Reliable Transactions in Serverless-Edge Architecture

Suyash Gupta†, Sajjad Rahnama, Erik Linsenmayer, Faisal Nawab‡, Mohammad Sadoghi
Exploratory Systems Lab
University of California, Davis
†University of California, Irvine
‡University of California, Berkeley

Abstract—Modern edge applications demand novel solutions where edge applications do not have to rely on a single cloud provider (which cannot be in the vicinity of every edge device) or dedicated edge servers (which cannot scale as clouds) for processing compute-intensive tasks. A recent computing philosophy, Sky computing, proposes giving each user ability to select between available cloud providers.

In this paper, we present our serverless-edge co-design, which extends the Sky computing vision. In our serverless-edge co-design, we expect edge devices to collaborate and spawn required number of serverless functions. This raises several key challenges: (1) how will this collaboration take place, (2) what if some edge devices are compromised, and (3) what if a selected cloud provider is malicious. Hence, we design SERVERLESSBFT, the first protocol to guarantee Byzantine fault-tolerant (BFT) transactional flow between edge devices and serverless functions. We present an exhaustive list of attacks and their solutions on our serverless-edge co-design. Further, we extensively benchmark our architecture on a variety of parameters.

Index Terms—edge computing, serverless, IoT

I. INTRODUCTION

This paper introduces SERVERLESSBFT, the first protocol to guarantee Byzantine fault-tolerant (BFT) transactional flow between edge devices and serverless functions. The design of SERVERLESSBFT is motivated from the recent introduction of Sky Computing, which envisages utility computing in a multi-cloud environment [1], [2]. Sky computing propounds the design of an inter-cloud broker that takes as input a client program and output specifications and selects the best cloud providers to execute the client program. Such a broker is extremely desirable for the edge and Internet of Things (IoT) applications, which run on edge devices, such as smart devices, sensors, UAVs, and phones, that have limited compute power and memory [3].

On the one hand, existing edge applications expect response latency in the order of tens of milliseconds [4], [5], [6]. On the other hand, they are forced to delegate compute-intensive tasks to a specific third-party cloud provider such as AWS and Azure [7], [8]. A recent way to solve this dilemma is to install dedicated edge-servers that are closer to the edge devices [9], [10]. These edge servers are installed and maintained by the enterprise behind the application [11], [12]. If any hardware crashes, then the enterprise may need to purchase new hardware. Moreover, with ever-growing application needs, these servers are impossible to seamless scale as third-party clouds.

SERVERLESSBFT realizes the Sky computing vision in edge computing by giving the edge applications flexibility to select any of the available cloud providers. As a result, the edge application can select different cloud providers based on the location of its users. However, moving data across cloud providers degrades system performance and is expensive. So, we take a step further and permit edge applications to make use of serverless technology, which (i) decouples storage, compute, and network, (ii) supports pay-as-you-go model where the enterprise pays only for the resources used, and (iii) supports auto-scaling policies [14], [15]. We refer to this interaction as serverless-edge co-design as it promotes lightweight tasks at the edge while compute-intensive tasks are done at the serverless cloud. Our serverless-edge co-design targets low latency by allowing edge devices to spawn serverless functions at the nearest cloud.

Our serverless-edge co-design also presents several research challenges, which we enlist next.

1) Task distribution between edge and serverless. Our SERVERLESSBFT protocol requires an edge application to push its compute-intensive task to the cloud by spawning serverless functions (for simplicity, we refer to these functions as executors). To do so, we need to design a compatibility layer. We build this compatibility layer on top of edge devices and refer to it as a shim. At shim, the edge devices collaborate and spawn serverless executors for executing compute-intensive client requests.

2) Lack of Trust at Shim. As edge devices may belong to different parties, which may not trust each other, it is hard for these devices to collaborate. Hence, our SERVERLESSBFT protocol runs a traditional BFT protocol to allow these edge devices reach a consensus [16], [17]. This consensus decides which edge device will spawn the desired number of executors and the order in which client requests are processed. For consensus, we opt for BFT protocols as they are resilient to malicious attacks. Further, depending on the location and nature of edge devices, SERVERLESSBFT permits various shim designs: a single shim of all devices running PBFT [16] consensus, multiple dependent shims of devices spread globally, running GeoBFT [17], and multiple independent shims running AHT. [18], Sharper [19], or RingBFT [20]. For simplicity, in this paper, we assume a single shim of 3f + 1 devices where up to f devices can act malicious.

3) Lack of Trust at Serverless cloud. Depending on the application requirement, shim may spawn serverless executors at one or more available cloud providers in the vicinity. Hence, there is again a lack of trust: some cloud providers may

†At present, switching cloud providers is common for most applications due to geo-political reasons and government regulations [13].
have mal-intent or may have poor QoS (crashed or failed executors) [21], [22]. As a result, SERVERLESSBFT requires the shim to spawn $2f + 1$ executors and permits up to $f$ of them to fail. This extra spawning is not new; Yahoo’s Hadoop also executes the same code multiple times to reduce latency due to stragglers [23].

(4) **Private Data access and retrieval.** Recent reports illustrate that around 90% of the industries are not only sticking with their existing on-premise servers, but also scaling them up [24], [25]. For at least 65% of these industries, the key reason for maintaining on-premise servers is to protect their consumer data from data-breaches and attacks [24]. In our serverless-edge co-design, we adhere to this design choice and assume that all the client data is stored in an on-premise storage at the enterprise. As a result, the enterprise can control access to the data. Hence, edge devices or executors lack rights to update the storage, but may request read access to the same. For updates to the storage, we write a lightweight wrapper (verifier) around the storage that collects execution results, updates the data-store, and forwards the results to the clients.

Furthermore, we observe several other new challenges with our architecture: (i) Byzantine shim devices may spawn less executors, for which we need to hold them accountable. (ii) During execution, executors may need to read data from the storage. (iii) If the client transactions are conflicting and their read-write sets are unknown until execution, we may have to abort such transactions.

We envision our serverless-edge architecture to seamlessly integrate with existing edge applications. To realize this goal experimentally, we design a shim of nodes and require them to spawn AWS Lambda functions as executors. On each shim node, we install RESILIENTDB’s light-weight and multi-threaded consensus framework [17], [26], [27], [28], [29]. We evaluate our SERVERLESSBFT protocol on eight distinct parameters. Our results illustrate that SERVERLESSBFT can facilitate shims of up to 128 devices in 11 global regions. Further, in our experiments, we are easily able to spawn 21 executors in parallel (could not scale further due to limits by cloud provider), and the peak throughput achieved by our SERVERLESSBFT protocol is 240 k txns/s while the minimum latency incurred is 30 ms.

In this paper, we make the following contributions:

- We design of a novel serverless-edge co-design that meets the vision of Sky computing and helps design low latency reliable edge applications where edge devices can select cloud providers based on desired output specifications.
- In our serverless-edge architecture, we neither trust the edge devices nor the serverless executors. Hence, we introduce a novel protocol SERVERLESSBFT that manages the flow of a client request in our serverless-edge architecture and shields the system against arbitrary results and malicious attacks.
- We enlist possible attacks in our serverless-edge architecture and present solutions to recover the system.
- Our SERVERLESSBFT protocol presents algorithms to handle conflicting transactions with or without the knowledge of read-write available to shim nodes prior to execution.

**II. MOTIVATION AND USE CASE**

The motivations behind our serverless-edge co-design are the emerging use cases of edge-computing, such as AR/VR video-streaming and Unmanned Aerial Vehicles (UAVs). These applications require massive data-processing as they need to run ML models to train data on-flight or provide the user useful insights. The key challenge these applications face is the rapidly changing user characteristics.

We consider a real-world use case of UAVs as a motivating example for this work [30]. In recent years, UAVs have been adopted by e-commerce industries, such as Amazon and Walmart, for product deliveries. These UAVs help to securely and quickly transport user goods in a cost-efficient manner. During the delivery process, each UAV travels over multiple geographical locations and performs an array of tasks, such as navigation, image recognition, and live video-streaming.

In Figure 1(b), we illustrate the traditional way of computing for UAVs, where each UAV offloads all the collected data to the dedicated edge servers for processing. In this model, UAVs are forced to communicate with dedicated servers. When the server is in the vicinity, the communication round-trip costs are low; otherwise, they are high. Each edge server executes the requests from various UAVs in an ordered-fashion. Moreover, these servers need to be continuously scaled, new software needs to be installed, and OS needs to be updated, which makes them a financially expensive choice.

In Figure 1(a), we reimagine the UAV delivery operation in our serverless-edge co-design. Switching to our serverless-edge model, allows UAVs in the vicinity to interact with each other and act as a shim that spawns serverless executors to process collected data. To alleviate concerns regarding round-trip costs, the shim is permitted to opt for services from local cloud providers. In fact, shim can spawn executors at multiple clouds and wait for whichever responds earliest. As there is a lack of trust among shim devices and executors, we have our SERVERLESSBFT protocol to manage all the transactional flow in a byzantine fault-tolerant manner. **Byzantine failures in the wild.** Do real-world systems face more than just crash failures? Unfortunately, yes. Exist-
ing systems suffer from *omission* failures where nodes can crash [31], and *arbitrary* failures where nodes can act in an unexpected manner [21]. Almost all real-world applications handle omission failures using protocols based on Paxos-family [32], [33]. However, the true challenge is to bulwark the system against often overlooked arbitrary failures: Google’s UpRight [21] provides fault-tolerance against byzantine failures, Google has also observed corrupt execution errors [22], and Cloudflare observed a misbehaving switch sending incorrect messages [34]. Hence, it is better to guard system against these failures.

III. PRELIMINARIES

We make standard assumptions as made by any BFT system [16], [17], [19], [26]. We represent our serverless-edge architecture $\mathcal{A}$ through a quintuple, $\mathcal{A} = \{C, R, E, V, S\}$, where we use $C$ to denote the set of clients, $R$ to denote the shim of edge devices or nodes, $E$ to denote the serverless executors, $V$ and $S$ to denote the verifier and data-store. As described in Section I, we assume an on-premise data-store maintained by the enterprise, while the verifier is a lightweight wrapper around the data-store. Hence, both verifier and storage are assumed to be honest and trusted.

**Fault-Tolerance Requirement at Shim.** We use the notation $n_R = |R|$ to represent total number of edge nodes in $\mathcal{A}$. At most $f_R$ of these nodes are byzantine and can crash-fail or act arbitrarily; $n_R \geq 3f_R + 1$. The remaining $2f_R + 1$ nodes are honest and follow the protocol.

**Authenticated Communication.** To exchange messages among different components, we employ Digital Signatures (DS) and Message Authentication Codes (MAC) [35]. To represent a message $m$ signed by a component $R$ using DS, we use the notation $(m)_R$. Anyone who has the signer’s public-key can verify this signature. One of the common ways to exchange public-keys is through a public-key certificates [36].

For MACs, signer and verifier use a common key, which is kept secret. We use Diffie-Hellman key exchange for securely sharing secret keys. In rest of the text, any message $m$ that does not indicate the identity of the signer implies the use of MAC. Although MACs offer higher throughput than DS, DS guarantee non-repudiation [16], [37]. We also employ a collision-resistant hash function $H(\cdot)$ to map a value $v$ to a constant-sized digest $H(v)$. We use a function id(\cdot) to assign an identifier to each node $R \in R$ and each executor $E \in E$. We assume that byzantine components can neither impersonate honest components, nor subvert cryptographic constructs. We do not make any assumptions on the behavior of the clients. We term a message as *well-formed* if it passes all the cryptographic and other necessary checks.

**A. Serverless Cloud Assumptions**

We expect access to one or more serverless clouds such as AWS Lambda and Google Functions. These serverless cloud should permit edge nodes to seamlessly upload the desirable code or transactions for processing as per the application specifications. For simplicity, in rest of the text, we assume that the shim nodes access only one cloud provider for spawning executors to execute client transactions. However, there is no free food as these serverless clouds follow a pay-per-use model where whoever spawns executors also pays for their use [38]. We expect these clouds to meet the following:  
- **Fault-Tolerance:** To handle arbitrary failures at the serverless cloud, we spawn $n_C \geq 2f_E + 1$ executors, and assume that at most $f_E$ are byzantine. Prior works have shown that $2f_E + 1$ executors guarantee successful execution of a transaction in the byzantine setting [39]. This leads us to observe the following:  
  1) The values for $f_E$ and $f_R$ may or may not be same.
  2) In Section VI, we illustrate that if the transactions are conflicting, then we need an additional $f_E$ executors to prevent an indistinguishable byzantine attack.
- **Identity:** We expect each spawned executor to be assigned a unique pair of public-private key, which it uses to digitally sign a message.
- **Accountability:** Each executor is spawned by some shim node that pays for this service. Hence, we expect that no executor can spawn more executors. Further, the expected number of executors to be spawned by shim nodes is known to all the components of our architecture.
- **Payment:** As executors are spawned by shim nodes, it implies that the spammer will be billed by the cloud provider. Hence, post successful consensus of a transaction, the edge application’s enterprise pays the spammer a fixed amount to cover its expenses.

IV. ARCHITECTURE

We now discuss in detail the BFT transactional flow guaranteed by our SERVERLESSBFT protocol in the serverless-edge co-design. In Figure 2, we schematically present this flow; the shim consists of $n_R = 4$ edge nodes and $n_C = 3$ executors are spawned per transaction. For understandability, we will periodically refer to the UAV use case of Section II.

As stated earlier, shim can have different abstractions and can run any BFT protocol. In this paper, we assume a single shim of $3f_E + 1$ and require shim nodes to run the PBFT [16] protocol. PBFT is considered as a representative BFT protocol as all the other protocols follow its design. PBFT protocol works in views. For each view, one node is designated as the primary and is responsible for successful completion of consensuses in that view. If the primary acts malicious, the view is changed and the primary is replaced.

**A. Client Request and Response**

Any user that accesses the edge application becomes a client in our system. E.g., each UAV that requires data-processing
from the cloud acts as a client and packages its request as a transaction. A client \( C \) sends a message \( ⟨T⟩_C \) to the primary node \( p \)\(^2\) of the current view \( v \) when it wants to process a transaction \( T \). Notice that \( C \) employs DS to sign this message (refer to Figure 3, Line 1). The client \( C \) marks \( ⟨T⟩_C \) as processed when it receives a RESPONSE message from the verifier \( V \). As \( C \) knows that \( V \) is a trusted entity in our infrastructure, it readily accepts the response (Line 3).

**B. Shim Ordering**

SERVERLESSBFT assigns each shim node (e.g., UAV) an identifier, 0, 1, 2, ..., \( n_R \). Initially, the shim node with identifier 0 is designated as the primary \( P \) of the shim. On receiving a client request \( ⟨T⟩_C \), \( P \) checks if \( ⟨T⟩_C \) is well-formed. If this is the case, \( P \) initiates the PBFT protocol as follows.

- **Pre-prepare.** The primary \( P \) assigns a sequence number \( k \) to the well-formed client message \( m := ⟨T⟩_C \) and sends it as a PREPARE message to all the nodes of the shim. This PREPARE message also includes a digest \( \Delta = H(m) \), which is used in future communication to save space. Notice that the primary signs this message using MAC, which provide sufficient guarantees for this process. When a node \( R \in \mathcal{R} \) receives a PREPARE message from the primary \( P \) of view \( v \), it runs the message through a series of checks. If the checks are successful, then \( R \) agrees to support the order \( k \) for this client request by broadcasting a PREPARE message.

- **Prepare.** When a node \( R \) receives identical PREPARE messages from \( 2f_R + 1 \) distinct nodes (can include its own message to reach the count), it marks the request \( m \) as prepared and broadcasts a COMMIT message. We require each node \( R \) to use DS to sign the COMMIT message.

- **Commit.** When \( R \) receives identical COMMIT messages from \( 2f_R + 1 \) nodes, it marks \( m \) as committed.

**Remark.** PBFT requires two phases of quadratic communication complexity. Instead, shim can employ BFT protocols like PoE [40] and SBFT [41] that guarantee linear communication with the help of advanced cryptographic schemes like threshold signatures. Note: in our architecture, the edge devices are acting as both clients and shim nodes.

**C. Serverless Optimistic Execution**

Once \( P \) commits a request, SERVERLESSBFT requires \( P \) to connect with the serverless cloud and spawn \( n_E \) executors. \( P \) sends each of these executors an EXECUTE message (Line 9), which includes a certificate \( C \); a set of signatures of \( 2f_R + 1 \) distinct shim nodes and proves that these nodes agreed to order this request (Line 8). Prior to executing the transaction \( T \), each executor \( E \in \mathcal{E} \) checks if the certificate \( C \) is valid.

During execution, \( E \) may need to access the value of read-write sets (rw). Hence, it connects with the storage \( S \) and fetches the required data (Lines 17-18). However, executors do not write to the storage. Any intermediate results are stored locally. Further, these executors do not communicate with each other. Post execution, each executor \( E \) sends a VERIFY message to the verifier \( V \), which includes the computed result \( r \), certificate \( C \), and accessed read-write sets \( rw \).

**Remark.** We allow shim to spawn either stateless or stateful executors [38], [42]. Stateful executors have memory and remember the results of last execution. By definition, severless executors are “fleeting” and return after execution; a common way to assign these executors memory is by having a layer that stores computed results [14]. To employ stateful executors in our model, we would need BFT guarantees on the additional layer. Hence, we focus on stateless executors. Including \( C \) in the EXECUTE and VERIFY messages helps to detect byzantine attacks (§ VI-B). Further, by employing threshold signatures, we can reduce the size of the certificate. Threshold signatures allow combining \( 2f_R + 1 \) signatures into a single signature.

**D. Verifier and Concurrency Control**

The verifier \( V \) is a lightweight wrapper around the data-store \( S \) and is assumed to be correct and trusted. The verifier collects well-formed VERIFY messages from the executors (in set \( \mathcal{V} \) and once it has a quorum of matching requests that do not violate the concurrency control constraints, it updates the data-store. It performs these tasks in the following order:

1) If set \( \mathcal{V} \) has at least \( f_R + 1 \) matching VERIFY messages, \( V \) marks the transaction as matched. Following this, \( V \) ignores any other VERIFY message for \( ⟨T⟩_C \) (Line 23).

2) If \( k \) is the sequence number for \( ⟨T⟩_C \) and \( k_{\text{max}} \) is the sequence number of last validated request, then if \( k_{\text{max}} \neq k \), \( V \) places the \( k \)-th request in the list \( \pi \) (Line 29).

3) If \( k_{\text{max}} = k \), \( V \) checks if the value of the read-write sets \( rw \) of the \( k \)-th request is same as that in the data-store \( S \) (Lines 31-32). If the read sets match, \( V \) sends the client and the shim primary RESPONSE messages and updates the write sets at the storage in accordance with the result \( r \) (Lines 33-34). Note: matching read-write sets is only required when the transactions are conflicting. We discuss this in Section VI.

4) Next, \( V \) increments \( k_{\text{max}} \) and checks if \( \pi \) includes the transaction with sequence number \( k_{\text{max}} \). If so, it removes the \( k_{\text{max}} \)-th transaction from \( \pi \) and runs steps in Lines 26-27.

These concurrency control checks ensure that consistent updates are written to the storage.

**E. System Guarantees**

We now state the guarantees offered by our different components of our serverless-edge architecture.

**Shim Consistency.** If an honest node commits a transaction \( T \), then all the honest nodes commit \( T \).

**Shim Non-Divergence.** If two honest nodes order a transaction \( T \) at sequence number \( k \) and \( k' \), then \( k = k' \).

**Shim Termination.** If an honest client sends a transaction \( T \), then an honest node will eventually commit \( T \).

**Executor Termination.** If an honest primary sends an EXECUTE message for transaction \( T \), then an honest executor will execute \( T \).

**Verifier Non-Divergence.** If the shim commits a transaction \( T \) at sequence \( k \), then the verifier will eventually update the corresponding result at the storage at order \( k \).

Together, shim consistency, shim non-divergence, and verifier non-divergence imply safety, while shim termination and executor termination imply liveness. Our SERVERLESSBFT protocol guarantees safety in an asynchronous environment where the messages can get lost, delayed, or duplicated, and byzantine components can collide or act arbitrarily. To guarantee liveness, our SERVERLESSBFT protocol expects periods of synchrony. Note: our SERVERLESSBFT offers standard safety
In our architecture, at most $f_S$ shim nodes and $f_E$ serverless executors can act byzantine. If the primary of shim is honest, then byzantine nodes cannot affect the ongoing transactional flow. Similarly, byzantine executors can either provide incorrect result or ignore execution, but as there are at least $f_E + 1$ honest executors, EXECUTE messages sent by honest primaries will be processed. Hence, following is an exhaustive list of attacks on our design.

(i) Request Suppression. If the primary of shim is byzantine, it can try to prevent consensus on some client requests.
(ii) Nodes in Dark. If shim’s primary is byzantine, it can keep up to $f_E$ honest shim nodes in dark by not involving them in consistencies.
(iii) Verifier Flooding. Byzantine components can flood the verifier with requests that have been already verified.

Next, we present algorithms to recover from these attacks.

A. Request Suppression

In the serverless-edge architecture, byzantine components can work together to deny service to one or more clients. This request suppression attack can take three different forms:

(i) Request Ignorance. If the shim’s primary node $P$ is byzantine, it can willfully drop a request $m$ from a client $C$, or indefinitely delay consensus on $m$.
(ii) Unsuccessful Consensus. A byzantine primary $P$ may involve less than $2f_S + 1$ nodes in consensus on a client request $m$. As a result, these nodes will not reach consensus on $m$.
(iii) Less Executors. A byzantine primary $P$ may permit consensus on a client request $m$, but disallow its execution by spawning less than $f_E$ serverless executors. In such a case, the verifier $V$ will not receive $f_E + 1$ matching execution results.

To detect these attacks, we setup three distinct timers at various components of our architecture.

- **Client timer.** Our SERVERLESSBFT protocol requires each client $C$ to start a timer $\tau_m$ prior to sending its request $m$ to the primary $P$. When $C$ receives a RESPONSE message for $m$ from the verifier $V$, it stops $\tau_m$.
- **Node timer.** Our SERVERLESSBFT protocol requires each node $R \in \mathcal{R}$ to start a timer $\tau_m$ when it receives a well-formed PREPARE message for a client request $m$ from the primary $P$. When $R$ marks $m$ as committed, it stops $\tau_m$.
- **Node re-transmission timer.** If a non-primary node $R \in \mathcal{R}$ receives an ERROR message from the verifier $V$ (see Section V-A2) then $R$ forwards the ERROR message to the primary $P$ and starts the re-transmission timer $\tau_T$. When $R$ receives a corresponding ACK message from $V$, it stops $\tau_T$.

In the case the timers of $C$ or $R$ expire, the respective component detects a request suspension attack and initiates the following mechanisms for recovery from this attack.

1) **Client action on timeout.** If a client $C$’s timer $\tau_m$ timeouts, then $C$ forwards its request to the verifier $V$ and restarts its timer (refer to Figure 4). In specific, each time $C$’s timer expires, after some exponential backoff, it re-sends its request to $V$ until it receives a RESPONSE message from $V$.

2) **Verifier action on receiving client request.** When the verifier $V$ receives a request $m := (\mathcal{T}_C)C$ from client $C$, it first determines if it has seen $\langle \mathcal{T}_C \rangle C$ till now or not. If $V$ has not received any VERIFY messages for $\langle \mathcal{T}_C \rangle C$, it sends $\langle \text{ERROR}(\langle \mathcal{T}_C \rangle C) \rangle C$ message to all the nodes in the shim. Otherwise, there can be only three cases:

(i) $V$ did send a RESPONSE message for $\langle \mathcal{T}_C \rangle C$, so it simply resends the RESPONSE message.

(ii) $\langle \mathcal{T}_C \rangle C$ resides in $\pi$. Further, assume that it was ordered by shim at some sequence number $k$. So $k_{\text{max}} < k$, and $V$ is waiting for the request with sequence number $k_{\text{max}}$. Unless the $k_{\text{max}}$-th request is validated by $V$, succeeding requests cannot
be processed. So, $V$ needs to notify shim nodes about the missing request at sequence $k_{\text{max}}$, and it does so by sending $\langle \text{ERROR}(k_{\text{max}}) \rangle_V$ to all the shim nodes. Note: this gap between $k_{\text{max}}$ and $k$ could have been created by Byzantine primary.

(iii) $V$ did not receive $f+1$ matching VERIFY messages for $\langle T \rangle_C$. This can only occur if the primary is Byzantine. So, $V$ sends $\langle \text{REPLACE}(\langle T \rangle_C) \rangle_V$ to all the shim nodes.

Once $V$ successfully verifies the request at sequence number $k_{\text{max}}$ or $\langle T \rangle_C$, $V$ creates a corresponding $\langle \text{ACK}(k_{\text{max}}) \rangle_V$ or $\langle \text{ACK}(\langle T \rangle_C) \rangle_V$ message and broadcasts it to $\text{shim}$.

3) Node action on ERROR message: When a shim node $R \in \mathcal{R}$ receives an ERROR message from the verifier, it can only conclude the following:

- $R$ received $\langle \text{ERROR}(k_{\text{max}}) \rangle_V$ message and has either committed or not committed the request at sequence number $k_{\text{max}}$.
- $R$ received $\langle \text{ERROR}(\langle T \rangle_C) \rangle_V$ message and has either committed or not committed the request $\langle T \rangle_C$.

Irrespective of these cases, the node $R$ starts a re-transmit timer $T$ to track the behavior of the primary. Next, it forwards the received ERROR message to the primary. If the timer $T$ expires before $R$ receives a corresponding acknowledgment message $\langle \text{ACK}(k_{\text{max}}) \rangle_V$ or $\langle \text{ACK}(\langle T \rangle_C) \rangle_V$ from the verifier, $V$, $R$ concludes that the primary is Byzantine and requests a view-change. Hence, the onus is on the primary to guarantee consensus and execution.

4) Node action on timeout: When the timer $T_{\text{run}}$ for a node $R \in \mathcal{R}$ expires, $R$ concludes that the shim’s primary for view $v$ is Byzantine, and it requests primary replacement by broadcasting a VIEWCHANGE message. We employ PBFT’s view-change protocol to replace a Byzantine primary. A node $R$’s request for change of view from $v$ to $v+1$ is only successful if it receives support of at least $2f_R+1$ nodes, that is, at least $2f_R+1$ shim nodes must broadcast VIEWCHANGE messages. Replacing the current primary requires designating another shim node as the next primary. Like PBFT, we assume nodes have a pre-decided order of becoming the primary. As a result, when the replica designated as the primary for view $v+1$ receives VIEWCHANGE requests from at least $2f_R+1$ nodes, it assumes the role of the primary and broadcasts a NEWVIEW message to bring all the nodes to the same state. Similarly, when a node $R$ receives a REPLACE message from the verifier $V$, it initiates the view-change protocol to replace the primary $P$ to view $v$. We defer the details for the exact view-change protocol to the original PBFT paper [16].

B. Shim Nodes in Dark

If the primary $P$ is Byzantine, it may attempt to only include $2f_R+1$ nodes in consensus as only $2f_R+1$ nodes are needed to mark any request as prepared and committed. As a result, the remaining $f_R$ nodes will be in dark. Next, we explain what we mean by being in dark.

(i) Node Exclusion. A Byzantine primary $P$ can exclude up to $f_R$ honest nodes from consensuses by not sending them the PREPARE messages for client requests.

(ii) Equivocation. A Byzantine primary $P$ can equivocate by associating two client requests with the same sequence number $k$. If $P$ is clever, it will ensure that one of these client requests is committed by at least $f_R+1$ honest nodes while the remaining $f_R$ honest nodes do not commit any request at sequence number $k$.

The key challenge to resolving the attack (i) is that it is impossible to detect. In this attack, the Byzantine primary $P$ is clever and does not want to risk replacement. Hence, $P$ facilitates continuous consensus on incoming client requests by at least $f_R+1$ honest nodes. As a result, the remaining $f_R$ nodes are unable to trigger view-change by themselves.

Lemma V.1. If at most $f_R$ shim nodes are in dark, then it is impossible to detect such an attack and replace the primary.

Proof. Let $D$ be the set of shim nodes in dark, such that $|D| \leq f_R$. We start with the assumption that the nodes in $D$ are able to prove that they are under an attack by the Byzantine primary $P$ and ensure $P$’s replacement by convincing a majority of nodes to participate in the view-change protocol.

For a view-change to take place at least $2f_R+1$ nodes need to support such an event. As $P$ is clever, it ensures that at least $U \geq f_R+1$ honest nodes continuously participate in consensus. Clearly, $U > D$, which implies that a majority of honest nodes will not request view-change. The remaining $n_R - U - D = f_R$ nodes are Byzantine and will support the primary in this attack. Moreover, the nodes in set $U$ cannot distinguish between the nodes in set $D$ and the up to $f_R$ honest Byzantine nodes, as the Byzantine nodes can always request a view-change in an attempt to derail the system progress by replacing an honest primary. Hence, the view-change request by nodes in $D$ will never be successful.

Featherweight Checkpoints. To recover from nodes in dark attacks, we design a featherweight variant of existing checkpoint protocols [16], [43]. Existing BFT protocols require nodes to periodically construct and exchange CHECKPOINT messages, but these messages are expensive as they include all the client requests and the proof that they are committed (COMMIT messages from $2f_R+1$ distinct nodes) since the last checkpoint. As our shim nodes neither execute client requests nor store any data, during our featherweight checkpoint protocol, these nodes only send the signed proofs (certificates) for each committed request since last checkpoint.
Remark. The nodes in dark attacks do not make the system unsafe but put it at the mercy of the byzantine nodes, which can stop responding after several consensuses have passed; the system suffers from massive communication during recovery.

C. Verifier Flooding

As the verifier manages all updates to the data-store, it is a desirable target by byzantine components. Specifically, byzantine components can try the following ways to disrupt the system by flooding the verifier with redundant requests.

(i) Duplicate Spawning by Primary. If the shim’s primary node is byzantine, it can spawn more executors than necessary.

(ii) Duplicate Spawning by Non-primary. A byzantine non-primary node that was once the primary node of shim has access to old certificates and EXECUTE messages. It can use these messages to spawn new executors at the serverless cloud.

(iii) Duplicate Messages by Executors. A byzantine executor can send duplicate VERIFY messages to the verifier.

Although flooding attacks seem trivial to perform, they have monetary impacts on the byzantine components. Spawning each serverless executor requires the spawner to pay a fixed amount of money. As a result, any flooding attack performed by a byzantine component will be self-penalizing. For example, in our architecture, each primary is paid a fixed amount per consensus by the edge application organization. Hence, a rational byzantine component will avoid this attack.

Moreover, all of these attacks are trying to flood the verifier with the VERIFY messages. To mitigate the impact of these flooding attacks: we require the verifier $V$ to ignore any VERIFY message for a client request $m$, once it has received matching VERIFY messages for $m$ from $f + 1$ executors.

Finally, it is a common practice to connect different entities on the network via sockets. If flooding attacks take place, the verifier can block communication from such connections.

VI. TRANSACTIONAL CONFLICTS

Two client transactions $T$ and $T'$ are termed as conflicting if $T$ and $T'$ require access to a common data-item $x$ and at least one of these operations writes to $x$ [44]. In our SERVERLESSBFT protocol, transactional conflicts arise from the following set of transactions: two transactions $T$ and $T'$ ordered at sequences $k$ and $k'$, respectively, and $k < k'$ and $T$ writes to $x$, which $T'$ reads.

Example VI.1. For ensuing discussions, we assume two conflicting transactions $T$ and $T'$. Let the sequence number for $T$ be $3$ and sequence number for $T'$ be $4$. Further, assume $T$ needs to write to data-item $x$ and $T'$ needs to read $x$.

A. Concurrent Spawning

On a close inspection of Figure 3, one can observe that the primary $P$ does not wait for consensus of the $k$-th request to finish before initiating consensus for the $(k + 1)$-th request. This process of concurrently invoking multiple consensus has been employed by prior works to increase the system throughput as it reduces the idle times for nodes [17], [45].

To further boost the throughput, we permit the primary to spawn the $n_x$ executors for the $(k + 1)$-th request prior to spawning executors for $k$-th request. We term this as concurrent spawning. If the client requests are non-conflicting, concurrent spawning helps to parallelize execution.

In the case transactions are conflicting, like $T$ and $T'$ of Example VI.1, we can have two cases: the read-write sets a transaction accesses are either known or unknown to the shim nodes prior to execution. Depending on the knowledge of read-write sets, transactions may or may not abort in our architecture. A naive way would be to ask the shim primary to sequentially spawn executors for each client request, but that will significantly reduce the throughput attained by our SERVERLESSBFT protocol. Hence, we design algorithms to handle either cases, which we discuss next.

B. Unknown Read-Write Sets

If the shim nodes cannot determine the read-write sets of a transaction during consensus, we require the shim nodes to continue following the algorithm in Figure 3. The only change is that the shim’s primary should spawn an additional $f_x$ executors; the shim primary now spawns $n_x + f_x$ executors instead of $n_x + 2f_x + 1$ as stated earlier. We prove the need for these additional executors later.

However, due to the conflicting transactions like $T$ and $T'$ of Example VI.1, the verifier $V$ may observe the following: (i) it did not receive $f_x + 1$ matching VERIFY messages for $T'$, or (ii) the read sets of $T'$ are stale. In such cases, the verifier would have to abort transaction $T'$.

Byzantine Aborts and Decentralized Spawning.

A big challenge to permitting the verifier to abort transactions is a byzantine primary that can intentionally delay spawning executors for some of the committed transactions to get them aborted. Moreover, this attack is impossible to detect by other shim nodes or the verifier. Prior works have shown that there are no easy solutions to prevent Byzantine aborts for conflicting transactions with unknown read-write sets [46]. One way to prevent this attack in our serverless-edge architecture is to require each node of the shim to spawn some executors at the serverless cloud. In specific, once a node $r \in R$ commits a client request $m$, it spawns $e$ executors.

$$e = \begin{cases} 1, & \text{if } n_x \leq n_R \\ \frac{n_x}{2f_R + 1}, & \text{otherwise} \end{cases}$$  

If $n_x$ is less than $n_R$, then each node $r \in R$ needs to spawn only one executor. This will guarantee that all of the spawned executors at least $f_x + 1$ are honest. Otherwise, each node $r$ needs to spawn $\frac{n_x}{2f_R + 1}$ executors. Why? Because up to $f_R$ nodes are Byzantine and may avoid spawning any executors. Hence, the remaining $2f_R + 1$ honest nodes need to spawn $n_x$ executors. Clearly, the total number of spawned executors ($e \times n_R$) is much larger than the required number of executors $n_x$. This is a trade-off we need to pay if we want to decentralize the spawning of serverless executors. Another major trade-off of this decentralized spawning is that if the read-write sets are known, then each node needs to sequentially spawn executors. Hence, like primary (refer to Section VI-C), each node has to track the dependencies. Moreover, the proposed value of $e$ is only valid if each honest node commits the client request. If up to $f_R$ honest nodes are in dark, then $e$ changes as follows:

$$e = \begin{cases} 1, & \text{if } n_x \leq n_R \\ \frac{n_x}{f_R + 1}, & \text{otherwise} \end{cases}$$

307
Conservatively, we can set \( e = n_f \), but that will lead to spawning \( n_f \times n_R \) executors in the worst case.

Verifier Abort Detection. With the addition of byzantine aborts, the verifier needs to determine when to abort a transaction \( T' \) and if possible, the cause for abort. As a result, the verifier needs to wait for \( f + 1 \) matching VERIFY messages for \( T' \). For this purpose, our SERVERLESSBFT protocol requires the verifier \( V \) to start a timer \( \tau_m \) when it receives the first VERIFY message for the transaction \( m := T' \). \( V \) stops \( \tau_m \) when it receives \( f + 1 \) matching VERIFY messages, or it receives VERIFY messages from all the \( 3f + 1 \) executors.

Like in Figure 3, say the verifier collects all the incoming VERIFY messages for \( m \) in a set \( V \). If the verifier’s timer expires while waiting, it takes one of the following actions:

- \( \left| V \right| < 2f + 1 \): This case implies that the verifier \( V \) received less than \( 2f + 1 \) VERIFY messages for transaction \( T' \). As a result, \( V \) concludes that the primary \( P \) is byzantine and it creates and broadcasts a REPLACE message to the shim nodes. Receiving less than \( 2f + 1 \) VERIFY messages implies that either the primary \( P \) spawned less than \( n_f \) executors or some messages got dropped; at most \( f \) executors can act byzantine and can decide to not send VERIFY messages to \( V \).

In either case, it is safe to conservatively blame the primary. Note: even existing BFT protocols decide to blame the primary if messages get dropped [16], [41], [43].

- \( n_f > |V| \geq 2f + 1 \): This case implies that the verifier \( V \) received more than \( 2f + 1 \) VERIFY messages for transaction \( T' \). As a result, the verifier \( V \) cannot conclude that the shim’s primary is byzantine as \( V \) has received VERIFY message from at least \( 2f + 1 \) distinct executors. Observing responses from at least \( 2f + 1 \) executors is a guarantee that at least \( f + 1 \) honest executors tried to execute \( T' \) to the best of their ability. Hence, even if the shim’s primary is byzantine and intentionally delays spawning executors for \( T' \), there is no way that the verifier can prove this (due to concurrent spawning).

This forces the verifier to abort this transaction. Assume \( k \) is the sequence number for \( T' \). If \( k_{\text{max}} = k \), then \( V \) sends the client an (ABORT(\( T' \)) \( \in \) message. Otherwise, \( V \) adds \( T' \) to the list \( \pi \), but tags it as abort. Later, when \( T' \) is extracted from the list \( \pi \), the verifier \( V \) aborts it.

We now describe the indistinguishable attack, which forces us to require primary to spawn \( n_f \geq 3f + 1 \).

**Theorem VII.2.** If client transactions are conflicting and the primary \( P \) spawns \( n_f < 3f + 1 \) executors, then the SERVERLESSBFT protocol faces an indistinguishable attack.

**Proof.** Assume that \( P \) spawns only \( 2f + 1 \) executors. We know that up to \( 2f \) of these executors can act byzantine. As a result, for any client request, the verifier \( V \) may receive only \( f + 1 \) VERIFY messages. Further, due to transactional conflicts, these \( f + 1 \) VERIFY messages may not match. Eventually, \( V \)'s timer will expire and it needs to take some action. \( V \) can decide to abort this transaction, but this would lead to a new problem—a byzantine primary \( P \) may never spawn more than \( f + 1 \) executors and up to \( f \) of those executors may be byzantine. Hence, all subsequent conflicting transactions may abort.

Alternatively, \( V \) can blame the primary for receiving less than \( f + 1 \) matching VERIFY messages, but such a decision could be wrong as \( P \) may not be byzantine and the lack of sufficient matching messages could be a result of conflicts and byzantine executors.

**C. Best Effort Conflict Avoidance**

In database literature, several works have employed the concept of deterministic databases for efficient conflict resolution [47], [48], [49]. In these databases, the order in which transactions are applied to the database is determined prior to its execution, which is only possible if the read-write sets of the transactions are known to the participating nodes.

In our SERVERLESSBFT protocol, we learn from these databases. If the primary has any knowledge of the read-write sets, it uses the queuing strategy of these databases, to create plans that allow running non-conflicting transactions in parallel [47], [48], [50], [49], [51]. Such a strategy would require us to make straightforward modifications to the algorithm presented in Figure 3. We would need the shim primary to maintain a logical map of all data-items. This map does not store any values of the data-items, but helps the primary to locally lock different data-items. Further, the primary can no longer concurrently spawn executors for a transaction until it has determined its conflicts. Next, we list the steps.

1) The primary \( P \) adds the \( k \)-th transaction to the execution queue after it has added (or spawned executors for) all the \( k \)-th transactions in the queue, where \( k < k' \).

2) If the \( k \)-th transaction does not conflict with any \( k \)-th transaction \( (k < k') \), \( P \) spawns serverless executors for the \( k' \)-th transaction after it has logically locked all the data-items that are written by the \( k \)-th transaction.

3) Next, \( P \) dequeues a non-conflicting transaction at the head of some queue and repeats Step 2.

4) When \( P \) is notified by the verifier \( V \) that \( T \) has been executed, it unlocks the data-items accessed by \( T \) and follows Step 3. We believe these steps can help to reduce aborts.

**VII. SAFETY AND LIVENESS GUARANTEES**

We now prove that SERVERLESSBFT guarantees safety and liveness. As the shim nodes employ PBFT protocol, we borrow the following proposition guaranteed by PBFT.

**Proposition VII.1.** Let \( R_i, i \in \{1, 2\} \), be two honest shim nodes that committed \( (T_1)_c_i \) as the \( k \)-th transaction of view \( v \). If \( n_R > 3f_R \), then \( (T_1)_c_1 = (T_2)_c_2 \).

**Theorem VII.2.** Given an architecture \( A = \{C, R, E, S, V\} \), if the number of byzantine shim nodes and byzantine serverless executors are bounded by \( f_R \) and \( f_E \), respectively, then SERVERLESSBFT protocol guarantees safety.

**Proof.** Prior to proving this, we note that as the verifier \( V \) is trusted, storage \( S \) will be updated in the order agreed by \( 2f_R + 1 \) of shim nodes. We prove the rest as follows:

*Non-conflicting transactions.* If the primary \( P \) is honest, then from Proposition VII.1, we can conclude that no two shim nodes will commit different transactions at the same sequence number and \( P \) will spawn \( 2f_E + 1 \) executors. These transactions will persist across views as in any view-change quorum of \( 2f_E + 1 \) replicas, there will be one honest replica that has executed this request. If \( P \) is byzantine and assigns two or more requests the same sequence number \( k \), then from Proposition VII.1, we know that \( P \) will not be successful. If the
byzantine P sends the PREPARE for some \( T \) to less than \( 2f_R + 1 \) replicas, this transaction will not commit. As a result, at least \( f_R + 1 \) replicas will timeout and a VIEWCHANGE will take place. The new primary waits for VIEWCHANGE messages from \( 2f_R + 1 \) replicas, and uses these messages to create a NEWVIEW message. This NEWVIEW message includes a list of requests for each sequence number present in the VIEWCHANGE message. Each replica on receiving the NEWVIEW message can verify its contents and update its state.

Conflicting transactions with unknown read-write sets. In the case of conflicting transactions, the only additional attack a byzantine primary P can do is to get a task abortion by delaying spawning executors. However, as P does not know which transactions are conflicting, this is all based on a guess. Note: this attack does not make the data-store unsafe.

**Theorem VII.3.** Given an architecture \( \mathcal{A} = \{C, R, E, S, V\} \), if the network is reliable and the number of byzantine shim nodes and serverless executors are bounded by \( f_E \) and \( f_R \), respectively, then SERVERLESSBFT guarantees liveness.

**Proof.** Prior to proving this, we note that as the verifier \( V \) is trusted, so if it receives \( 2f_E + 1 \) matching VERIFY messages with correct read-write sets, it will send a reply to the client. We prove the rest as follows:

**Non-conflicting transactions.** If the primary P is honest, then every transaction will be committed by at least \( 2f_R + 1 \) shim nodes. P will use this to create a certificate and spawn \( 2f_E + 1 \) executors and \( V \) will receive \( f_E + 1 \) matching responses.

If P is byzantine, it can perform one of the many types of request suspension attacks described in Section V-A. For each such attack, either the client C or the nodes in R will timeout. This will force P to either ensure consensus of C’s transaction, or be replaced through the view-change protocol. Post view-change, if the subsequent primary is also byzantine, then it will also be eventually replaced. This process can happen at most \( f_R \) consecutive times, after which the system will be live. In the case a byzantine primary P attempts to keep up to \( f_R \) nodes in dark, then using the featherweight checkpoint protocol these nodes will be brought to the same state.

**Conflicting transactions with unknown read-write sets.** In the case of conflicting transactions, the only additional attack a byzantine primary P can do is to spawn less than \( 3f_E + 1 \). In such a case, if the verifier \( V \) receives less than \( 2f_E + 1 \) VERIFY messages, such that less than \( f_E + 1 \) are matching, \( V \)'s timer \( \tau_m \) will timeout and it will send a REPLACE message to the shim nodes. For other cases, \( V \) will send the client a RESPONSE or ABORT message depending on if it receives \( f_E + 1 \) matching VERIFY messages.

**VIII. IMPLEMENTATION**

To gauge the practicality of our vision of a BFT serverless-edge architecture, we implement and evaluate our design.

**Shim.** As the shim nodes represent edge devices, which may have access to limited resources, we want the shim nodes to have a lightweight BFT implementation. So, on each shim node, we install RESILIENTDB’s node architecture [17], [26], [27], [40], [52], [53]. RESILIENTDB provides access to a multi-threaded, pipelined, and modular architecture for designing BFT applications. The codebase is written in C++ and we deploy RESILIENTDB’s PBFT protocol at the shim. Clients also employ C++ to create YCSB transactions (refer Section IX) and use NNG [54] sockets for communication.

**Invoker.** At each shim node, we deploy an invoker to spawn \( n_k \) executors when indicated by the node’s consensus instance. RESILIENTDB provides at each node an execute-thread, which calls invoker as soon as a request is committed. Our implementation of the invoker is written in Go [55] using the AWS SDK for Go. Further, our invoker does not wait for the spawned executors to finish and proceeds to spawn the executors for the next client request.

**Serverless Function.** Each AWS Lambda executor receives a function written in C++ that includes the client transaction. This function instructs the executor to: (i) verify the certificate \( C \), (ii) execute the transaction, (iii) fetch necessary read-write sets from the storage database, and (iv) send the result to the verifier. We encode the communication between the Lambda function and the verifier in a stateless HTTP request. We use CryptoPP[56] library for digital signatures and verification and use CPR[57] to create and send HTTP requests.

**Verifier.** We implement the verifier in Go and install a simple HTTP/Net webserver at the verifier for receiving the executor responses. Further, our verifier includes a hashmap to count the matching responses for each transaction. Post validation, the verifier uses NNG to send a response to the client.

**IX. EVALUATION**

Our evaluation aims to answer following questions regarding our SERVERLESSBFT protocol.

(Q1) Impact of client congestion?
(Q2) Impact of increasing the number of executors?
(Q3) Impact of batching client requests?
(Q4) Impact of expensive execution?
(Q5) Impact of spawning executors across globe?
(Q6) Impact of resource limitations at edge devices?
(Q7) Impact of conflicting transactions?
(Q8) Baseline comparison of SERVERLESSBFT?
(Q9) Impact of task offloading?

**Setup.** We deploy the verifier, shim nodes, and clients on the Oracle Cloud Infrastructure (OCI). These components use VM.Standard.E3.Flex architecture with 10 GiB NICs. Each shim node has 16 cores and 16 GiB RAM and the verifier has 8 cores. We use AWS Lambda Functions for spawning serverless executors in up to 11 regions in the following order: North California, Oregon, Ohio, Canada, Frankfurt, Ireland, London, Paris, Stockholm, Seoul, and Singapore. In our experiments, we use up to 128 shim nodes and 21 executors. We run each experiment for 180 seconds with 60 seconds warmup time and report the average results over three runs.

Unless explicitly stated, we use the following setup. We require the primary node to spawn 3 AWS Lambda executors, each of which is spawned in a distinct region. Further, we deploy up to 80 k clients on 4 OCI machines to concurrently issue requests. Each client waits for a response prior to sending its next request. We also require clients and edge nodes to employ batching and run consensuses on batches of 100 client transactions. The size of each type of message communicated is: PREPARE (5392 B), PREPARE (216 B), COMMIT (220 B), EXECUTE (3320 B), and RESPONSE (2270 B).
with 8 existing records in the storage. Transactions represent user transactions that require access to YCSB to create key-value transactions that access a database designing transactions [17], [49], [58], [59], [60]. We use been used by several prior works in database literature for fixing the number of shim nodes. We learn from existing across different parameters, for some experiments, we need sending requests to the shim.

![Fig. 5. Comparing latency against throughput on varying the number of clients sending requests to the shim.](image)

**Benchmark.** To evaluate our serverless-edge architecture across different parameters, for some experiments, we need to fix the number of shim nodes. We learn from existing database literature, specifically the Blockbench [58] paper, and select two configurations. **SERVBFT-8**: Medium size shim with 8 nodes. **SERVBFT-32**: Large size shim with 32 nodes (maximum number of nodes in any Blockbench experiment).

Similarly, we adopt the popular Yahoo Cloud Serving Benchmark (YCSB) from Blockbench suite, which has also been used by several prior works in database literature for designing transactions [17], [49], [58], [59], [60]. We use YCSB to create key-value transactions that access a database of 600k records. Specifically, our transactions perform read and write operations. With regards to edge applications, these transactions represent user transactions that require access to existing records in the storage.

### A. Impact of Client Congestion

In Figure 5, we vary the number of deployed clients from 2k to 88k. For the first five data-points on the graph, we double the number of clients and for succeeding points, we increase the number of clients by 8k. Initially, an increase in the number of clients causes an increase in system throughput, post which the throughput saturates. This happens because each entity in our serverless-edge architecture has to now do more work than before, which causes an increase in computational and communication costs. As a result, the latency keeps increasing as each request spends a longer time in the architecture. Hence, SERVBFT-8 outperforms SERVBFT-32 as fewer nodes are involved in each consensus, which implies smaller wait time for each request. **Summary:** We observe that initially SERVBFT-8 attains up to 1.6× more throughput and 1.2× less latency than SERVBFT-32. However, on increasing the number of clients, the gap increases to 2.8× more throughput and 2.71× less latency.

### B. Impact of Executors

In Figures 6(i) and 6(ii), we vary the number of serverless executors spawned by the primary node: 3, 5, 11, 15, and 21. For these experiments, we spawned executors in up to seven regions and tried to evenly split these executors across these regions. These figures illustrate that an increase in the number of executors causes a decrease in throughput and an increase in latency. Although all the executors process the requests in parallel, there is an increase in the task of processing at the primary and increase in validation at the verifier. Further, as executors are spread across distinct regions, the reduced bandwidth and increased ping costs delays communication. **Summary:** At 3 executors, SERVBFT-8 attains 2.59× more throughput and 43% less latency than SERVBFT-32, while at 15 executors, 47% more throughput and 5% less latency.

### C. Impact of Batch Size

In Figures 6(iii) and 6(iv), we vary the size of batch of client requests from 10 to 8k. With an increase in batch size, we first observe an increase in the system throughput followed by an eventual decrease. Although larger batches imply a corresponding decrease in the number of runs of the SERVERLESSBFT protocol, it substantially increases the costs of communicating batches across the shim nodes and executors. Further, larger batches are much more expensive to process for shim nodes and executors.

**Summary:** From batch size 10 to 5k, SERVBFT-8 observes an increase in throughput by 11.42× and SERVBFT-32 observes an increase in throughput by 18.5×.

### D. Impact of Expensive Execution

In Figures 6(v) and 6(vi), we test with transactions that require large execution time; we vary the time required for execution from few milliseconds to 8 seconds. As the time required to execute a transaction increases, the time required by the shim and the verifier to process this request becomes insignificant. Prior works show that such transactions or codes, which bottleneck the system throughput and latency are prevalent [61]. This experiment also proves that our serverless-edge architecture introduces minimal costs to the applications that require large execution times. **Summary:** From execution length of few milliseconds to 8 seconds, SERVBFT-8’s throughput reduces by 74.5% and latency increases by 21×, while SERVBFT-32’s throughput reduces by 51% and latency increases by 13.6×.

### E. Impact of Spawning Executors across Globe

In Figures 6(vii) and (viii), we require the primary node to spawn 11 executors in 5, 7, 9, and 11 regions; we vary the number of regions while spawning same number of executors. The primary node uses the round-robin protocol to spawn executors in each region. In this experiment, we want to observe the impact of system performance on increasing the number of regions. We observe that the throughput and latency remain constant. The primary node spawns 11 executors (F_e = 5), so the verifier needs to wait for only F_e + 1 = 6 matching VERIFY messages. The first 6 messages received by the verifier (deployed at North California) are from nearby regions: North American and European.

### F. Impact of Computing Power

We use Figures 6(ix) and 6(x) to limit the available computing resources at shim nodes. As shim nodes represent edge devices, these devices may have limited cores and memory. So we test the impact of this restricted hardware on SERVERLESSBFT. Unsurprisingly, as we increase the number of available cores, the protocols achieve higher throughputs and lower latencies. This is the case because our shim nodes adopt the multi-threaded pipelined architecture of RESILIENTDB, which performs better with an increase in available cores.

**Summary:** From experiments at 2 cores to 16 cores, SERVBFT-8’s throughput increases by 6× and latency decreases by 70%, while SERVBFT-32’s throughput increases by 5× and latency decreases by 64%.
Fig. 7. Comparing ServerlessBFT against our three baseline designs: ServerlessCFT, PBFT and NoSHIM.

G. Impact of Conflicting Transactions

We now vary the degree of transactional conflicts from 0 to 50% and illustrate our findings in Figures 6(xi) and 6(xii). As the read-write sets are unknown, the primary node cannot lock the conflicting data-items. As a result, some transactions get aborted at the verifier. This leads to an expected observation—a decrease in throughput with an increase in the rate of conflicts. However, the latency remains unchanged as the response time for the client remains the same.

Summary: From 0% conflicting transactions to 50% conflicting, ServerBFT-8’s throughput decreases by 43%, and ServerBFT-32’s throughput decreases by 46%.

H. Shim Scalability

Until now, in all the experiments, we ran the PBFT protocol at the shim. So, we create three baseline designs to compare against ServerlessBFT:

(a) NoSHIM—Represents the experiment where there is no shim; no BFT consensus takes place. All the clients send their requests to a node, which instantaneously spawns executors.

(b) ServerlessCFT—Represents the experiment where the shim nodes employ a crash fault-tolerant (CFT) like Paxos [32] for consensus. As CFT protocols do not protect against byzantine attacks, they do not require cryptographic signatures, which in turn reduces the amount of work done per consensus. Further, unlike PBFT, Paxos is linear.

(c) PBFT—We also test our ServerlessBFT protocol against a BFT system (e.g. ResilientDB) running the PBFT protocol. In this system, we assume each node is a replica and executes the request in the agreed order post consensus [16], [17]. As a result, there are no costs associated with spawning executors and waiting for verifer to validate the requests.

In these experiments, we also gauge how the shim scales with an increase in the number of edge devices. For this purpose, we vary the number of shim nodes from 4 to 128. We use Figure 7 to illustrate the throughput and latency metrics and observe the following order for throughput attained:

ServerlessBFT < PBFT < ServerlessCFT < NoSHIM

NoSHIM has a constant throughput because there is no change in the number of shim nodes. Moreover, PBFT performs slightly better than our ServerlessBFT protocol. This implies that the verifier and executors do not adversely impact the throughput of PBFT. Finally, ServerlessCFT outperforms PBFT, which implies that the throughput of the serverless-edge architecture can be increased by replacing PBFT with faster consensus protocols. Summary: ServerlessBFT and
Efficient stateful executors. However, neither these works target stateful executors consistent; and Faasm \cite{67} aims to design solutions in this direction: AFT \cite{14} introduces a shim to make transactions (no serverless). For this experiment, we compare our ServBFT-32 with 3 serverless executors against a PBFT shim with 32 nodes.

We make two observations: (1) If transactions can be executed in parallel, our serverless-edge model is only bounded by the rate of consensus and the number of executors that can be spawned in parallel. This is in contrast to setups where shim performs all tasks and becomes resource-bounded, which adversely decreases the throughput. To further validate this resource-boundedness, we calculate monetary costs of these experiments (in cents/ktxn) and use the precise costs for spawning serverless executors at AWS Lambda and running machines on OCI. Resource-boundedness increases monetary costs as machines need to be run for a larger period of time to complete the same set of transactions. (2) Serverless clouds permit selecting optimal hardware. To illustrate this, for experiments where shim does all tasks, we vary the number of execution threads (ET) at shim nodes \cite{1,8,16}. If the available hardware has few cores, then a smaller set of transactions (1 or 8) can execute in parallel, which impacts throughput. Alternatively, an enterprise can require edge devices to have more cores \cite{16}, which may be underutilized if there is less available parallelism.

X. RELATED WORK

Edge computing is a decade old problem for which prior works have presented several interesting solutions \cite{62}, \cite{63}, \cite{64}, \cite{65}, \cite{66}. These solutions aim to reduce latency for edge applications, but they cannot handle byzantine attacks and require developers to perform managerial tasks.

In recent years, Serverless computing has also gained a lot of interest with the aim of offloading the managerial tasks such as server provisioning and resource scaling to the cloud provider while the developer only uploads the code required to be executed \cite{15}, \cite{38}. Prior works have presented novel solutions in this direction: AFT \cite{14} introduces a shim to make stateful executors consistent; and Faasm \cite{67} aims to design efficient stateful executors. However, neither these works target edge applications, nor they consider byzantine attacks.

To design applications that can handle byzantine attacks, existing works have employed Byzantine Fault-Tolerant consensus protocols in the context of blockchain technology \cite{19}, \cite{46}, \cite{68}, \cite{69}, \cite{70}, \cite{71}, \cite{72}, \cite{73}, \cite{74}, \cite{75}, \cite{76}. These applications assume that a set of nodes holding the same data run a BFT protocol. Each committed transaction is noted in an append-only ledger, blockchain, which can be queried in future to track transactions. EdgeChain \cite{4} introduces a blockchain layer in the edge-compute model, which allocates the resources to edge devices. However, it does not tackle byzantine attacks from edge-clouds. Bajoudah et al \cite{77} introduce a blockchain-based edge model where IOT devices maintain the blockchain. Blockene \cite{78} wants to allow mobile devices to participate in blockchain consensus by delegating all the storage, computation, and communication tasks to a set of powerful servers.

Aslanpur et al. \cite{79} present the vision of a serverless-edge framework. Their proposal does not assign tasks to edge devices and delegates all jobs to the serverless cloud. Further, there is no discussion on handling byzantine failures. Moreover, their vision is neither implemented nor does their paper present any evaluation. Baresi et al. \cite{80} present a similar design, but their design focusses on mobile computing. They do present a small evaluation of their design, but neither is their code available, nor do they make use of actual serverless cloud providers (like AWS). Their design delegates everything to the mobile edge servers (where they create a serverless cloud) and does not handle byzantine failures. Our NoShim experiment (Figure 7) approximates their architecture.

In comparison, our serverless-edge co-design handles byzantine attacks, permits edge devices to select any serverless provider in vicinity, offloads compute-intensive tasks to cloud while allowing light-weight ordering on edge devices.

XI. CONCLUSIONS

In this paper, we presented SERVERLESSBFT, the first protocol to guarantee Byzantine Fault-Tolerant transactional flow among edge devices and serverless functions. SERVERLESSBFT facilitates collaboration among edge devices, which spawn serverless executors at one or more cloud providers in their vicinity to process compute-intensive operations. Our proposed architecture ensures that only consistent updates are written to the database. We also present solutions to resolve various attacks on our proposed architecture. Our extensive evaluation illustrates that our architecture is scalable and is a good fit for the emerging edge applications.

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