Fault Tolerance for Service Function Chains

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Abstract

Enterprise network traffic typically traverses a sequence of middleboxes forming a service function chain, or simply a chain. Tolerating failures when they occur along chains is imperative to the availability and reliability of enterprise applications. Service outages due to chain failures severely impact customers and cause significant financial losses. Making a chain fault-tolerant is challenging since, in the case of failures, the state of faulty middleboxes must be correctly and quickly recovered while providing high throughput and low latency.

In this paper, we present *FTC*, a novel system design and protocol for fault-tolerant service function chaining. FTC provides strong consistency with up to \( f \) middlebox failures for chains of length \( f + 1 \) or longer without requiring dedicated replica nodes. In FTC, state updates caused by packet processing at a middlebox are collected, piggybacked into the packet, and sent along the chain to be replicated. We implement and evaluate a prototype of our system. Our results for a chain of 2-5 middleboxes show that FTC improves throughput by \( 2-3.5 \times \) compared with state of the art [50] and adds only 20 \( \mu s \) latency overhead per middlebox. In a geodistributed Cloud deployment, our system recovers lost state in \( \sim 271 \) ms.

1 Introduction

Middleboxes are ubiquitous in networks. They provide data link functions to improve performance (e.g., load balancers), security (e.g., firewalls), and application support (e.g., media gateways) [44, 51, 59]. Enterprise traffic typically passes through an ordered sequence of middleboxes called a service function chain, or simply a chain [43, 44]. For instance, traffic from a server can pass through a chain comprised of an intrusion detection system, a firewall, and a network address translator (NAT) before reaching the Internet [59].

The reliability of chains is crucial, and the end-to-end availability of applications and services relies on the fault tolerance of these chains. For example in an enterprise network, HTTP traffic is processed by an intrusion detection system (IDS), proxy, and firewall [49], and the failure of any of them can cause the system to become unprotected and insecure, and even cause service and application outages. Service outages due to failures of a chain severely impact customers and can result in significant financial losses [10, 42, 55, 56].

Traditionally, hardware middleboxes compose a chain whose availability depends on the reliability of these devices. A hardware middlebox is developed by a single vendor, and the vendor carefully designs and tests the device to provide built-in reliability using mechanisms such as a redundant power supply and error correcting codes [31]. Additionally, a dedicated backup appliance can be deployed for each middlebox to recover from device failure [42, 50].

The high cost and lack of flexibility of proprietary hardware middleboxes motivated the move toward network function virtualization (NFV) [1]. NFV decouples functions from underlying hardware and implements them in software that runs on commodity hardware. NFV’s flexible deployment and the diversity of underlying infrastructure have motivated recent work [26, 28, 32, 45, 50] to provide fault-tolerant designs for virtualized middleboxes.

Recent systems have focused on providing fault tolerance for individual middleboxes. For a chain, they consider individual middleboxes as fault tolerant units that comprise a fault tolerant chain. This design comes at high performance costs. Snapshot-based solutions checkpoint the state of a middlebox per packet-batch [32] or periodically (e.g., in 20-200 ms intervals) [45, 50]. To make a chain fault tolerant, these snapshots must be taken for every middlebox in the chain. With longer chains, most packets experience some snapshot related overhead, incurring per middlebox latency from 400 \( \mu s \) [32] to 8-9 ms [45]. More importantly, the operation of a middlebox is stalled while it is checkpointing. With a moderate snapshot period of 50 ms per middlebox [50], we measured a \( \sim 40\% \) throughput drop going from a single middlebox to a chain of 5 middleboxes (see § 7.4). Moreover, StatelessNF [26] and CHC [28] store middlebox state in a remote data-store, resulting in round-trip network delays in accessing state [34].
In this paper, we design a system called fault tolerant chaining (FTC) that provides fault-tolerance for a chain. Instead of making individual middleboxes of a chain fault tolerant, FTC considers the entire chain as a fault tolerant unit. FTC design includes three main mechanisms to provide fault tolerance for a chain: i) using transactional packet processing, FTC ensures consistent state recovery without sacrificing performance during normal chain operation, ii) using state piggybacking, our system effectively carries state updates due to packet processing in the packets themselves, and iii) using in-chain replication, FTC takes advantage of the chain structure to replicate state at other on-path middleboxes concurrently.

This paper makes three main contributions:

- We describe FTC’s mechanisms and show that packet transactions simplify the system design, and in-chain replication and state piggybacking allow higher concurrency in packet processing and state replication. Doing so achieves a simpler and more efficient fault tolerant design compared to existing work.

- FTC adapts the chain replication protocol [58] to replicate the state of middleboxes of the chain. Using this protocol, FTC reuses the servers hosting the middleboxes of the chain to serve as replicas for other middleboxes. In the chain replication, only the first and last replicas of a chain can process requests. We extend this protocol to enable all servers of a chain to process packets in addition to state replication.

- We implement FTC and compare its performance with state of the art [50]. Our results for a chain of 2 to 5 middleboxes show that FTC improves throughput of the state of art [50] by 2× to 3.5× while adding only 20 µs per middlebox latency overhead. Our evaluation in a geo-distributed Cloud shows that FTC recovers the state of a failed middlebox in 271 ms and restores the chain operation in less than 320 ms.

2 Background

A service function chain is an ordered sequence of middleboxes. In an NFV environment, as shown in Fig. 1, an orchestrator (e.g., a SDN controller) manages and steers traffic through the chain’s middleboxes. Each middlebox in a chain runs multiple threads and is equipped with a multi-queue network interface card (NIC) [13, 40, 48]. A middlebox thread receives packets from a NIC’s input queue and sends packets to a NIC’s output queue. Fig. 1 shows two threaded middleboxes processing two flows.

2.1 Middleware State

Stateful middleboxes keep dynamic state for packets that they process [21, 52]. For instance, a stateful firewall filters packets based on statistics that it collects for network flows [5], and a NAT translates network addresses using a flow table that it dynamically generates for network flows [22, 53].

The middlebox state can be partitionable or shared [5, 18, 20, 45]. Partitionable state variables describe the state of a single traffic flow (e.g., MTU size and timeouts in stateful firewalls [5, 18]) and are only accessed by a single middlebox thread. Shared state variables are for a collection of flows, and multiple middlebox threads query and update them (e.g., port-counts in an IDS, and available address-pools in a NAT).

2.2 Middleware Failure Model

A stateful middlebox is subject to both hardware and software failures that can cause the loss of its state [42, 50]. We model these failures as fail-stop in which failures are detectable, and failed components are not restored.

2.3 Challenges

To recover from a middleware failure, traffic must be rerouted to a redundant middlebox where the state of the failed middlebox is restored. With state being replicated on multiple servers during normal operation, the state of the failed middlebox can be restored from one of these replicas at failover. State replication involves following challenges that affect middleware performance and consequently that of the chain:

Handling the non-determinism. In a multi-threaded middlebox, the order in which interleaving threads access shared state is non-deterministic. Parallel updates can lead to observable states that are hard-to-restore. Devising an approach that allows high concurrency to achieve high performance while guaranteeing a correct recovery can be challenging. One approach to accommodate non-determinism is to log any state read and write, so that any potential observed state upon a failure can be restored from these logs [50]. However, doing so complicates the middlebox design and failure recovery procedure, and can cause high performance overheads during normal operation.

Synchrony in state replication. To tolerate f failures, a packet is released only when at least f + 1 replicas acknowledge that state updates, due to processing of this packet, are replicated. In addition to inflating latency, such synchrony degrades throughput since expensive coordinations among
packet processing and state replication are required for consistency (e.g., pausing packet processing until replication is acknowledged [26, 28, 32, 45]). The amount of overhead of such synchro-ny for a middlebox depends on where its replicas are located, and how state updates are disseminated to these locations. For a solution that is designed for individual middleboxes, the overheads can accumulate for each middlebox of the chain.

2.4 Limitations of Existing Approaches
Existing fault tolerant approaches are designed for individual middleboxes. Applying these approaches to a chain whose middleboxes are deployed over multiple servers significantly impacts the chain’s performance. They use two approaches:

- Replication using checkpointing. Snapshot-based systems checkpoint the state of a middlebox for state replication [32, 45, 50]. During checkpointing, middlebox operations are stalled for consistency. The existing approaches take snapshots in different rates. For a single middlebox, snapshots taken per packet batch or per packet [32, 45] introduce 400 µs to 8-9 ms of per packet latency overhead. Periodic snapshots (e.g., at every 20-200 ms intervals) can cause periodic latency spikes up to 6 ms [50]. We measure that per middlebox snapshots cause 40% throughput drop going from a single middlebox to a chain of 5 middleboxes (see § 7.4).

- Replication in a fault-tolerant data-store. Other systems [26, 28] redesign the architecture of middleboxes to separate and push their state into a fault-tolerant back-end data-store. However, this separation incurs high performance penalties. Querying state takes at least a round trip delay. Furthermore, a middlebox can release a packet only when it receives an acknowledgement from the data-store that relevant state updates are replicated. Due to such overheads, the throughput of stateful middleboxes can drop by ∼60% [26] and reduce to 0.5 Gbps (for packets with median size of 1434 B) [28].

3 System Design Overview
The limitations of the existing work lead us to design fault tolerant chaining (FTC), a new system that approaches the chain’s fault tolerance problem from a different perspective by considering a chain as a fault tolerant unit.

3.1 Requirements
A fault-tolerant chain adheres to the following requirements:

- Correct recovery. Strom and Yemeni [54] define correct recovery as follows: “A system recovers correctly if its internal state after a failure is consistent with the observable behavior of the system before the failure”. The necessary condition for correct recovery in our system is as follows: no packet is released to the outside of a chain until all the information needed to reconstruct internal state (i.e., state of every middlebox that has processed the packet) consistent with this packet is stored in sufficient number of stable storage systems.

- Low overhead and fast failure recovery. A chain processes a high traffic volume and the state of middleboxes can be modified very frequently. At each middlebox of a chain, latency should be within 10 to 100 µs [50], and the fault tolerance mechanism must support an access rate of 100 k to 1 M times per second [50]. Further, the processing required to achieve fault-tolerance should not significantly affect the throughput of the chain. Finally, recovery time must be short enough to prevent application outages (e.g., TCP timeout).

- Resource efficiency. To isolate the effect of possible failures, replicas of a middlebox must be deployed on separate physical servers. We are interested in a system that requires fewer replicas and consequently fewer servers.

- Generality. We are also interested in a system that supports different middleboxes.

3.2 Design Choices
We model packet processing as a transaction. FTC carefully collects updated values of state variables changed during a packet transaction and appends them into the packet. As the packet passes through the chain, FTC replicates piggybacked state updates in servers hosting the middleboxes.

- Transactional packet processing. To accommodate nondeterminism, we model the processing of a packet as a transaction where concurrent accesses to shared state are serialized to ensure that consistent state is captured and later replicated. In this way, FTC avoids complex observable system states due to parallel packet processing. This model also does not reduce concurrency in popular middleboxes, since they already implement similar logic for the correct operation. For instance, a load balancer and a NAT ensure connection persistence for traffic connections (i.e., a connection is always directed to a unique destination) while accessing a shared flow table [8, 53]. Concurrent threads in these middleboxes must coordinate to provide this property.

- In-chain replication. A high-availability clustering scheme Consensus-based state replication (e.g., Raft [38]) requires 2f + 1 replicas for each middlebox. For a chain of n middleboxes, these schemes need n × (f + 1) and n × (2f + 1) replicas, respectively. Replicas are placed on separate servers, and a naive placement requires the same number of servers. FTC observes that packets already flow through a chain; each server hosting a middlebox of the chain is naturally amendable to serve as a replica for the other middleboxes. Instead of allocating dedicated replicas, FTC replicates the middleboxes state across the chain. In this way, FTC tolerates f failures with no cost of extra replica servers. Moreover, combined with state piggybacking, as described next, in-chain replication enables more asynchrony in state replication.

- State piggybacking. To replicate state modified by a packet, existing schemes send separate messages to replicas. In FTC, modified state is piggybacked on data packets; a packet disseminates its own state updates (the state modified
shows our protocol to provide fault tolerance for a replicated middlebox's state. In §4.1, we describe our protocol for a single middlebox. Then, in §4.2, we extend this protocol to a chain of middleboxes. This protocol is based on a state management API for the middlebox to read and write state during packet processing. The API follows the specification described in §2.1, and existing middleboxes can be modified to become compatible with our system. State variables are handled through this API.

Centralized orchestration. In our system, a central orchestrator (Orch) manages the network and chains. Orch deploys fault tolerant chains, reliably monitors them, detects their failures, and initiates failure recovery. The functionality of Orch is provided by a fault-tolerant SDN controller [6,27,39]. After deploying a chain, to avoid performance bottlenecks, Orch is not involved in the normal chain operations.

Our goal is supporting fault-tolerance for a chain of multi-threaded middleboxes as modeled in §2. We first discuss our protocol for a single middlebox in §4, then extend this protocol for a chain of middleboxes in §5.

4 FTC for a Single Middlebox

In this section, we present our protocol for a middlebox. We first describe our protocol for a simpler middlebox model, i.e., a middlebox where a middlebox is single-threaded, and its state is replicated by single-threaded replicas. Later, we augment this model to support multi-threaded middleboxes and multi-threaded replication respectively in §4.2 and §4.3. From now on, we use $f$ to denote the number of failures.

4.1 Middlebox State Replication

In a single thread middlebox model, only one thread reads and writes state variables while processing packets. To support state recovery of the middlebox, we replicate the middlebox’s state consistently in $f+1$ servers across a network during normal middlebox operations. With middlebox state replicated on $f+1$ servers, the state remains available even when $f$ of these servers fail. We adapt the Chain Replication protocol [58] for state replication across replicating servers. In transmission of the middlebox state to these servers, we use sequence numbers (seq-numbers), similar to TCP, to handle out-of-order deliveries and packet drops within the network.

4.1.1 Replication and Middlebox State

We describe where a middlebox’s state is replicated, and which data-structures are used to store and disseminate state.

Replication group. Fig. 2 shows that the state of a middlebox is replicated by $f+1$ Replicas during normal operation. These Replicas are called the replication group of this middlebox. Each Replica has a unique ID and is placed on a separate server whose failure is isolated. Replicas are arranged in a linear order, i.e., traffic is steered through them in order. Head and Tail are the first and last Replicas, respectively. Head is placed in the same server hosting the middlebox.

In-operation state in Head. Our system separates the middlebox logic from its state. In this abstraction, state is moved from a middlebox and is stored in Head that provides a state management API for the middlebox to read and write state during packet processing. The API follows the specification described in §2.1, and existing middleboxes can be modified to become compatible with our system. State variables are accessed via this API.

Log store in a Replica. To replicate the middlebox state, each Replica (including Head) keeps a log store maintaining log entries where each entry stores $(s,v,t)$ denoting value $v$ of state variable $s$ at seq-number $t$. Log operation inserts $(s,v',t')$ into the log store.

Piggyback log to disseminate state. To transmit state to Replicas, Head appends a piggyback log (PL) to incoming packets. In a PL $(S,t)$, $S$ is a list of state updates each of which is $(s,v)$ denoting value $v$ of state variable $s$ updated at seq-number $t$.

4.1.2 Normal Operation of Protocol

Fig. 2 shows our protocol to provide fault tolerance for a middlebox. Replicas $r_1$ and $r_{f+1}$ are respectively the Head and Tail in the replication group of middlebox $m$. As Fig. 2 shows, a packet passes through i) middlebox $m$ that processes the packet and Head that constructs and appends a PL to the packet, ii) successor Replicas that replicate the PL, and iii) Tail that, after replication, strips the PL and releases the packet. We detail these stages next.

At server hosting Head and middlebox. Head keeps a seq-number $t$ denoting the highest seq-number that it has assigned to any processed packet. After a middlebox finishes processing a packet, Head increments its seq-number only if a state variable was updated during packet processing. Head assigns a seq-number of zero to a packet processed with no state update. Head logs updated variables as follows. For each updated variable $s$, Head records its value $v$ in the log store by logging entry $(s,v,t)$ where $t$ is Head’s seq-number. Then, Head appends a PL $(S,t)$ to the packet, where $S$ includes each state update $(s,v)$ at Head’s seq-number $t$ ($S=\emptyset$ if no variable is updated). Next, Head forwards the packet to the next Replica in the replication group.

At a Replica. Each Replica continuously receives packets piggybacking PL with assigned seq-numbers. If a
packet is lost, a Replica requests its predecessor to re-transmit the log-entries at the lost seq-numbers. A Replica keeps max denoting the largest seq-number that it has received in sequence order (i.e., it has already received all PLs with seq-numbers less than or equal to max). max is initialized to zero and is updated only if the Replica receives a PL \((S,t)\) with seq-number \(t = \text{max} + 1\). Upon receiving a packet with PL \((S,t)\), a Replica compares \(t\) with max. A packet with \(t > \text{max} + 1\) is withheld from releasing. Once \(t = \text{max} + 1\) holds, each state update \((s,v)\) in \(S\) is logged at seq-number \(t\), and then the packet is forwarded. Packets with \((S,t)\) where \(t = 0\) are immediately forwarded because \(s = \emptyset\).

At Tail. Finally, Tail replicates state-updates as a Replica, strips the PL from the packet, and releases the stripped packet to its original destination.

Further, Tail’s max is periodically disseminated to Head and propagated along the chain to the other Replicas. They can prune their log entries up to this seq-number.

4.1.3 Correctness

Packets pass through Replicas in order. When a packet reaches Replica \(r_s\), this packet has already traversed all Replicas preceding \(r_s\). Since packets are forwarded in a linear order, when Tail releases a packet, the state carried by the packet has already been logged in \(f + 1\) Replicas. Each Replica replicates the piggybacked state, a packet at a time, in the order specified by the piggybacked seq-number. As a result, when a Replica releases a packet piggybacking PL \((.,t)\), it has logged each log entry with seq-number \(t' \leq t\). Log operations performed in the replication group are redundant, and \(f + 1\) redundant log entries allow FTC to tolerate \(f\) failures.

4.1.4 Failure Recovery

Recall that we assume that Orch is a fault-tolerant SDN controller which can reliably detect failures. Orch differentiates the failures of Head from other Replicas. Because the middlebox and Head are in the same server, their failures are not isolated. Upon the detection of a Replica failure, lost state has to be recovered. Doing so depends on how the state logs are propagated through the chain.

Let \(T_j = (s,v_j,t_j)\) be a log entry in Replica \(r_j\) such that \(t_j \geq t'_j\) for each \(s,v_j\). We can state that

\[
T_j \preceq T_k
\]

holds if \(t_j \leq t_k\), i.e., \(v_j\) is a prior value of \(s\) to \(v_k\). Because a single log entry is propagated in order through Replicas, the last log entry recorded in each Replica \(r_j\) is a prior value of the last log entry recorded in the predecessor of \(r_j\). Thus, we have the following invariant:

**Log propagation invariant.** For Replicas \(r_j\) and \(r_k\) in the replication group of the middlebox such that \(j \leq k\) (meaning that Replica \(r_j\) is predecessor of \(r_k\)), Invariant 1 holds:

\[
T_k \preceq T_j
\]

**Handling the failure of Head.** Three steps are performed:

i) Initialization: Orch instantiates a new Replica \(r^*\) and informs it about other alive Replicas.

ii) State recovery: \(r^*\) fetches the log store and seq-number of the first alive Replica \(r_j\) successor to the failed Head (such that \(j \leq k\) for each alive Replica \(r_k\) in the replication group). Such a Replica exists since at most \(f\) failures occur, and the replication group contains \(f + 1\) Replicas.

Invariant 1 implies that \(r_j\) maintains the most recently updated log entries among alive Replicas. To ensure that the log-propagation will hold after state recovery, upon receiving a fetch request, Replica \(r_j\) discards pending packets (out-of-order packet that their state-updates have not been logged) and will no longer admit packets in flight that the failed Replica has sent before the failure and has yet to reach \(r_j\). If Replica \(r_j\) also fails during recovery, Orch detects this failure and informs the new Replica \(r^*\) to discard the transmitted log store and seq-number, and to send a new fetch request to the successor of \(r_j\). If \(r^*\) fails, Orch starts a new recovery procedure. In operation state can be easily reconstructed by retrieving \((s,v)\) from each log entry \((s,v,t)\) in the fetched log store such that \(t \geq t'\) for each \(s,v,t\). Then, Orch instantiates a new middlebox in the same server hosting Head.

iii) Rerouting: Finally, Orch updates routing rules to steer traffic through the new Replica in the position of the failed Head. If multiple Replicas have failed, Orch waits until all new Replicas acknowledge that they have successfully recovered the state. Then, Orch updates the necessary routing rules in order from Tail to Head.

**Handling the failure of other Replicas.** FTC performs the same steps of handling Head’s failure for the successor Replicas, with a slight modification to the state recovery step. For a failed Replica \(r_k\) in the replication group other than Head, new Replica fetches from the first alive Replica \(r_j\) predecessor to \(r_k\) (such that \(j \geq i\) for each alive Replica \(r_i\) between Head and \(r_k\)).

4.2 Concurrent Packet Processing

Our protocol for a single threaded middlebox provides correct recovery; however, its performance is limited to that of a single thread. To achieve higher performance, we augment our protocol by supporting multi-threaded packet processing and state logging respectively in the middlebox and Head. Replicas are still single threaded. Later in § 4.3, we support multi-threaded replications in other Replicas.

In concurrent packet processing, multiple packets are processed in interleaving threads. They can read from and write to same state variables in parallel. Accordingly, Head must consistently log state updates for a multi-threaded middlebox. We use the notion of transactional packet processing that effectively serializes packet processing. This notion supports concurrency if packet transactions access disjoint subsets of
shared variables.

### 4.2.1 Transactional packet processing

Concurrent packet processing can reduce latency and increase throughput, but the middlebox must ensure that the effects on state variables are equivalent to processing packets in some serial order. Furthermore, the updates must be applied to the replicas in the same order to ensure that the system returns to a consistent state after failure recovery. To support this requirement, replay-based replication systems, such as FTMB [50], carefully log every state access, including state reads, which can be challenging to perform efficiently.

In FTC, we model the processing of a packet as a transaction. In this model, state reads and writes by a packet transaction have no influence on another concurrent packet transaction. This isolation allows us to only keep track of the relative order between transactions, without the need to track per state variable dependencies.

**Packet transactions.** Each packet arrival is treated as the start of a transaction in which multiple reads and writes are performed. We use fine-grained 2-phase locking to provide serializability, and a wait-then-scheme to prevent possible deadlocks if a lock ordering is not known in advance. Aborted transactions are immediately re-executed.

**State partitions and transaction locks.** To simplify the lock management for packet transactions, we partition the key space of state variables in a deterministic way (e.g., hashing state variable keys) and introduce per partition locks. Head and Replicas use the same state partitioning.

We modify our protocol operation discussed in § 4.1.2 to support concurrent packet processing. All other parts of the protocol remain the same.

**At server hosting Head and middlebox.** Before partition locks are released at the end of a transaction⁴, the thread at Head that is responsible for the packet transaction performs the following: It atomically increments Head’s seq-number \( t \) only if one or more state variables were updated during this packet transaction. Next, it logs variables updated in the transaction at seq-number \( t \), appends PL to the packet, and then forwards the packet.

### 4.2.2 Correctness

Due to mutual exclusion, when a packet transaction logs entry \((s, v, \_ )\), no other concurrent transaction writes \( s \), thus value \( v \) is consistent with the final value of the packet transaction. Head’s seq-number \( t \) maps this transaction to a valid serial order. Because a single-threaded Replica will replicate the state updates of the transaction in the same serial order denoted by seq-number \( t \), its log for variable \( s \) is consistent with that of Head.

### 4.3 Concurrent State Replication

Our system for a multi-threaded middlebox processes packets concurrently. Previously, we assumed single-threaded

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⁴After a middlebox thread performs its last state read/write.
thread applies Rule-2 for updated partitions and Rule-3 for all involved partitions (see Fig. 3). Next, Head’s thread logs every variable \( s \) updated in the transaction at seq-number \( V[i][s] \) where \( s \) belongs to state partition \( i \). Then, it appends a modified version of piggyback log, as described next, and forwards the packet.

**Modification of piggyback log.** Since multiple state-partitions can be updated during a write-transaction, the range of updated vectors must be disseminated. A PL is re-defined as \( (S, V_1, V_2) \) where \( S \) is a list of state updates and \( V_1 \) and \( V_2 \) specify the respective start and end of the updated range. \( V_1 \) can be obtained from only applying Rule-3 (without applying Rule-2). \( V_2 \) can be obtained from Head’s \( V[i] \) if state partition \( i \) received any write in the transaction (after applying Rule-2 and Rule-3).

**At successor Replicas.** A Replica keeps a vector clock \( MAX \) which captures the latest state updates that it has replicated in order (i.e., it has already received every PL \( (.., V_2) \) with each element in vector clock \( V_2 \) being less than or equal to its corresponding element in \( MAX \)). All elements of \( MAX \) are initially zero. Each Replica continuously receives packets, and in case of packet drops, it requests its predecessor to re-transmit missing state-updates. Upon receiving a packet with a PL \( (S, V_1, V_2) \), a Replica’s thread compares \( V_1 \) with \( MAX \). Once \( V_1[i] \leq MAX[i] \) for each state partition \( i \), Replica’s thread logs each state update \( (s, v) \in S \) at seq-number \( V_2[i] \) where \( s \) belongs to state partition \( i \). Replica’s thread applies \( MAX[i] \leftarrow \max(MAX[i], V_2[i]) \) for each \( i \) and forwards the packet.

**At Tail.** Finally, Tail replicates state-updates as a Replica, strips the PL from the packet, and releases the stripped packet to its original destination.

Similar to our protocol in § 4.1, Tail’s \( MAX \) is periodically disseminated to Head and propagated along the chain. Finally, to recover Head’s \( V \) in case of its failure, a new Head fetches \( MAX \) from an alive Replica from which it recovers the state, and set \( V[i] \leftarrow MAX \) for each state-partition \( i \).

5 FTC for a Chain

In this section, we extend our protocol, developed through § 4, for a chain of \( n \) middleboxes. We adapt our protocol so that every middlebox in the chain can replicate the chain’s state while it processes packets. Doing so extends the original chain replication protocol [58] to support parallel processing across the entire chain. We assume that \( n \geq f + 1 \). Later, we will discuss the case without this assumption.

Fig. 4 illustrates that FTC treats a chain deployed over multiple servers as a single fault-tolerant unit. For a chain of \( n \) middleboxes, FTC places \( n \) Replicas in servers hosting middleboxes. Replicas form \( n \) logical replication groups, each of which provides fault tolerance for a single middlebox.

In some replication groups, Replicas may precede their corresponding middleboxes in the chain. For example in Fig. 4, the replication group of middlebox \( m_n \) includes Replica \( r_1 \) hosted in the first server of the chain. FTC places two additional elements, Forwarder and Buffer respectively as ingress and egress points of the chain. Forwarder and Buffer are also multi-threaded, and they are placed in servers hosting the first and last middleboxes, respectively.

Buffer holds a packet until the state updates associated with all of the middleboxes in the chain have been replicated to \( f + 1 \) Replicas. It also forwards state updates to Forwarder for middleboxes with Replicas at the beginning of the chain. Forwarder appends state updates from Buffer to incoming packets before forwarding those packets to the first middlebox.

5.1 Chain State and Replication

**Multiple log stores in Replicas.** For a chain of \( n \) middleboxes, as shown in Fig. 4, Orch instantiates \( n \) Replicas arranged in a linear order. Let \( m_i \) and \( r_i \) be a middlebox and a Replica respectively at position \( i \) in the chain. Viewing a chain as a *logical ring*, the replication group of middlebox \( m_i \) consists of Replica \( r_i \) (as Head) and its \( f \) succeeding Replicas. In this logical ring, instead of being dedicated to a single middlebox, a Replica is shared among \( f + 1 \) middleboxes. For instance for \( f=1 \) in Fig. 4, \( r_1 \) is in the replication groups of middleboxes \( m_1 \) and \( m_n \), and \( r_2 \) is in the replication groups of \( m_1 \) and \( m_2 \). As a member of multiple replication groups, a Replica \( r_i \) replicates the state updates of \( m_i \) and the state of \( f \) preceding middleboxes. To do so, each Replica keeps \( f + 1 \) log stores, one for each replication group.

**Piggyback message to disseminate chain state.** To disseminate the state of multiple middleboxes, we append a piggyback message to each packet, which consists of a list of piggyback commit log (PCLs) with each PCL defined as \( (m, C, (S, V_1, V_2)) \). In a PCL, \( m \) identifies a middlebox, and \( (S, V_1, V_2) \) is a PL relevant to \( m \). \( C \) is a commit vector that captures the state updates that the Tail of middlebox \( m \) has replicated. Once received in Buffer, this field allows Buffer

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Footnote 1: Recall from § 4.3.2, \( S \) is state update list, and \( V_1 \) and \( V_2 \) are two vectors.
to determine the state updates that have been replicated to $f + 1$ Replicas, the details of which we will describe in the next section. Buffer can then safely release the packets associated with those state updates.

5.2 Normal Operation of Protocol

For a chain of length $n$, one may consider our protocol as running $n$ instances (per middlebox) of the protocol developed earlier in § 4. As shown in Fig. 4, a packet is steered in order through Forwarder, the chain of Replicas and middleboxes, and Buffer.

At Forwarder, Forwarder receives incoming packets from outside world and piggyback messages from Buffer. Each thread in Forwarder stores piggyback messages received from Buffer in a circular queue. The thread reads a piggyback message from its queue and appends the piggyback message to an incoming packet. If its queue is empty, Forwarder appends an empty piggyback message.

At a server hosting a middlebox and a Replica. A Replica strips and processes a delivered piggyback message before the packet transaction. Then, the packet is processed in a transaction. Finally, the Replica updates and reattaches the piggyback message to the packet, and forward the packet.

Processing a piggyback message. A Replica $r$ is in the replication group of $f$ preceding middleboxes. For each of these middleboxes, $r$ maintains a vector $\text{MAX}_m$. Upon receiving a packet, a replica's thread processes each PL $(S, V_1, V_2)$ of a relevant middlebox $m$ as described in § 4.3.2. Once $V_i[i] \leq \text{MAX}_m[i]$ for each $i$ holds, it replicates state updates $S$ and updates $\text{MAX}_m$ by merging it with $V_2$ [17].

Updating a piggyback message. If a Replica $r$ is Head or Tail in the replication group of a middlebox $m$, it updates $\text{PCL} \langle m, C, (S, V_1, V_2) \rangle$ from the piggyback message. If $r$ is a Head, a thread updates PL $(S, V_1, V_2)$ from the PL constructed in the packet transaction to disseminate state-updates. If $r$ is a Tail, a thread replaces $C$ with its $\text{MAX}_m$. Later by reading $C$, Buffer is informed about the latest state updates that have been replicated $f + 1$ times for middlebox $m$, captured by vector clock $\text{MAX}_m$. Moreover, since $r$ as the Tail has replicated the PL for $f + 1$-th time, the thread sets $(S, V_1, V_2) \leftarrow \emptyset$ to reduce the size of the piggyback message.

Releasing packets at Buffer. To correctly release packets, Buffer ensures that the state of each middlebox $m$ whose Tail precedes $m$ in the chain have been replicated. Let $q = \langle m, C_q, . . . \rangle$ and $p = \langle m, . . . , V_2 \rangle$ be respective PCLs of $m$ in the just received piggyback message and a stored piggyback message. For each packet held in Buffer and its corresponding PCL $p$, if $V_2 \leq C_q$ holds for each middlebox $m$, then Buffer releases this packet and removes its corresponding piggyback message from the memory.

Finally, Replicas can read $C$ from a PCL $\langle m, C, . . . \rangle$ to prune their log stores belonging to middlebox $m$ up to $C$.

Other considerations. There may be time periods that a chain receives no incoming packets. In such cases, the state is not propagated through the chain, and Buffer does not release packets. To resolve this problem, Forwarder keeps a timer to receive incoming packets. Upon the timeout, Forwarder's thread sends a propagating-packet carrying a piggyback message it has received from Buffer. Replicas do not forward a propagating-packet to middleboxes. They process and update the piggyback message as described previously and forward this packet along the chain. Buffer processes the piggyback message to release held packets.

Further, a middlebox $m$ in a chain can also filter packets (e.g., a firewall blocks certain traffic), and consequently the state of middleboxes preceding $m$ is not passed on. If a middlebox filters a packet, its Head generates a propagating-packet to disseminate the piggyback message of the filtered packet. Finally, we assumed $f + 1 \leq n$ for simplicity. If the chain length $n < f + 1$, we extend the chain by lining $f + 1 - n$ extra Replicas between $r_m$ and Buffer. These extra Replicas only process and update piggyback messages.

5.3 Failure Recovery

Middleboxes, Forwarder, Buffer, and Replicas may fail. We assume that the failure of a middlebox and that of its Head are not isolated. Similar to the protocol described in § 4.1.4, Orch differentiates the failures of Forwarder, Buffer, and Replicas. Handling the failure of Forwarder or Buffer is straightforward. They contain only soft state, and spawning a new Forwarder or a new Buffer restores the correct operation of the chain. To handle the failure of a Replica, the lost state must be recovered from alive Replicas that previously replicated the state. Doing so depends on how log-entries are propagated through the replication groups.

Log propagation invariant. Let $r_j$ be $j$-th Replica in the replication group of middlebox $m$, and $T_j = (s, v_j, t_j)$ be a log entry of $m$ in Replica $r_j$ such that $t_j \geq t_j'$ for each $(s, v_j, t_j')$ of $m$. If $j \leq k$, then Invariant 2 holds:

$$T_k \preceq T_j$$

(2)

Invariant 2 implies that $v_k$ is prior value of $s$ to $v_j$, and $t_k \leq t_j$. This Invariant holds because of the same argument discussed for Invariant 1.

Handling a Replica failure. Similar to handling the failure of a Replica for a single middlebox in § 4.1.4, FTC performs three steps as follows. i) Initialization: Recall from § 5.1 that a Replica is a member of $f + 1$ replication groups and replicates the state of $f + 1$ middleboxes. Orch instantiates a new Replica and informs it about the list of replication groups in which the failed Replica was a member. For each of them, the new Replica runs an independent state recovery procedure as follows. ii) State recovery: Let $r$ be the failed Replica. For the replication group of middlebox $m$ where $r$ was Head, its failure is handled in a similar way as in handling the failure of Head explained in § 4.1.4. From the first alive Replica successor to $r$, the log store and $\text{MAX}_m$ are fetched. In-operation state is recovered from log
store, and Head’s matrix $V$ by $V[i] \leftarrow MAX_m$ for each state-partition $i$. For any other replication group, the recovery is similar to handling the failure of other Replicas as explained in § 4.1.4. iii) Rerouting: Orch updates routing rules to route traffic through new Replica. Finally, simultaneous failures are handled per replication group in the same manner as described in § 4.1.4.

6 Implementation

Our system components are Forwarder, Buffer, Replicas, and Orch. Forwarder and Buffer are implemented as Click elements. The implementation detail of a Replica and Orch are as follow.

Replica is the core component of FTC and is deployed in the server of each middlebox in the chain. This component is a sequence of multiple Click built-in elements and our developed elements. This component consists of control and data-plane modules. Control module is a daemon that communicates with Orch and the control modules in other Replicas. During failover, the control module receives the information of replication groups related to this Replica. For each replication group, a thread is spawned to fetch state. Using a reliable TCP connection, the thread sends a fetch request to the appropriate member in the replication group and waits to receive state. Data-plane module processes piggyback messages, sends and receives packets to and from a middlebox, constructs piggyback messages, and forwards packets to next element in the chain (the data-plane module of next Replica or Buffer).

Orch is developed on top of ONOS controller [6]. To monitor and detect failures, ONOS provides services to rapidly detect and react to events, such as link and port failures. Orch detects a Replica failure by registering for “port down” events. Orch performs chain deployment/recovery in two steps. To deploy a chain, Orch places middleboxes and Replicas in available servers, then inserts OpenFlow rules in switches to steer traffic through the chain.

7 Evaluation

We evaluate FTC in this section. We describe our setup and methodology in § 7.1 and evaluate FTC’s performance for middleboxes and chains in § 7.3 and § 7.4, respectively. Finally, we evaluate failure recovery in § 7.5.

7.1 Experimental Setup and Methodology

We compare FTC with NF, a non fault-tolerant baseline system, and FTMB, our implementation of [50]. Our FTMB implementation is a performance upper bound of the original work that performs the logging operations described in [50] but does not take snapshots. Following the original prototype, FTMB dedicates a server in which a middlebox master (M) runs, and another server where the fault tolerant components input logger (IL) and output logger (OL) execute. Packets go through IL, M, then OL. M tracks accesses to shared state using packet access logs (PALS) and transmits them to OL.

In the original prototype, no data packet is released until all corresponding dropped PALS are retransmitted. Our prototype assumes that PALS are delivered on the first attempt, and packets are released immediately afterwards. Further, OL maintains only the last PAL.

We used two environments. The first is a local cluster of 12 servers. Each server has an 8-core Intel Xeon CPU D-1540 clocked at 2.0 Ghz, 64 GiB of memory, and two NICs, a 40 Gbps Mellanox ConnectX-3 MT27500 and a 10 Gbps Intel Ethernet Connection X552/X557. The servers run Ubuntu 14.04 with kernel 4.4 and are connected to 10 and 40 Gbps top-of-rack switches. We use MoontGen [15] and pktgen [57] to generate traffic and measure latency and throughput, respectively. Traffic from the generator server, passed in the 40 Gbps links, is sent through middleboxes and back to the generator. FTC uses a 10 Gbps link to disseminate state changes from Buffer to Forwarder.

The second environment is a distributed Cloud comprised of several core and edge data-centers deployed across a continent. We use virtual machines (VMs) with 4 virtual processor cores and 8 GiB memory running Ubuntu 14.04 with Kernel 4.4. We use the published ONOS docker container [37] to control a virtual network of OVS switches [36] connecting these VMs. We follow the multiple interleaved trials methodology [3] to reduce the variability that come from performing experiments on a shared infrastructure.

We use the middleboxes and chains shown in Table 1. The middleboxes are implemented in Click [30]. MazuNAT is an implementation of the core parts of a commercial NAT [2], and SimpleNAT provides basic NAT functionalities. They represent read-heavy middleboxes with a moderate write load on the shared state (i.e., a flow table mapping private and public addresses). Monitor is a read/write heavy middlebox that counts the number of packets in a flow or across flows. It takes a sharing level parameter that specifies the number of threads sharing the same state variable. For example, no state is shared for the sharing level 1, and 8 Monitor’s threads share the same state variable for sharing level 8. Gen represents a write-heavy middlebox that takes a state size parameter, which allows us to test the impact of a middlebox’s state size on performance. texttGen is a write-heavy middlebox that takes a size parameter. Gen updates a state variable with this size per packet allowing us to test the impact of a middlebox’s state size on performance. Firewall is a stateless firewall. Our experiments also test three chains (Ch–n,
that are composed of combinations of these middleboxes.

For experiments in the first environment, we report latency and throughput. For a latency data-point, we report the average of hundreds of samples taken in a 10 second interval. For a throughput data-point, we report the average of maximum throughput values measured every second in a 10-second interval. Unless shown, we do not report confidence intervals as they are negligible. Unless otherwise specified, the packet size in our experiments is 256 B, and $f = 1$.

### 7.2 Micro-benchmark

We use a micro-benchmark to determine the impact of a state size on the performance of FTC. We measured the latency overhead for the middlebox $Gen$ and the chain $Ch-Gen$. We observed that under 2 Mpps for 512 B packets, varying the size of the generated state from 32-256 B has a negligible impact on latency for both $Gen$ and $Ch-Gen$ (the difference is less than 2 $\mu$s). Thus, we focus on the throughput overhead.

**Throughput.** Fig. 5 shows the impact of state size generated by $Gen$ on throughput. $Gen$ runs a single thread. We vary the state size from 16 to 256 B and measure $Gen$’s throughput for packet sizes 128, 256, and 512 B. As expected, the size of piggyback messages impacts the throughput only if it is proportionally large compared to packet sizes. For 128 B packets, throughput drops by only 9% when $Gen$ generates states that are 128 B in size or less. The throughput drops by less than 1% with 512 B packets and state up to 256 B in size. We expect popular middleboxes to generate state much smaller than some of our tested values. For instance, a load balancer and a NAT generate a record per traffic flow [8, 25, 53] that is roughly 32 B in size ($2 \times 12$ B for the IPv4 headers in both directions and 8 B for the flow identifier).

### 7.3 Fault-Tolerant Middleboxes

**Throughput.** Figures 6 and 7 show the maximum throughput of 2 middleboxes. In Fig. 6, we configure $Monitor$ to run with 8 threads and measure its throughput with different sharing levels. As the sharing level for $Monitor$ increases, the throughput of all systems, including $NF$, drops due to the higher contention in reading and writing the shared state. For sharing levels of 8 and 2, FTC achieves a throughput that is $1.2-1.4 \times$ that of $NF$’s and incurs an overhead of 9-26% compared to $NF$. These overheads are expected since $Monitor$ is a write-heavy middlebox, and the shared state is modified non-deterministically per packet. For sharing level 1, $NF$ and FTC reach the NIC’s packet processing capacity\(^1\). $FTMB$ does not scale for sharing level 1, since for every data packet, a PAL is transmitted in a separate message, which limits $FTMB$’s throughput to 5.26 Mpps.

For Fig. 7, we evaluate the throughput of $MazuNAT$ while varying the number of threads. FTC’s throughput is 1.37-1.94 $\times$ that of $FTMB$’s for 1-4 threads. Once a traffic flow is recorded in the NAT flow table, processing the next packets of this flow only requires reading the shared record (until the connection terminates or times out). The higher throughput compared for $MazuNAT$ is because FTC does not replicate these reads, while $FTMB$ logs them to provide fault tolerance [50]. We observe that FTC incurs 1-10% throughput overhead compared to $NF$. Part of this overhead is because FTC has to pay the cost of adding space to packets for possible state writes, even when state writes are not performed. The pattern of state reads and writes impacts FTC’s throughput. Under moderate write workloads, FTC incurs 1-10% throughput overhead, while under write-heavy workloads, FTC’s overhead remains less than 26%.

**Latency.** Fig. 8 illustrates the latency of $Monitor$ (8 threads with sharing level 8) and $MazuNAT$ (two configurations, 1 thread and 8 threads) under different traffic loads. For both $Monitor$ and $MazuNAT$, the latency remains under 0.7 ms for all systems as the traffic load increases until the systems reach their respective saturation points. Past these points, packets start to be queued, and per-packet latency rapidly spikes. As shown in Fig. 8a, operating under sustainable loads, FTC and $FTMB$ respectively add overhead within 14-25 $\mu$s and 22-31 $\mu$s to the per-packet latency, out of which 6-7 $\mu$s is due to the additional one-way network latency to forward the packet and state to the replica. For this write-heavy

\(^1\)Although the 40 GbE link is not saturated, our investigation showed that the bottleneck is the NIC’s packet processing power. We measured that the Mellanox ConnectX-3 MT 27500, at the receiving side and working under the DPDK driver, at most can process 9.6-10.6 Mpps for varied packet sizes. Though we have not found any official document by Mellanox describing this limitation, similar behavior (at higher rates) has been reported for Intel NICs (see Sections 5.4 and 7.5 in [15] and Section 4.6 in [23]).
middlebox, FTC introduces a smaller latency overhead compared to FTMB. Fig. 8b shows that, when running MazuNAT with a single thread, FTC can sustain nearly the same traffic load as NF, and FTC and FTMB have similar latencies. For 8 threads shown in Fig. 8c, both FTC and NF reach the packet processing capacity of the NIC. The latency of FTC is largely independent of the number of threads, while FTMB experiences a latency increase of 24-43 µs when going from 1 to 8 threads.

7.4 Fault Tolerant Chains

In the following experiments, we evaluate the performance of FTC for a chain of middleboxes during normal operation. For a NF chain, each middlebox is deployed in a separate physical server. We use the same number of servers for FTC, while we dedicate 2× the number of servers to FTMB: A server for each middlebox (Master in FTMB) and a server for its replica (IL and OL in FTMB).

Chain length impact on throughput. Fig. 9 shows the maximum traffic throughput passing in 4 chains (Ch-2 to Ch-5 listed in Table 1). Monitors in these chains run 8 threads with sharing level 1. We also report for FTMB+Snapshot that is FTMB with snapshot simulation. To simulate the overhead of periodic snapshots, we add an artificial delay (6 ms) periodically (every 50 ms). We get these values from [50].

As shown in Fig. 9, FTC’s throughput is within 8.28-8.92 Mpps and 4.83-4.80 Mpps for FTMB. FTC imposes a 6-13% throughput overhead compared to NF. The throughput drop from increasing the chain length for FTC is within 2-7%, while that of FTMB+Snapshot is 13-39% (its throughput drops from 3.94 to 2.42 Mpps). This shows that throughput of FTC is largely independent of the chain length, while, for FTMB+Snapshot, periodic snapshots taken at all middleboxes significantly reduce the throughput. No packet is processed during a snapshot. Packet queues get full at early snapshots and remain full afterwards because the incoming traffic load is at the same rate. More snapshots are taken in a longer chain. Non-overlapping (in time) snapshots cause shorter service time at each period and consequently higher throughput drops. An optimum scheduling to synchronize snapshots across the chain can reduce this overhead; however, This is not trivial [9].

Chain length impact on latency. We use the same experimental settings as the previous experiment, except we run single threaded Monitors due to a limitation of the traffic generator. The latter is not able to measure the latency of the chain beyond size 2 composed of multi-threaded middleboxes. We resort to experimenting with single threaded Monitors under the load of 2 Mpps, a sustainable load by all systems.

As shown in Fig. 10, FTC’s overhead compared to NF is within 39-104 µs for Ch-2 to Ch-5, translating to roughly 20 µs latency per middlebox. The overhead of FTMB is within 64-171 µs, approximately 35 µs latency overhead per middlebox in the chain. As shown in Fig. 11, the tail latency of individual packets passing through Ch-3 is only moderately higher than the minimum latency. FTC incurs 16.5-20.6 µs per middlebox latency which is respectively three and two
orders of magnitudes less than Pico’s and REINFORCE’s, and is around 2/3 of FTMB’s. In-chain replication eliminates the communication overhead with remote replicas. Doing so also does not cause latency spikes unlike snapshot-based systems. In FTC, packets experience constant latency, while the original FTMB reports up to 6 ms latency spikes at periodic checkpoints (e.g., at every 50 ms intervals) [50].

**Replication factor impact on performance.** For replication factors of 2-5 (i.e., tolerating 1-4 failures), Fig. 12 shows FTC’s performance for Ch-5 in two settings where Monitors run with 1 or 8 threads. We report the throughput of 8 threaded Monitor, while only report the latency of 1 threaded Monitor due to a limitation of our test harness.

To tolerate 2.5× failures, FTC incurs only 3% throughput overhead as its throughput decreases to 8.06 Mpps. The latency overhead is also insignificant as latency only increases by 8 µs. By exploiting the chain structure, FTC can tolerate a higher number of failures without sacrificing performance. However, the replication factor cannot be arbitrarily large as encompassing the resulting large piggyback messages inside packets becomes impractical.

### 7.5 FTC in Failure Recovery

Recall from § 6, failure recovery is performed in three steps that incur initialization, state recovery, and rerouting delays. To evaluate FTC during recovery, we measure the recovery time of Ch-Rec (see Table 1). Each middlebox is placed in a different region of our Cloud testbed. As Orch detects a failure, a new Replica is placed in the same region as the failed middlebox. The Head of Firewall is deployed in the same region as Orch, while the Heads of SimpleNAT and Monitor are respectively deployed in a neighboring region and a remote region compared to Orch’s region. Since Orch is also a SDN controller, we observe negligible values for the rerouting delay, thus we focus on the state recovery delay and initialization delay.

**Recovery time.** As shown in Fig. 13, the initialization delays are 1.2, 49.8, and 5.3 ms for Firewall, Monitor, and SimpleNAT, respectively. The longer the distance between Orch and the new Replica, the higher the initialization delay. The state recovery delays are in the range of 114.38 ± 9.38 ms to 270.79 ± 50.47 ms⁴. In a local area network, FTMB paper [50] reports comparable recovery time of ~100 to 250 ms for SimpleNAT. FTC replicates the values of state variables, and its state recovery delay is bounded by the state size of a middlebox. Moreover, upon any failure, a new Replica fetches state from a remote region. The WAN latency between two remote regions becomes the dominant delay during failover. Using ping, we measured the network delay between all pairs of remote regions, and the observed RTTs confirmed our results. Finally, since in FTC, a new instantiated Replica fetches state in parallel from other Replicas (see § 6), the replication factor has a negligible impact on recovery time.

### 8 Related Work

We already discussed NFV related work in § 2.4. Next, we position FTC related to three lines of work.

**Fault tolerant storage.** Prior to FTC, the distributed system literature used chain and ring structures to provide fault tolerance. However, the focus in this literature is on ordering read/write messages at the process level (compared to, middlebox threads racing to access shared state in our case), at lower non-determinism rates (compared to, per-packet frequency), and at lower output rates (compared to, several Mpps releases). Chain replication protocol [58] is the first scheme where servers form a chain that provides a fault-tolerant storage service. Other systems adapted this protocol for key-value storages. In HyperDex [16] and Hibari [19], servers shape multiple logical chains replicating different key ranges. They respectively leverage consistent hashing and hyperspace hashing of keys to select a chain. NetChain [24] replicates in the network on a chain of programmable switches. FAWN [4], Flex-KV [41], and parameter server [35] use consistent hashing rings that form a replication ring of servers. Unlike these systems, FTC takes advantage of the natural structure of service function chains, uses transactional packet processing, and piggybacks state updates on packets.

**Primary-backup replication.** In active replication [47], all replicas process requests. This scheme requires determinism in middlebox operations, while middleboxes are non-deterministic [13, 23]. In passive replication [7], only a primary server processes requests. The primary sends state updates to the replicas. Despite the active replication, this scheme makes no assumption on determinism. Generic virtual machine high availability solutions (e.g., VM checkpointing [12, 14, 46]) freeze a VM for each checkpointing. These solutions are not effective for chains because the operation of chains freezes during long checkpoints.

**Consensus protocols.** Classical consensus protocols, such as Paxos [33] and Raft [38] are known to be slow and cause unacceptable low performance if used for middleboxes.

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⁴The large confidence intervals reported are due to latency variability in the wide area network connecting different regions.
9 Conclusion

Existing fault tolerant approaches designed for individual middleboxes can introduce high performance penalties when they are used for a service function chain. In this paper, we presented FTC, a system that takes advantage of the structure of a chain to provide efficient fault tolerance for a service function chain. FTC provides strong consistency under failures for a chain of at least $f+1$ middleboxes. Our evaluation demonstrates that FTC can provide high degrees of fault-tolerance with small overhead in the latency and throughput of a chain.

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