestamp. A client can use these gossip messages to know that all log positions smaller than the log size are filled. This still leaves the opportunity for omission attacks on recent data. The time-window of this threat is a function of the frequency of gossip messages. (We also discuss omission attacks as they pertain to key-value operations in Section V-D.)

**Disputes.** A dispute can arise if the client discovers that the edge node has lied in its response. There are malicious acts that can be detected trivially, such as responding with a digest that does not match the block or signing with the wrong signature. Other than these types of malicious acts, an edge node might respond to an add or read request with incorrect information that cannot be immediately detected:

- 1. add-response: the edge node responds that the entry is going to be in block *i*, but then the actual certified block *i* does not include the entry.
- 2. read-response: the edge node responds with block i and no proof, but it turns out the block is not the one committed with id i.

In both cases, the client discovers the malicious act after the call has entered Phase II Commit. Because the edge node lied about the content of the block, it cannot provide the block-proof message, since it must be signed from the cloud node. The client waits for the block-proof message. If it does not receive it for a predefined time threshold, it sends a request to the cloud node with the block id and digest. The cloud node detects that the digest does not match what is reported by the edge node. In such a case, the edge node is punished.

A dispute can also be sent if an omission attack is detected (described above by using the gossip from the cloud node). A dispute message is sent to the cloud node to force the edge node to respond, and if it does not, then a punishment procedure starts.

Availability attacks such as an edge node that delays responding to messages (but responds correctly) to degrade the system performance are more complicated and remain as an open problem.

## V. LSMERKLE DESIGN

In this section, we extend WedgeChain with a data indexing structure that enables accessing the key-value pairs in the log through a key-value interface of get and put operations.

Our proposal provides an index on top of WedgeChain that is both efficient and trusted. This means that a potentially malicious edge node can respond to client requests without having to involve the cloud node. Our data index—called LSMerkle—builds upon mLSM [32] and extends it to work in the edge-cloud environment of WedgeChain and to support lazy (asynchronous) certification. Specifically, LSMerkle uses mLSM as the data structure and builds around it a protocol to coordinate with clients and the cloud node the update and compaction operations as well as integrating a WedgeChain log/buffer as the memory component to allow Phase I Commit with asynchronous trust.

## A. System and Data Model

The indexing structure extends WedgeChain. This means that it inherits the system model of WedgeChain that consists of clients, edge nodes and a cloud node. The LSMerkle tree is stored in the edge node and its interface consists of:

- put(IN: key, value, OUT: block, bid): this request takes a key-value pair and applies it to the index. The return values are ones that correspond to the block where the key-value pair are added.
- get(IN: key, OUT: value, index\_proof): This call returns the value of the requested key and a proof of the authenticity of the response. We provide more details about the index\_proof, but at a high-level it consists of certified parts of the index that prove that the value is part of the index. It also includes certifications similar to log read Phase I and Phase II Commits.

#### B. LSMerkle Design

We propose *LSM Merkle tree* (LSMerkle), a data indexing structure that can be integrated into WedgeChain and utilize lazy (asynchronous) certification. LSMerkle builds on mLSM [32] that combines techniques from LSM trees (for fast ingestion) and Merkle trees (for trusted data access). The immutable-nature of updates in mLSM enables us to extend it to support lazy certification and overcome the problem of baseline solutions (Section II-C).

**Structure and configuration.** The structure of the LSMerkle tree consists of n levels—structured in the same way as a LSM tree. Each level has a threshold number of pages, *i.e.*, the threshold of level i,  $L_i$ , is  $|L_i|$  pages. A page represents the updates in a block. The first level,  $L_0$ , resides in memory and contains the most recent updates to the LSMerkle tree. Each page consists of put operations in addition to meta-information such as the range of keys in the page and a timestamp of the time the page was created.

For the rest of this section, we assume that the number of levels is 3 and the threshold number of pages per level are: 2 for levels  $L_0$  and  $L_1$ , and 4 for  $L_2$ . This is not a practical configuration, but is chosen for ease of exposition and to simplify the presented examples.

**Merklizing LSM.** The state of a LSMerkle tree is shown in Figure 3(a). Each block in the figure contains two put operations ( $x_i$  denotes the  $i^{th}$  version of the key x.) Level  $L_0$  in LSMerkle is a WedgeChain log/buffer as described in Section IV, which allows Phase I Commit blocks of key-value operation using asynchronous trust before they are compacted by the cloud. The LSMerkle tree maintains a hash for each page in  $L_0$ . This hash is certified by the cloud node through block-certify and block-proof messages, similar to certifying

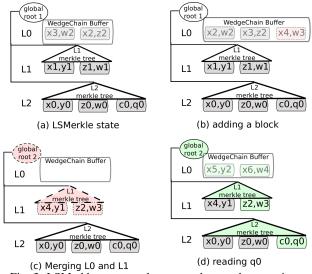


Fig. 3: LSMerkle tree sample state and example operations.

blocks for add() operations. For every other level in the LSMerkle tree, a Merkle tree is maintained. For example, if  $L_1$  has two pages, then it has a Merkle tree,  $LSM_i$ , consisting of two leaf nodes, where each leaf node contains the hash of a page. The Merkle root of  $LSM_i$  is certified by the cloud node. LSMerkle maintains a *global root* that is the hash of all Merkle roots.

**Put operations.** When a block is ready to be inserted in the log, it is also added as a new page in  $L_0$ . The new page contains the put data operations. The certification of the block in log and the certification of the hash of its corresponding page in  $L_0$  are going to be done through the same block-certify and block-proof message exchange with the cloud node. Operations on pages in  $L_0$  would leverage lazy (asynchronous) certification in the same way it is leveraged for put operations.

**Merging** If the number of pages in the edge node exceeds the threshold in  $L_0$ , then all pages in  $L_0$  are merged with the pages in the next level,  $L_1$ . More generally, when the number of pages in level  $L_i$  exceeds  $|L_i|$ , the pages in  $L_i$ are merged with the pages in  $L_{i+1}$ . The merge protocol is an asynchronous protocol that does not interfere with the normal operation of the LSMerkle tree. Consider a merge of pages from  $L_i$  into pages in  $L_{i+1}$ . The edge node sends a copy of all pages undergoing the merge in  $L_i$  and  $L_{i+1}$  and the corresponding Merkle tree hashes to the cloud node. When the cloud node receives the pages, it verifies the authenticity of the pages and their state by checking the associated certification proofs. Then, it performs the merge of the pages, similar to how a LSM tree merge is performed. The resulting merged pages replace the old pages.

The cloud node computes the new level's Merkle tree to derive the corresponding Merkle root and global root. Then, the cloud node sends back the new pages for in addition to the signed Merkle root for the changed levels and a new signed global root. When the edge node receives the merge response, it replaces the pages undergoing the merge with the new merged pages. Also, the Merkle roots and global root are updated with the received ones.

**Reading.** Like an LSM tree, the LSMerkle might have redundant versions of the same key. It is possible that the same key has multiple versions in different pages in  $L_0$ . Also, a key might have versions in more than one level. However, levels other than  $L_0$  are guaranteed to have at most one version of each key because the redundancies are removed in the merge process. The read algorithm should take these redundancies in consideration to ensure that only the most recent version is returned. This is trivial in regular LSM trees. However, in LSMerkle, we need to return the most recent version in addition to a proof that it is indeed the most recent version.

To prove that a returned version of a key is the most recent one, the edge node must provide a proof that all pages in  $L_0$ and pages in other levels do not have a more recent version. Consider the case when the edge node finds the most recent version in a page p in  $L_0$ . In this case, the edge node only needs to send the page p in addition to the other pages in  $L_0$ . The client checks that the returned p has the most recent version by reading the other  $L_0$  pages. There is no need to return pages at other levels because even if they contain other versions of the key, they are guaranteed to be older versions.

Now, consider the case when the most recent version is in page p in level  $L_i$ , for i > 0. The edge node returns p. Also, it needs to return a proof that every level  $L_i$ , where j < i, does not contain a more recent version of the key. All pages in  $L_0$  need to be returned in the response because they all might have a more recent version of the key than the one in  $L_i$ . For other levels between  $L_0$  and  $L_i$ , the edge node needs to return the page that has the range that contains the key. For example, in  $L_i$  (0 < j < i), keys are sorted across pages. Only one page has the range that include the key. The edge node returns such page for each level between  $L_0$  and  $L_i$ . Each page contains special values called min and max that denote the minimum and maximum keys in the range of that page. We enforce that the first page has a min of 0 and the last page has a max of infinity. Also, every two consecutive pages  $p_x$  and  $p_y$  have the invariant that  $p_x.max = p_y.min - 1$ . This ensures that a client can use the min and max to verify that the key it is looking for is not in any other page in that level.

When the client receives the response from the edge node, it verifies the authenticity of the response and that the returned version is indeed the most recent one from the returned state. Afterwards the read terminates. Some of the returned blocks might not have been certified by the cloud node in the response. In this case, the read is considered in the Phase I Commit. The client waits for the block-proof to enter the Phase II Commit.

If the key does not exist, then the edge node returns the intersecting pages from all levels in addition to all pages in  $L_0$  to the client with their corresponding Merkle roots and global root.

# C. Example

We now present an example of doing put, merge and read operations on the LSMerkle in Figure 3(a). The first example

is of adding a new block with new values of keys  $x(x_4)$  and  $w(w_3)$ . This is shown as the new page (shaded with the color red) in Figure 3(b). This new block triggers a merge request since the number of blocks in L0 exceeds the threshold of two blocks. Figure 3(c) shows the outcome of the merge operation. The edge node sends all the blocks in L0 and L1 to the cloud node, and the cloud node responds with the merged blocks. The edge node updates the tree by emptying L0 and L1 and adding the received merged blocks to L1. The Merkle tree for L1 and the global root are updated to reflect the changes (all changes in the LSMerkle are represented with the components shaded with the color red.)

Figure 3(d) shows an example of reading the key q. (we assume that there are two blocks added in L0 before the read.) Since the most recent value of the key is in L2, the edge node returns the intersecting pages in both L1 and L2 along with their corresponding partial Merkle trees. The edge node also sends all the pages in L0 in addition to the signed global root. (all the components that form the response to the read request are shaded with the color green.)

## D. Read Data Freshness

The LSMerkle algorithms ensures that the returned value is one that has been added in the past and is part of a consistent snapshot of the LSMerkle tree. However, LSMerkle does not guarantee that the read is going to return the most recent value. This is because an edge node might serve the read from a stale snapshot of the data. Enforcing that a read would return the most recent value requires extensive coordination between clients, edge nodes and the cloud node, which we view as prohibitive. Alternatively, we propose a guarantee of reading from a *freshness window*. For example, a guarantee that the read returns the state from a consistent snapshot as of a time no longer than X seconds ago. To enforce this freshness property, the following changes need to be applied to our algorithms:

(1) The cloud node timestamps the global root of each merged LSMerkle. The signature would be of both the timestamp and the global root.

(2) When a client receives a read response, it also checks the timestamp of the received global root and verify its authenticity using the signature. If the timestamp is within the freshness window, the client accepts the response. Otherwise, it retries the request.

An issue may arise if updates are not happening frequently enough to trigger updating the global root by the cloud node. In such a case, the edge node can add no-op operations to trigger merges more rapidly and reconstruct the LSMerkle tree.

Effect of time synchronization bounds. Another issue is that of clock synchronization. Depending on the distance between nodes, current time synchronization technologies achieve synchronization with an accuracy of 10s to 100s of milliseconds. This limits the use of our technique to the bounds of time synchronization.

An alternative to the method we present above is to maintain more state information at the client side (e.g., similar to client-side session consistency solutions) that would allow a client to check whether the read state is consistent and fresh

TABLE I: The average Round-Trip Times in milliseconds between California and other datacenters.

by checking with its local client-side information. Another alternative is to establish a secure communication channel between the client and the cloud node to verify freshness.

## VI. EXPERIMENTAL EVALUATION

We present a performance evaluation of WedgeChain in this section. To emulate edge-cloud coordination, we run our experiments across geographically distributed Amazon AWS datacenters. In most of our experiments, one datacenter— California (C)—will act as the edge location, hosting clients and edge nodes and another datacenter—Virginia (V)—will host the cloud node. We vary the place of the edge and cloud nodes in some experiments across datacenters in California (C), Virginia (V), Oregon (O), Ireland (I), and Mumbai (M). The Round-Trip Times (RTTs) between the four datacenters range between 19ms and 238ms (Table I.) In each datacenter we use Amazon EC2 m5d.xlarge machines. Each machine runs Linux and have 4 virtualized CPUs and 16 GB memory.

We compare with a baseline that processes all requests in the cloud node. We call this baseline, cloud-only. We also compare with a baseline where all requests are certified first at the cloud and then sent to the edge node. This is the baseline we described in Section II-C. We call this baseline the edgebaseline. The cloud-only baseline represents the case where clients can fully trust the results since no edge nodes are involved in processing them. However, clients incur the widearea latency to the cloud for every request. The edge-baseline, on the other hand, represents the current way of utilizing untrusted nodes for data access, where data is certified first in the trusted node (the cloud node in our case) and then sent to the untrusted node (the edge node in our case.) In the edgebaseline implementation we tested with both a vanilla Merkle Tree as well as a mLSM as the trusted index component. The choice of the index did not have a significant effect on performance as the edge-cloud coordination dominated the performance overhead. The results shown are for using mLSM as the index in edge-baseline.

We use key-value operations in our experiments since it affects both logging and indexing components. We batch add and put requests in all experiments. Unless mentioned otherwise, each batch consists of 100 put operations, and the size of the value of each operation is 100 bytes. Each edge node maintains one partition of the data, which consists of 100,000 key-value pairs. In the experiments, we report the performance of one partition. The LSMerkle tree has four levels. The thresholds for the levels are 10, 10, 100, and 1000 pages for levels 0, 1, 2, and 3, respectively.

## A. Baseline Performance of Put Operations

In Figure 4, we vary the batch (*i.e.*, block) size from 100 to 2000 operations per batch. Figure 4(a) shows the latency results. WedgeChain achieves the lowest latency, which is

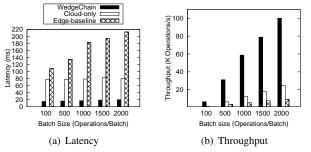


Fig. 4: The performance of Put operations while varying the block size

below 20ms. This latency corresponds to the Phase I Commit latency. This low latency is expected since it is the time needed to communicate with the nearby edge node. On the other hand, Cloud-only incurs a latency around 80ms which corresponds roughly to the round-trip time from California to Virginia in addition to the processing overhead. Edge-baseline also incurs a cost due to having to wait for the response from the cloud which leads to a latency higher than 100ms in all cases. Edgebaseline performs worse than Cloud-only due to the need to involve the edge node in the commitment of the block which requires more time.

As we increase the batch size, the latency increases slightly for WedgeChain from 15ms to 20ms and Cloud-only from 78ms to 83ms. However, Edge-baseline is affected significantly by the increase in the batch size resulting in increasing the latency from 109ms to 213ms. The reason for this increase is that both the edge node and cloud node are involved in the commitment of the block and are in the path of execution, which leads to stressing the network bandwidth resources faster than the other two approaches. WedgeChain masks the effect of this edge-cloud coordination by utilizing the concept of lazy (asynchronous) certification that removes the cloud node from the path of execution when adding blocks or performing put operations.

Throughput results are shown in Figure 4(b). Due to WedgeChain's low latency, throughput increases from 6.6K operations/s to roughly 100K operations/s, which is a 15x increase that results from multiplying the batch size 20 times (from 100 to 2000 operations per block.) Cloud-only's throughput experiences a 18.5x increase when varying the batch size from 100 to 2000 operations. The poor latency performance of Edge-baseline causes the throughput to scale poorly, where the throughput only doubles when increasing the block size from 100 to 2000 operations.

## B. Multi-Client and Mixed Workload

Figure 5 shows experiment results while varying the number of clients and read-to-write ratio. Figure 5(a) presents experiments with an 100%-write workload while varying the number of clients from 1 to 9. Increasing the number of clients allows more concurrency. This leads to an increase in throughput by 22-30% for WedgeChain and Edge-baseline. However, the increase for Cloud-only is much higher at 433% which enables

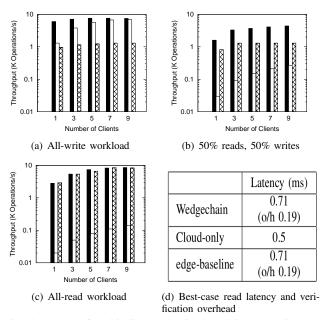


Fig. 5: Results of multi-client and mixed workload experiments

Cloud-only to catch up to WedgeChain throughput and be only 7% lower than the throughput of WedgeChain. The main reason for this is that by increasing the number of clients, Cloud-only is offsetting the overhead of communication (edgecloud latency) while not incurring the communication and computations overheads of WedgeChain. On the other hand, Edge-baseline suffers from the synchronous communication overhead which causes its latency to be the lowest out of the three.

Figure 5(b) shows experiments with a mixed workload of 50% reads and 50% writes. In this experiment, writes are buffered, but reads are interactive (we show a case that stresses read performance later in Figure 5(d)). Interactive reads are very expensive for Cloud-only as each read requires the client to wait for the response that takes a duration proportional to the edge-cloud latency. This causes the throughput of Cloud-only to reach only 270 operations/s while WedgeChain achieves 4K operations/s and Edge-baseline achieves 1.3K operations/s. The reason for Edge-baseline achieving a lower performance than WedgeChain is due to the 50% writes that incur the synchronous coordination overhead.

Figure 5(c) shows experiments with a read-only workload. In this experiment, WedgeChain and Edge-baseline perform similarly. In both solutions, interactive read operations involve the same steps of communication and verification for WedgeChain and Edge-baseline. However, Cloud-only requires communication with the cloud and since interactive reads requires the client to wait until the read is served, this leads to a high overhead and achieving a small fraction of the performance of WedgeChain and Edge-baseline.

The significant difference between the read performance of WedgeChain and Edge-baseline on the one hand and Cloudonly is due to the communication latency. However, Cloud-

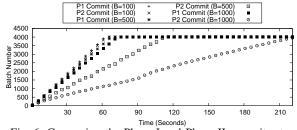


Fig. 6: Comparing the Phase I and Phase II commit rates.

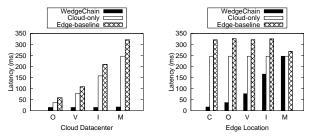
only does not incur the complex computations needed in edge nodes since its results are trusted. This would enable the cloud node to process more reads than what the edge nodes can process. Observing this while increasing the number of clients is challenging as it would require emulating a huge number of clients. Instead, we perform an experiment in Figure 5(d) where we measure the best-case read latency directly at the cloud node for Cloud-only and at the edge node for the others. WedgeChain and Edge-baseline achieves a similar read performance of 0.71ms, 0.19ms of which is due to the verification overhead performed at the client. Cloud-only, on the other hand, achieves a better latency of 0.5ms without incurring a verification overhead as the results are trusted.

#### C. Asynchronous Certification and Commit Phases

The performance advantage of WedgeChain is due in a large part to the concept of lazy (asynchronous) certification that distinguishes between two phases of commitment. In this section, we provide more insights about lazy certification by showing the relation between the two phases of commitment. Figure 6 shows the results of three experiments, each for a different batch size. In each experiment, WedgeChain commits 4000 batches (blocks). The figure shows how rapidly the batches are being committed by plotting the number of committed batches against the x-axis that represents time.

For the case of 100 operations per batch (B=100), the rates of both Phase I Commit (P1) and Phase II Commit (P2) are similar—the two plots are overlapping and the 4000 batches are committed within 60 seconds. This means that although Phase II Commit takes more time, it is happening at the same rate of the Phase I Commit. This is different when we start increasing the batch size. For the case of 500 operations/batch (B=500), there is a difference in the rate of P1 and P2 commits. P1 commit is still fast; committing the 4000 batches within 60s. However, P2 commits take more than 100s. The reason for this is that the buffering and processing of larger batch sizes lead the P2 throughput to be lower than the P1 throughput. This is the same case with larger batch sizes, such as the third experiment with 1000 operations/batch (B=1000).

The main takeaway of this set of experiments is the behavior of P1 and P2 commits and how WedgeChain is able to mask both the latency and throughput overhead of edge-cloud communication. Notice that in all cases, the P1 commit is still able to commit the 4000 batches in close to 60s, even if P2 commit takes much longer. This is the feature of lazy



(a) Varying the cloud node location (b) Varying the edge node location

Fig. 7: The latency of committing blocks of Put operations while varying the location of the cloud and edge nodes.

certification that we desire, which is masking the overhead of expensive edge-cloud coordination and enjoying the low latency and high performance that can be delivered by the nearby edge node.

## D. The Effect of Edge-to-Cloud and Client-to-Edge Latency

The performance advantage of WedgeChain relies on the close proximity of clients and edge nodes, which masks the wide-area latency between the clients and the cloud node. Therefore, the magnitude of the performance advantage depends on the relative communication latency between the client and the edge node on one hand, and the communication latency between the edge node and the cloud node on the other hand. To measure the effects of these relative latencies, we performed two sets of experiments that vary the locations of the edge and cloud nodes.

Figure 7(a) shows the latency while varying the location of the cloud node and fixing the locations of the client and edge node in California. WedgeChain is able to preserve the latency benefit of utilizing an edge node-the latency in all cases is within 15ms and 17ms. This shows that it successfully masks the wide-area latency even in cases when the roundtrip time to the cloud node is 238ms (between California and Mumbai). Cloud-only is affected by the location of the cloud node since all requests are served by the cloud node. The latency for Cloud-only ranges between 37ms and 247ms, which corresponds to the round-trip latency to the cloud node. This is also the case for Edge-baseline where the latency ranges between 59ms and 321ms. Edge-baseline performs worse than Cloud-only due to the bandwidth and computation stress incurred to synchronously coordinate between the edge and cloud nodes as we observed in the previous experiments.

Figure 7(b) varies the location of the edge node while fixing the client in California and the cloud node in Mumbai. WedgeChain latency is affected directly by the location of the edge node, since that is where requests are committed. WedgeChain's latency vary between 17ms (when the edge node is in Oregon) and 247ms (when the edge node is in Mumbai). The latency in all cases corresponds to the roundtrip latency from the client to the edge node. Cloud-only does not utilize an edge node and thus experiences the same performance in all cases, which corresponds to the latency from the client to the cloud node. Edge-baseline incurs a similar latency in all cases while varying the location of the edge node except for the case when the edge node is co-located with the cloud node. The reason for the similarity in all cases except an edge in Mumbai is because the sum of the latencies between the client, the edge, and cloud nodes are similar. This makes the total time spent for communication be similar. Additionally, in these cases, an additional overhead is incurred for edge-cloud coordination as we observed in the evaluations above. The reason for achieving a better performance when the edge node is co-located with the cloud node is that the overhead of edge-cloud coordination diminishes, leaving the communication cost to be the only dominating cost for latency. This is why the latency of Edge-baseline is similar to both Cloud-only and WedgeChain.

In all cases, WedgeChain outperform both Cloud-only and edge-baseline except for the case when the edge node is colocated with the cloud node. When the edge node is co-located with the cloud node, all three systems perform similarly.

# E. Dataset Size

Here, we vary the size of the key range from 100K to 100M keys. Although we target edge-cloud environments where we expect that edge partitions would be small, we perform this evaluation to test the effect of the size of the partition. Increasing to 100M keys, we do not observe a significant effect on write performance. WedgeChain achieves a latency between 15–16ms, Edge-baseline achieves a latency between 88–95ms, and Cloud-only achieves a latency of 78–79ms across all cases. The reason for this is that the communication and verification overheads (in the order of 10s of milliseconds) outweigh the potential I/O overhead caused by increasing the database size (in the order of milliseconds or less).

## VII. RELATED WORK

Edge-cloud data management is the area of utilizing edge nodes [13], [33] that are closer to user to perform data management tasks to augment existing cloud deployments [16], [22], [26], [27], [34] This area is also related to early work in mobile data management [17], [31], [35]. WedgeChain shares the goal of utilizing edge resources for data management. The distinguishing feature of WedgeChain compared to this set of work is that it considers a byzantine fault-tolerance model where the edge nodes are not trusted.

Coordination with untrusted nodes (Byzantine faulttolerance) [20], [30] has been investigated extensively in the context of data systems [8], [10], [14], [15], [18], [19], [21], [36] and databases [12], [23], [28], and is recently gaining renewed interest due to emerging blockchain and cryptocurrency applications [4]–[7], [9], [11]. WedgeChain contribution to this body of work is (1) the introduction of the concept of lazy (asynchronous) certification to byzantine fault-tolerance. Existing byzantine fault-tolerance protocols require extensive communication and coordination to prevent malicious activity, which makes them infeasible in real scenarios. Lazy certification makes a shift from a paradigm of "preventing" malicious activity that is expensive, to a paradigm of "detect and eventually punish" that allows better performance. (2) our work also tackles the unique challenges that arise from edgecloud systems such as a hybrid trust model, edge-cloud trusted indexing, and asymmetric coordination.

WedgeChain's index, LSMerkle, builds on mLSM [32] that combines features of both LSM trees [24], [29] and Merkle trees [25] to produce a fast-ingestion trusted data index. The choice of building on mLSM is due to its append-only and immutable nature that makes it amenable to be integrated into WedgeChain's lazy certification method. LSMerkle uses mLSM as the data structure at the edge and builds an asynchronous (lazy) certification protocol around it to enable coordinating updates and compaction with the trusted cloud node. LSMerkle also integrates a WedgeChain log/buffer as a replacement to the memory component of mLSM to enable incoming key-value requests to be Phase I Committed with lazy (asynchronous) certification. If mLSM is used with no changes in an edge-cloud environment, then it would resemble the baseline (Sections II-C) in that each put operation must go to the cloud node first before being part of the state in the edge nodes. LSMerkle, on the other hand, allows lazy certification where put operations can be Phase I Committed on the (untrusted) edge nodes without involving the (trusted) cloud node. The same is true for get operations where LSMerkle modifies the protocol for get operations to allow reading Phase I committed data. To allow these extensions, LSMerkle builds a protocol around mLSM to perform put, get, and merge operations. This protocol enables a pattern of Phase I committing locally at the edge and then coordinating with the cloud for Phase II commit.

#### VIII. CONCLUSION

WedgeChain is an edge-cloud system that tolerates malicious edge nodes. WedgeChain's main innovations are (1) a lazy (asynchronous) certification strategy. Lazy certification allows edge nodes to lie—however, it also guarantees that a lie is going to be discovered. With proper penalties when malicious acts are discovered, the guarantee of eventually catching the lie would deter edge nodes from acting maliciously. (2) WedgeChain takes the trusted cloud node out of the execution path and minimizes edge-cloud coordination using data-free coordination. (3) We propose the LSMerkle tree that extends mLSM [32] to support trusted fast-ingestion indexing while utilizing WedgeChain's features of lazy certification and data-free coordination.

## IX. ACKNOWLEDGMENTS

This research is supported in part by the NSF under grant CNS-1815212.

#### REFERENCES

- [1] AT&T Integrating 5G with Microsoft Cloud to Enable Next-Generation Solutions on the Edge. https://about.att.com/story/2019/att\_microsoft\_cloud.html.
- [2] AWS IoT Greengrass. https://aws.amazon.com/greengrass/.
- [3] AWS Wavelength. https://aws.amazon.com/wavelength/.
- [4] Chain. http://chain.com/.
- [5] Ethcore. Parity: next generation ethereum browser. https://ethcore.io/parity.html.
- [6] Quorum. http://www.jpmorgan.com/global/Quorum.
- [7] Ripple. https://ripple.com.

- [8] M. Abd-El-Malek, G. R. Ganger, G. R. Goodson, M. K. Reiter, and J. J. Wylie. Fault-scalable byzantine fault-tolerant services. ACM SIGOPS Operating Systems Review, 39(5):59–74, 2005.
- [9] M. Al-Bassam, A. Sonnino, S. Bano, D. Hrycyszyn, and G. Danezis. Chainspace: A sharded smart contracts platform. In 25th Annual Network and Distributed System Security Symposium, NDSS 2018, San Diego, California, USA, February 18-21, 2018, 2018.
- [10] Y. Amir, C. Danilov, D. Dolev, J. Kirsch, J. Lane, C. Nita-Rotaru, J. Olsen, and D. Zage. Steward: Scaling byzantine fault-tolerant replication to wide area networks. *IEEE Transactions on Dependable* and Secure Computing, 7(1):80–93, 2010.
- [11] E. Androulaki, A. Barger, V. Bortnikov, C. Cachin, K. Christidis, A. De Caro, D. Enyeart, C. Ferris, G. Laventman, Y. Manevich, et al. Hyperledger fabric: a distributed operating system for permissioned blockchains. arXiv preprint arXiv:1801.10228, 2018.
- [12] R. S. Barga and D. B. Lomet. Phoenix project: Fault-tolerant applications. SIGMOD Record, 31(2):94–100, 2002.
- [13] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli. Fog computing and its role in the internet of things. In *Proceedings of the first edition of the MCC workshop on Mobile cloud computing*, pages 13–16. ACM, 2012.
- [14] M. Castro, B. Liskov, et al. Practical byzantine fault tolerance. In OSDI, volume 99, pages 173–186, 1999.
- [15] J. Cowling, D. Myers, B. Liskov, R. Rodrigues, and L. Shrira. Hq replication: A hybrid quorum protocol for byzantine fault tolerance. In *Proceedings of the 7th symposium on Operating systems design and implementation*, pages 177–190. USENIX Association, 2006.
- [16] I. Eyal, K. Birman, and R. van Renesse. Cache serializability: Reducing inconsistency in edge transactions. In *ICDCS*, pages 686–695. IEEE, 2015.
- [17] J. Gray, P. Helland, P. O'Neil, and D. Shasha. The dangers of replication and a solution. ACM SIGMOD Record, 25(2):173–182, 1996.
- [18] R. Kotla, L. Alvisi, M. Dahlin, A. Clement, and E. Wong. Zyzzyva: speculative byzantine fault tolerance. In ACM SIGOPS Operating Systems Review, volume 41, pages 45–58. ACM, 2007.
- [19] R. Kotla and M. Dahlin. High throughput byzantine fault tolerance. In Dependable Systems and Networks, 2004 International Conference on, pages 575–584. IEEE, 2004.
- [20] L. Lamport, R. Shostak, and M. Pease. The byzantine generals problem. ACM Transactions on Programming Languages and Systems (TOPLAS), 4(3):382–401, 1982.
- [21] J. Li and D. Maziéres. Beyond one-third faulty replicas in byzantine fault tolerant systems. In NSDI, 2007.
- [22] Y. Lin et al. Enhancing edge computing with database replication. In SRDS, pages 45–54, 2007.
- [23] A. F. Luiz, L. C. Lung, and M. Correia. Mitra: Byzantine fault-tolerant middleware for transaction processing on replicated databases. ACM SIGMOD Record, 43(1):32–38, 2014.
- [24] C. Luo and M. J. Carey. Lsm-based storage techniques: A survey. arXiv preprint arXiv:1812.07527, 2018.
- [25] R. C. Merkle. Protocols for public key cryptosystems. In Proceedings of the 1980 IEEE Symposium on Security and Privacy, Oakland, California, USA, April 14-16, 1980, pages 122–134, 1980.
- [26] F. Nawab, D. Agrawal, and A. El Abbadi. Dpaxos: Managing data closer to users for low-latency and mobile applications. In *SIGMOD*, 2018.
- [27] F. Nawab, D. Agrawal, and A. El Abbadi. Nomadic datacenters at the network edge: Data management challenges for the cloud with mobile infrastructure. In *EDBT*, pages 497–500, 2018.
- [28] R. Neiheiser, D. Presser, L. Rech, M. Bravo, L. Rodrigues, and M. Correia. Fireplug: Flexible and robust n-version geo-replication of graph databases. In 2018 International Conference on Information Networking (ICOIN), pages 110–115. IEEE, 2018.
- [29] P. O'Neil, E. Cheng, D. Gawlick, and E. O'Neil. The log-structured merge-tree (lsm-tree). *Acta Informatica*, 33(4):351–385, 1996.
- [30] M. Pease, R. Shostak, and L. Lamport. Reaching agreement in the presence of faults. *Journal of the ACM (JACM)*, 27(2):228–234, 1980.
- [31] F. Perez-Sorrosal et al. Consistent and scalable cache replication for multi-tier j2ee applications. In ACM/IFIP/USENIX International Conference on Distributed Systems Platforms and Open Distributed Processing, pages 328–347, 2007.
- [32] P. Raju, S. Ponnapalli, E. Kaminsky, G. Oved, Z. Keener, V. Chidambaram, and I. Abraham. mlsm: Making authenticated storage faster in ethereum. In 10th {USENIX} Workshop on Hot Topics in Storage and File Systems (HotStorage 18), 2018.

- [33] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies. The case for vm-based cloudlets in mobile computing. *IEEE pervasive Computing*, 8(4):14–23, 2009.
- [34] H. Saxena and K. Salem. Edgex: Edge replication for web applications. In 2015 IEEE 8th International Conference on Cloud Computing, pages 1041–1044, 2015.
- [35] D. B. Terry. Replicated data management for mobile computing. Synthesis Lectures on Mobile and Pervasive Computing, 3(1):1–94, 2008.
- [36] J. Yin, J.-P. Martin, A. Venkataramani, L. Alvisi, and M. Dahlin. Separating agreement from execution for byzantine fault tolerant services. *ACM SIGOPS Operating Systems Review*, 37(5):253–267, 2003.