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Partitioned Paxos via the Network Data Plane

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Abstract

Consensus protocols are the foundation for building fault-tolerant, distributed systems and services. They are also widely acknowledged as performance bottlenecks. Several recent systems have proposed accelerating these protocols using the network dataplane. But, while network-accelerated consensus shows great promise, current systems suffer from an important limitation: they assume that the network hardware also accelerates the application itself. Consequently, they provide a specialized replicated service, rather than providing a general-purpose high-performance consensus that fits any off-the-shelf application.
To address this problem, this paper proposes Partitioned Paxos, a novel approach to network-accelerated consensus. The key insight behind Partitioned Paxos is to separate the two aspects of Paxos, agreement and execution, and optimize them separately. First, Partitioned Paxos uses the network forwarding plane to accelerate agreement. Then, it uses state partitioning and parallelization to accelerate execution at the replicas. Our experiments show that using this combination of data plane acceleration and parallelization, Partitioned Paxos is able to provide at least ×3 latency improvement and ×11 throughput improvement for a replicated instance of a RocksDB key-value store.

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1 Introduction

Consensus protocols are used to solve a fundamental problem in distributed systems: getting a group of participants to reliably agree on some value. They are the foundation for building fault-tolerant, distributed applications and services (e.g., OpenReplica [41], Ceph [56], Google's Chubby [6]). Moreover, many classic distributed systems problems can be reduced to consensus, including atomic broadcast [48] and atomic commit [17]. Unfortunately, consensus protocols are also widely acknowledged as a performance bottleneck, causing many systems to eschew strong consistency [55]. Twenty years ago, researchers cautioned against using consensus in-band for systems with high demand [16]. Still, despite two decades of research on optimizations [38, 2, 27, 42, 28, 47, 33, 48], consensus performance remains a problem in real-world systems [23].

Recently, several projects [47, 19, 30, 21] have explored a promising new approach to achieving high-performance consensus. These systems leverage the emerging trend of programmable networks hardware [22, 5, 57] to optimize consensus, achieving eye-popping performance results. For example, NoPaxos [30] use a Cavium network processor to enforce ordered message delivery, and reaches a throughput of around 250K messages per second with a no-op, closed-loop client—a 370% increase over a standard Paxos baseline. An implementation of Chain Replication [54] on a Tofino ASIC [21] is able to process commands at a throughput of 4 billion messages per second, which is several orders of magnitude greater than a software-only alternative.

But, while network-accelerated consensus shows great promise, current systems suffer from an important limitation: they do not address how the replicated application can cope with the increased rate of consensus messages. For example, the aforementioned NoPaxos [30], when used to replicate a transactional key-value store, can only achieve a throughput of 13K transactions per second. Improving the performance in the network is not sufficient. By solving one bottleneck, a new one is revealed at the host, in the replicated application.

Prior work such as Consensus in a Box [19] and NetChain [21] sidestep this issue to some extent, by implementing the replicated application itself in network hardware (i.e., both systems implement a key-value store in their target hardware devices). This approach severely limits the applicability of in-network consensus, as the network really provides a specialized replicated service, rather than a general-purpose, high-performance consensus that can be used by any off-the-shelf application.

The usefulness of in-network computing becomes questionable if the application can not take advantage of the performance it delivers, especially as network acceleration comes at a cost, in terms of money, power consumption, or design time. Indeed, the main problem that motivates this paper is that *even if consensus protocols can execute at 6.5Tbps, the exercise is purely academic if replicated applications cannot cope with that rate of consensus messages.*

To address this problem, this paper proposes Partitioned Paxos, a novel approach to network-accelerated consensus. Partitioned Paxos is based on the observation that there are two aspects to consensus, *execution* and *agreement*. Execution governs how replicas execute transitions in a state machine, while agreement ensures that replicas execute transitions in the same order. Consensus in a Box [19] and NetChain [21] perform both execution and agreement inside the network. In contrast, the key insight behind Partitioned Paxos is to isolate and separately optimize these two concerns. This allows any application to take advantage of optimized consensus.

Partitioned Paxos uses programmable network hardware to accelerate agreement, following Lamport's Paxos algorithm [24]. Thus, it accelerates consensus protocols without strengthening assumptions about the behavior of the network. Then, to leverage the increased rate of consensus and optimize execution, Partitioned Paxos shards the application state, and runs parallel Paxos deployments for each shard. By sharding the state of the application, we multiply the performance of the application by the number of partitions/shards. Overall, our solution indicates that the only way to significantly improve application performance is through close hardware/software co-design, and an across-stack optimization of all the components, from the network, through network stack (kernel bypass), file system and storage.

Partitioned Paxos provides significant performance improvements compared with traditional implementations. In a data center network, Partitioned Paxos reduces the latency by ×3. In terms of agreement throughput, our implementation on Barefoot Network's Tofino ASIC chip [5] can process over 2.5 billion consensus messages per second, a four-order-of-magnitude improvement. In terms of execution, we have used Partitioned Paxos to accelerate an unmodified instance of RocksDB. When using 4 separate partitions, the replicated application can process close to 600K messages per second, a ×11 improvement over baseline implementations.

In short, this paper makes the following contributions:

- It describes a novel approach to network-accelerated consensus that separates agreement from execution.
- It describes a re-interpretation of the Paxos protocol that maps the consensus protocol logic into stateful forwarding decisions.
- It discusses a technique for partitioning and parallelizing replica state and execution.
- It presents an open-source implementation of Paxos with at least ×3 latency improvement and ×11 throughput improvement for unmodified applications.

This paper first provides evidence of performance obstacles in Paxos (§2). It then presents the Partitioned Paxos design, focusing on how the system accelerates agreement (§3) and execution (§4). Next, it presents an evaluation on programmable ASICs (§5). Related work is discussed in (§6). Finally, it concludes in (§7).

2 Paxos Bottlenecks and Solution Overview

Before presenting the design of Partitioned Paxos, we briefly review background on Paxos and the obstacles for achieving high-performance consensus.

2.1 Paxos Overview

Paxos [24] is a consensus protocol that makes very few assumptions about the network behavior (e.g., point-to-point packet delivery and the election of a non-faulty leader), making it widely applicable to a number of deployment scenarios. It has been proven safe under asynchronous assumptions, live under weak synchronous assumptions, and resilience-optimum [26].

Paxos distinguishes the following roles that a process can play: *proposers*, *acceptors* and *replicas*. The proposers submit commands that need to be ordered by Paxos before they are learned and executed by the replicated state machines. The acceptors are the processes that actually agree on a value.

An instance of Paxos proceeds in two phases. During Phase 1, a proposer that wants to submit a value selects a unique round number and sends a prepare request to at least a quorum of acceptors. Upon receiving a prepare request with a round number bigger than any previously received round number, the acceptor responds to the proposer promising that it will reject any future requests with smaller round numbers. If the acceptor already accepted a request for the current instance, it will return the accepted value to the proposer, together with the round number received when the request was accepted. When the proposer receives answers from a quorum of acceptors, the second phase begins.

In Phase 2, the proposer selects a value according to the following rule. If no value is returned in the responses, the proposer can select a new value for the instance; however, if any of the acceptors returned a value in the first phase, the proposer must select the value with the highest round number among the responses. The proposer then sends an accept request with the round number used in the first phase and the value selected to at least a quorum of acceptors. When receiving such a request, the acceptors acknowledge it by sending the accepted value to the replicas, unless the acceptors have already acknowledged another request with a higher round number. When a quorum of acceptors accepts a value, consensus is reached.

Once consensus is reached, the accepted value is delievered to the application. Usually, the value is a state-machine transition that will modify the application state (e.g., write a value). As will be discussed in Section 4, one of the Partitioned Paxos optimizations depends on sharding or partitioning this state.

If multiple proposers simultaneously execute the procedure above for the same instance, then no proposer may be able to execute the two phases of the protocol and reach consensus. To avoid scenarios in which proposers compete indefinitely, a *leader* process can be elected. Proposers submit values to the leader, which executes the first and second phases of the protocol. If the leader fails, another process takes over its role. Paxos ensures consistency despite concurrent leaders and progress in the presence of a single leader.

In practice, replicated services run multiple executions of the Paxos protocol to achieve consensus on a sequence of values [7] (i.e., multi-Paxos). An execution of Paxos is called an instance. In this paper, we implicitly describe a multi-Paxos protocol.

2.2 Performance Obstacles

Given the central role that Paxos plays in fault-tolerant, distributed systems, improving the performance of the protocol has been an intense area of study [38, 2, 27, 42, 28, 47, 33, 48]. There are obstacles related to the protocol itself, in terms of latency and throughput, and related to the application.

Protocol Latency. The performance of Paxos is typically measured in “communication steps”, where a communication step corresponds to a server-to-server communication in an abstract distributed system. Lamport proved that it takes at least 3 steps to order messages in a distributed setting [26]. This means that there is not much hope for significant performance improvements, unless one revisits the model (e.g., [9]) or assumptions (e.g., *spontaneous message ordering* [28, 43, 44]).

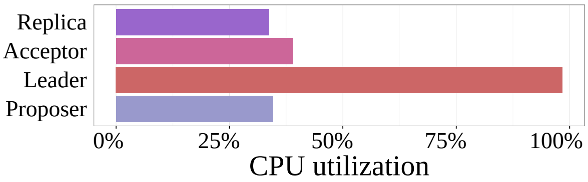


Figure 1: The leader process becomes a bottleneck at a throughput of ~65K values/second.

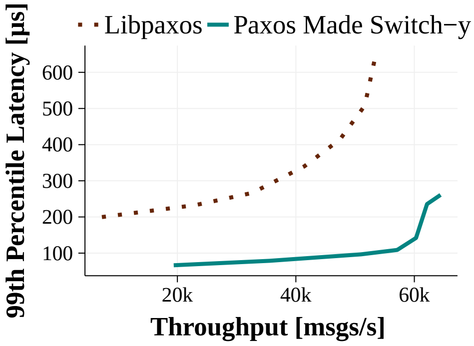


Figure 2: Throughput vs. latency (w/ RocksDB).

Protocol Throughput. Beyond latency due to communication steps, throughput is also a challenge for Paxos. Under load, a Paxos leader becomes a bottleneck [30], since the role interposes on all messages that proposers submit. To demonstrate, we performed a basic experiment in which we measured the CPU utilization for each of the Paxos roles when transmitting messages at peak throughput. As a representative implementation of Paxos, we used the open-source `libpaxos` library [31]. We chose `libpaxos` because it is a faithful implementation of Paxos that distinguishes all the Paxos roles. And, it has been extensively tested and is often used as a reference implementation (e.g., [19, 32, 45, 51]). In the experiment, a client application sent 64-byte messages at increasing rates until we reached the saturation point at a peak throughput rate of ~65K values/sec. As shown in Figure 1, the leader is the first process to become CPU bound.

Application Bottleneck. To ensure correctness, replicas must execute commands in a deterministic order. This ordering becomes a bottleneck, even if the rest of the Paxos protocol can be accelerated. This problem has been mentioned, or alluded to, in prior work [30, 19, 21]. To further illustrate the point, we implemented Lamport's Paxos in P4, following the design in Paxos made Switch-y [11]. We ran the program on a switch with Barefoot Network's Tofino ASIC chip [5], and used the protocol to replicate an unmodified instance of RocksDB. Figure 2 plots the latency vs. throughput for deployments using `libpaxos` and the P4 Paxos implementation. While a network implementation of Paxos certainly improves the performance, increasing the throughput from ~54K messages per second to ~65K messages per second, the performance gains are a far cry from what seems possible. The limiting factor becomes the replica.

2.3 Solution Approach

Paxos is a protocol for implementing state-machine replication [50]. Each replica is a state-machine that makes a transition based on a given input and current state. Paxos requires $f+1$ replicas to tolerate f failures. However, Paxos requires an additional $2f+1$ processes (because of the majority voting among acceptors) to ensure that the replicas execute transitions in the same order, despite potential message loss. These two aspects of the protocol are referred to as *execution* and *agreement*, respectively.

Existing approaches to network-accelerated consensus [19, 21] optimize both execution and agreement by offloading to hardware. In contrast, Partitioned Paxos uses two separate techniques for optimizing the different aspects of Paxos. First, it uses the network forwarding plane to accelerate the agreement components of Paxos. Then, it uses state partitioning and parallelization to accelerate the performance of the replicas. As a result, replicated applications can leverage the performance provided by in-network acceleration and multiple threads to implement strongly consistent services that make only weak assumptions about the network. In our experiments, we have used Partitioned Paxos to replicate an unmodified instance of RocksDB, a production quality key-value store used at Facebook, Yahoo!, and LinkedIn.

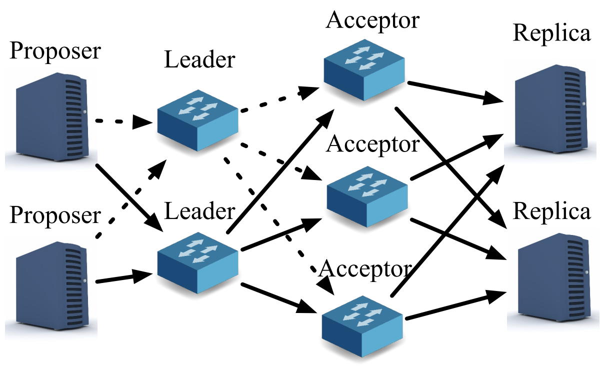


Figure 3: Example deployment for Partitioned Paxos.

3 Accelerating Agreement

Partitioned Paxos accelerates consensus by moving some of the logic—the agreement aspect—into the network forwarding plane. This addresses two of the major obstacles for achieving high-performance. First, it avoids network I/O bottlenecks in software implementations. Second, it reduces end-to-end latency by executing consensus logic as messages pass through the network.

However, accelerating consensus is not as straightforward as simply "implementing Paxos on faster hardware". There are several challenges that arise when considering how to execute consensus protocols in the network forwarding plane: (i) What is the expected deployment? (ii) How do you map the protocol into the match-action abstractions exposed by network hardware? (iii) How is the failure model of Paxos impacted? and (iv) How do the limited resources in network hardware impact the protocol? Below, we discuss these issues in detail.

3.1 Deployment

Figure 3 illustrates a minimal deployment for Partitioned Paxos. With Partitioned Paxos, network switches execute the logic for the leader and acceptor roles in Paxos. The hosts serve as proposers and replicated applications.

For availability, Paxos intrinsically assumes that if a node fails, the other nodes can still communicate with each other. By moving this logic into network devices, Partitioned Paxos necessarily mandates that there are redundant communication paths between devices. In Figure 3, a redundant path between proposers and a backup leader is illustrated with dashed lines. In a more realistic, data center deployment, this redundancy is already present between top-of-rack (ToR), aggregate, and spine switches.

Figure 4 illustrates the difference in number of hops needed by Partitioned Paxos and traditional deployments. While in a standard Paxos implementation, every communication step requires traversing the network (e.g., Fat-tree), in Partitioned Paxos, each network device fills a role in achieving consensus. Note that the number of uplinks from a ToR does not need to reach a quorum of aggregators, as the aggregator may also reside at the fourth hop. Partitioned Paxos saves two traversals of the network compared to Paxos, meaning ×3 latency improvement.

In absolute numbers, this reduction is significant. Our experiments show that the Paxos logic execution time takes around 2.5us, without I/O. Using kernel-bypass [13], a packet can be sent out of host in ∼5us (median) [58]. One way delay in the data center is ∼100us (median) [46], more than ×10 the host! Implementing Paxos in switch ASICS as "bumps-in-the-wire" processing allows consensus to be reached in sub-round-trip time (RTT).

It is worth mentioning that this deployment does not require additional hardware to be deployed in the network, such as Middleboxes or FPGAs. Partitioned Paxos leverages hardware resources that are already available.

3.2 Paxos as Match-Action

Conceptually, implementing Paxos in network hardware involves mapping the logic into a sequence of match-action units. Perhaps surprisingly, Paxos logic maps well into this abstraction. In the pseudocode

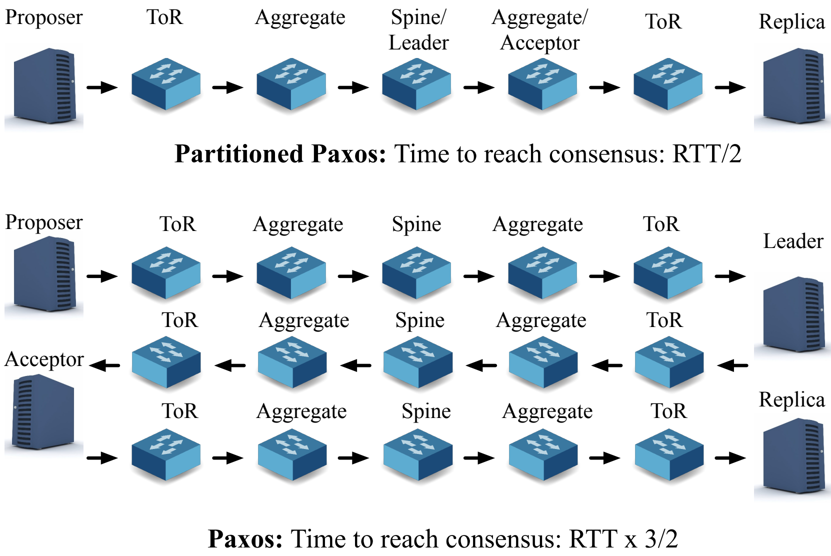


Figure 4: Contrasting propagation time for Partitioned Paxos with server-based deployment.

Algorithm 1 Leader logic.

```
Initialize State:
  instance[NumPartitions][1] := {0}
upon receiving pkt(msgtype, inst, rnd, vrnd, swid, pid, value)
  match pkt.msgtype:
    case REQUEST:
      pkt.msgtype ← PHASE2A
      pkt.rnd ← 0
      pkt.inst ← instance[pid][0]
      instance[pid][0] := instance[pid][0] + 1
      multicast pkt
    default :
      drop pkt
```

below, we describe the protocol as responses to different input messages. In other words, we re-interpret the Paxos algorithm as a set of stateful forwarding decisions. This presentation of the algorithm presents a different way of understanding the notoriously complex and subtle protocol [25, 34, 53, 7].

Prior work on Paxos made Switch-y [11] presented P4 code for the Phase 2 logic of Paxos leaders and acceptors. Partitioned Paxos extends their approach in two key ways. First, Partitioned Paxos implements both Phase 1 and Phase 2 of the protocol. Second, Partitioned Paxos targets an ASIC deployment, which imposes new constraints on the implementation, including how to trim the acceptor log.

Beyond the presentation, Partitioned Paxos differs from a standard Paxos deployment in that each command that is submitted must include the partition identifier. A partition identifier corresponds to a shard of the application state. Many distributed systems, such as key-value stores or databases, are naturally partitioned, e.g., by key-space. We refer to these partitions as application state shards. Each shard is processed by a parallel deployment of Paxos. Thus, the partition identifier is threaded through all of the pseudocode.

Notation. Our pseudocode roughly correspond to P4 statements. The `Initialize` blocks identify state stored in registers. `id[N]` indicates a register named `id` with `N` cells. The notation ":= {0}" indicates that every cell element in the register should be initialized to 0. The `match` blocks correspond to table matches on a packet header, and the `case` blocks correspond to P4 actions. We distinguish updates to the local state (":="), from writes to a packet header ("←"). We also distinguish between unicast (`forward`) and multicast (`multicast`).

Partitioned Paxos Packets. The Partitioned Paxos packet header includes six fields. The six fields are as follows: (i) `msgtype` distinguishes the various Paxos messages (e.g., `REQUEST`, `PHASE1A`, `PHASE2A`, etc.) (ii)

Algorithm 2 Acceptor logic.

```
Initialize State:
  round[NumPartitions][MaxInstances] := {0}
  value[NumPartitions][MaxInstances] := {0}
  vround[NumPartitions][MaxInstances] := {0}
upon receiving pkt(msgtype, inst, rnd, vrnd, swid, pid, value)
  if pkt.rnd ≥ round[pid][pkt.inst] then
    match pkt.msgtype:
      case Phase1A:
        round[pid][pkt.inst] := pkt.rnd
        pkt.msgtype ← Phase1B
        pkt.vrnd ← vround[pid][pkt.inst]
        pkt.value ← value[pid][pkt.inst]
        pkt.swid ← swid
        forward pkt
      case Phase2A:
        round[pid][pkt.inst] := pkt.rnd
        vround[pid][pkt.inst] := pkt.rnd
        value[pid][pkt.inst] := pkt.value
        pkt.msgtype ← Phase2B
        pkt.swid ← swid
        forward pkt
      default :
        drop pkt
  else
    drop pkt
```

`inst` is the consensus instance number; (iii) `rnd` is either the round number computed by the proposer or the round number for which the acceptor has cast a vote; `vrnd` is the round number in which an acceptor has cast a vote; (iv) `swid` identifies the sender of the message; The `pid` is used to identify the partition; and (v) `value` contains the request from the proposer or the value for which an acceptor has cast a vote. Our prototype requires that the entire Paxos header, including the value, be less than the maximum transmission unit of 1500 bytes. Note that the proposer is responsible for populating the header. The client application simply provides the `value`.

Proposer. A Partitioned Paxos proposer mediates client requests, and encapsulates the request in a Paxos header. It is implemented as a user-space library that exposes a small API to client applications.

The Partitioned Paxos proposer library is a drop-in replacement for existing software libraries. The API consists of a single `submit` function. The `submit` function is called when the application uses Paxos to send a value. The application simply passes a character buffer containing the value, and the buffer size.

When a Partitioned Paxos proposer submits a command, it must include the partition identifier. The proposer library adds the partition id to each Paxos command. The id is not exposed to the client application.

We note that an optimal sharding of application state is dependent on the workload. Our prototype uses an even distribution of the key-space. Determining an optimal sharding of application state is an orthogonal problem, and an interesting direction for future work.

Leader. A leader brokers requests on behalf of proposers. The leader ensures that only one process submits a message to the protocol for a particular instance (thus ensuring that the protocol terminates), and imposes an ordering of messages. When there is a single leader, a monotonically increasing sequence number can be used to order the messages. This sequence number is written to the `inst` field of the header.

Algorithm 1 shows the pseudocode for the primary leader implementation. The leader receives `REQUEST` messages from the proposer. `REQUEST` messages only contain a value. The leader must perform the following: for a given partition, write the current instance number and an initial round number into the message header; increment the instance number for that partition for the next invocation; store the value of the new instance number; and broadcast the packet to acceptors.

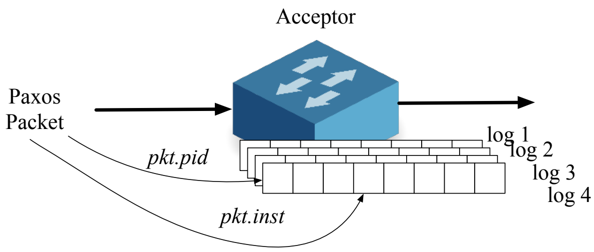


Figure 5: Partitioned Acceptor log, indexed by partition id and instance number.

Partitioned Paxos uses a well-known Paxos optimization [17], where each instance is reserved for the primary leader at initialization (i.e., round number zero). Thus, the primary leader does not need to execute Phase 1 before submitting a value (in a `REQUEST` message) to the acceptors. Since this optimization only works for one leader, the backup leader must reserve an instance before submitting a value to the acceptors. To reserve an instance, the backup leader must send a unique round number in a `PHASE1A` message to the acceptors. For brevity, we omit the backup leader algorithm since it essentially follows the Paxos protocol.

Acceptor. Acceptors are responsible for choosing a single value for a particular instance. For each instance of consensus, each individual acceptor must "vote" for a value. Acceptors must maintain and access the history of proposals for which they have voted. This history ensures that acceptors never vote for different values for a particular instance, and allows the protocol to tolerate lost or duplicate messages. This history is referred to as the acceptor log. The acceptor log must be periodically trimmed, which we describe in Section 3.3.

Partitioned Paxos differs from traditional implementations of Paxos in that it maintains multiple acceptor logs, as illustrated in Figure 5. Each log corresponds to a separate partition, and each partition corresponds to a separate shard of application state. The acceptor log is implemented as a ring-buffer.

Algorithm 2 shows logic for an acceptor. Acceptors can receive either `PHASE1A` or `PHASE2A` messages. Phase 1A messages are used during initialization, and Phase 2A messages trigger a vote. In both cases, the acceptor logic must access the log for a particular partition and see if the round number for the arriving packet is greater than the round number stored at the switch. If not, the packet is dropped. Otherwise, the switch modifying packet header fields and stored state, depending on the message type.

3.3 Resource Constraints

Lamport's Paxos algorithm does not specify how to handle the ever-growing, replicated log that is stored at acceptors. On any system, including Partitioned Paxos, this can cause problems, as the log would require unbounded disk space, and recovering replicas might need unbounded recovery time to replay the log. To cope with log files, an application using Partitioned Paxos must implement a mechanism to trim the log [7].

In Partitioned Paxos, each acceptor maintains P acceptor logs, where P is the number of partitions. Each log is implemented as a ring buffer that can hold I instance numbers. Thus, the memory usage of Partitioned Paxos is $\mathcal{O}(P*I)$. And, that the memory usage is inversely proportional to the frequency of a log trim.

As will be described in Section 4, each partition of a replica must track how many instance numbers have been agreed upon, and the largest agreed upon instance number, i. When the number of decided instances approaches I, the partition must send a `TRIM` message to the acceptor. Upon receipt of the `TRIM` message, the acceptor removes all state for instance numbers less than that i Note that the `TRIM` message is sent as a data plane command, not a control plane command.

With this static design, Partitioned Paxos must trim as frequently as the slowest partition. An alternative design would allow for dynamic partitioning, i.e., if all commands are for a single partition, then that partition could use all available acceptor-dedicated switch memory. However, this design requires scanning over the ring buffer to clean the instance numbers for the trimmed partition. This is difficult to implement in hardware.

3.4 Failure Assumptions and Correctness

Partitioned Paxos assumes that the failure of a leader or acceptor does not prevent connectivity between the consensus participants. As a result, it requires that the network topology allows for redundant routes between components, which is a common practice in data centers. In other respects, the failure assumptions of Partitioned Paxos are the same as in Lamport's Paxos. Below, we discuss how Partitioned Paxos copes with the failure of a leader or acceptor.

Leader failure. Paxos relies on a single operational leader to order messages. Upon the failure of the leader, proposers must submit proposals to a backup leader. The backup leader can be, for example, implemented in software. If a proposer does not receive the response for a request after a configurable delay, it re-submits the request, to account for lost messages. After a few unsuccessful retries, the proposer requests the leader to be changed.

Routing to a leader or backup is handled in a similar fashion as the way that load balancers, such as Maglev [14] or Silk Road [36], route to an elastic set of endpoints. Partitioned Paxos uses a reserved IP address to indicate a packet is intended for a leader. Network switches maintain forwarding rules that route the reserved IP address to the current leader. Upon suspecting the failure of the hardware leader, a proposer submits a request to the network controller to update the forwarding rules to direct traffic to the backup. A component that "thinks" it is the leader can periodically check network controller that the reserved leader IP address maps to its own address. This mechanism handles hardware leader failure and recovery. To ensure progress, it relies on the fact that failures and failure suspicions are rare events.

Acceptor failure. Acceptor failures do not represent a threat in Paxos, as long as a majority of acceptors are operational. Moreover, upon recovering from a failure, an acceptor can promptly execute the protocol without catching up with operational acceptors. Paxos, however, requires acceptors not to forget about instances in which they participated before the failure.

There are two possible approaches to meeting this requirement. First, we could rely on always having a majority of operational acceptors available. This is a slightly stronger assumption than traditional Paxos deployments. Alternatively, we could require that acceptors have access to persistent memory to record accepted instances.

Our prototype implementation uses the first approach, since the network hardware we use only provides non-persistent SRAM. However, providing persistent storage for network deployments of Partitioned Paxos can be addressed in a number of ways. Prior work on implementing consensus in FPGAs used on-chip RAM, and suggested that the memory could be made persistent with a battery [19]. Alternatively, a switch could access non-volatile memory (e.g., an SSD drive) directly via PCI-express [15].

Correctness Given this alternative interpretation of the Paxos algorithm, it is natural to question if this is a faithful implementation of the original protocol [24]. In this respect, we are aided by our P4 specification. In comparison to HDL or general purpose programming languages, P4 is high-level and declarative. By design, P4 is not a Turing-complete language, as it excludes looping constructs, which are undesirable in hardware pipelines. Consequently, it is particularly amenable to verification by bounded model checking.

We have mapped the P4 specification to Promela, and verified the correctness using the SPIN model checker. Specifically, we verify the safety property of *agreement*: the learners never decide on two separate values for a single instance of consensus.

4 Accelerating Execution

To accelerate the execution, Partitioned Paxos shards the application state at replicas and assigns a worker thread to execute requests at each shard. Our prototype currently only supports commands that access a single shard. However, the approach can be generalized to support commands that access multiple shards (i.e., multi-shard requests).

When a proposer submits a message with a request, it must include in the message the shard (or shards) involved in the request (i.e., the partition id, `pid`). Satisfying this constraint requires proposers to tell the read and write sets of a request before the request is executed, as in, e.g., Eris [29] and Calvin [52]. If this information is not available, a proposer can assume a superset of the actual shards involved, in the worst case all shards.

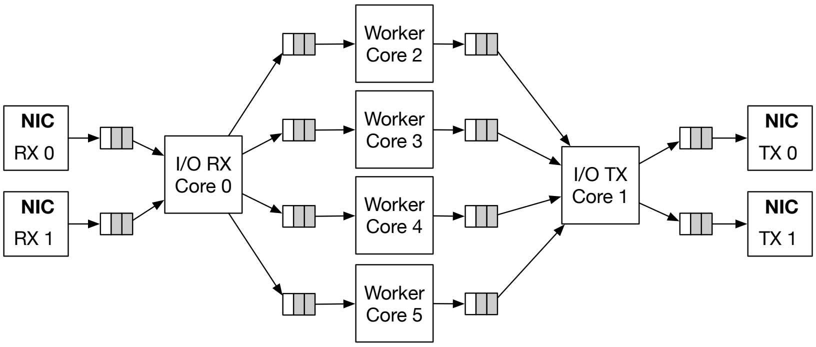


Figure 6: Partitioned Paxos replica architecture.

Partitioned Paxos orders requests consistently across shards. Intuitively, this means that if a multi-shard request req_1 is ordered before another multi-shard request req_2 in a shard, then req_1 is ordered before req_2 in every shard that involves both requests. Capturing Partitioned Paxos ordering property precisely is slightly more complicated: Let $<$ be a relation on the set of requests such that $req_1 < req_2$ iff req_1 is ordered before req_2 in some shard. Partitioned Paxos ensures that relation $<$ is acyclic [10].

Every worker executes requests in the order assigned by Paxos. Multi-shard requests require the involved workers to synchronize so that a single worker executes the request. Therefore, multi-shard requests are received by workers in all involved shards. Once a multi-shard request is received, the involved workers synchronize using a barrier and the worker with the lowest id executes the requests and then signals the other workers to continue their execution. Supporting multi-shard commands introduces overhead at the replica, which limits throughput. Consequently sharding is most effective when requests are single-shard and the load among shards is balanced.

Note that each worker must track how many instance numbers have been agreed upon, and the largest agreed upon instance number. When the number of agreed-upon instances exceeds a threshold, the worker must send a `TRIM` message all acceptors. This message includes the largest agreed upon instance number and the partition identifier. Upon receipt of this message, acceptors will trim their logs for that partition up to the given instance number.

4.1 Replica Architecture

For a replica to realize the above design, there are two challenges that must be solved. First, the replicas must be able to process the high-volume of consensus messages received from the acceptors. Second, as the application involves writing to disk, file-system I/O becomes a bottleneck. Below, we describe how the Partitioned Paxos architecture, illustrated in Figure 6, addresses these two issues.

Packet I/O To optimize the interface between the network-accelerated agreement and the application, Partitioned Paxos uses a kernel-bypass library (i.e., DPDK [13]), allowing the replica to directly read packets from the server NIC.

Partitioned Paxos de-couples packet I/O from the application-specific logic, dedicating a separate set of logical cores to each task. The *I/O Cores* are responsible for interacting with the NIC ports, while the *Worker Cores* perform the application-specific processing. The I/O Cores communicate with the Worker Cores via single-producer/single-consumer lock-free queues (i.e., ring buffers). This design has two key benefits. First, the worker cores are oblivious to the details of packet I/O activity. Second, the number of cores dedicated to each task can be scaled independently, depending on the workload and the characteristics of the replicated application.

Figure 6 illustrates a deployment with one core dedicated to receiving packets (I/O RX), one core dedicated to transmitting packets (I/O TX), and four cores dedicated as workers. Both I/O cores are connected to two NIC ports.

The I/O RX core continually poles its assigned NIC RX ring for arriving packets. To further improve throughput, packet reads are batched. The I/O RX core then distributes the received packets to the worker threads. Our current implementation simply assigns requests using a static partitioning (i.e., worker core = pkt.pid (mod NUM_WORKER_CORES)). Although, more complex schemes are possible, taking into ac-

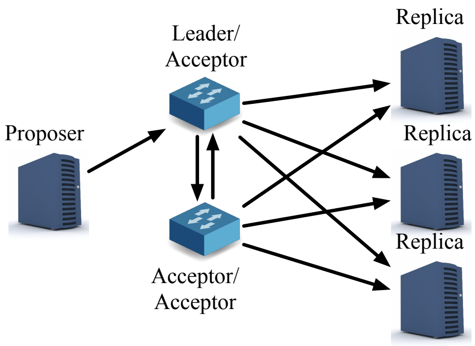


Figure 7: Topology used in experimental evaluation.

count the workload. The only restriction is that all packets with the same `pid` must be processed by the same worker.

Each Worker Core implements the Paxos replica logic—i.e., it receives a quorum of messages from the acceptors, and delivers the value to the replicated application via a callback. It is important to stress that this code is application-agnostic. The application-facing interface would be the same to all applications, and the same for any Paxos deployment.

Disk and File-System I/O The design described above allows Partitioned Paxos to process incoming packets at a very high throughput. However, most replicated applications must also write their data to some form of durable storage (e.g., HDD, SSD, Flash, etc.). While different storage media will exhibit different performance characteristics, our experience has been that the file system is the dominant bottleneck.

Unfortunately, many existing file system including ext4, XFS, btrfs, F2FS, and tmpfs, have scalability bottlenecks for I/O-intensive workloads, even when there is no application-level contention [37, 1]. Therefore, to leverage the benefits of sharding application state across multiple cores, Partitioned Paxos uses a separate file-system partition for each application shard. In this way, each file system has a separate IO scheduler thread.

5 Evaluation

Our evaluation of Partitioned Paxos explores four questions:

1. What is the absolute performance of individual Partitioned Paxos components?
2. What is the resource overhead of in-network consensus on the network?
3. What is the end-to-end performance of Partitioned Paxos as a system for providing consensus?
4. What is the performance under failure?

As a baseline, we compare Partitioned Paxos with a software-based implementation, the open-source `libpaxos` library [31]. Overall, the evaluation shows that Partitioned Paxos dramatically increases throughput and reduces latency for end-to-end performance, when compared to traditional software implementations.

Implementation. We have implemented a prototype of Partitioned Paxos. The switch code is written in P4 [4], and compiled to run on switches with Barefoot Network's Tofino ASIC [5]. The replica code is written in C using the DPDK libraries. We have an implementation of the Partitioned Paxos switch code that targets FPGAs, as well. In the evaluation below, we focus on the ASIC deployment. All source code, other than the version that targets Barefoot Network's Tofino chip, is publicly available with an open-source license.

Experimental setup. In our evaluation, we used two different experimental setups. Both setups used 64-port, ToR switches with Barefoot Network's Tofino ASIC [5]. The switches can be configured to run at 10/25G or 40/100G.

In the first setup—used to test the absolute performance of individual components—we used one switch configured to 40G per port. We followed a standard practice in industry for benchmarking switch performance, a snake test. With a snake test, each port is looped-back to the next port, so a packet passes through every port before being sent out the last port. This is equivalent to receiving 64 replicas of the same packet. To generate traffic, we used a $2 \times 40Gb$ Ixia XGS12-H as packet sender and receiver, connected to the switch with 40G QSFP+ direct-attached copper cables. The use of all ports as part of the experiments was validated, e.g., using per-port counters. We similarly checked equal load across ports and potential packet loss (which did not occur).

The second setup—used to test end-to-end performance and performance after failure—was the testbed illustrated in Figure 7. Two Tofino switches were configured to run at 10G per port and logically partitioned to run 4 Paxos roles. One switch was a leader and an acceptor. The second switch acted as two independent acceptors.

The testbed included four Supermicro 6018U-TRTP+ servers. One was used as a client, and the other three were used as replicas. The servers have dual-socket Intel Xeon E5-2603 CPUs, with a total of 12 cores running at 1.6GHz, 16GB of 1600MHz DDR4 memory and two Intel 82599 10 Gbps NICs. All connections used 10G SFP+ copper cables. The servers were running Ubuntu 14.04 with Linux kernel version 3.19.0.

5.1 Individual Components

The first set of experiments evaluate the performance of individual Partitioned Paxos components deployed on a programmable ASIC.

Latency and throughput. We measured the throughput for all Paxos roles to be 41 million 102 byte consensus msgs/sec per port. In the Tofino architecture, implementing pipelines of 16 ports each [18], a single instance of Partitioned Paxos reached 656 million consensus messages per second. We deployed 4 instances in parallel on a 64 port x 40GE switch, processing over 2.5 billion consensus msgs/sec. Moreover, our measurements indicate that Partitioned Paxos should be able to scale up to 6.5 Tb/second of consensus messages on a single switch, using 100GE ports.

We used Barefoot's compiler to report the precise theoretical latency for the packet processing pipeline. The latency is less than 0.1 μs. To be clear, this number does not include the SerDes, MAC, or packet parsing components. Hence, the wire-to-wire latency would be slightly higher.

Overall, these experiments show that moving Paxos into the forwarding plane can substantially improve component performance

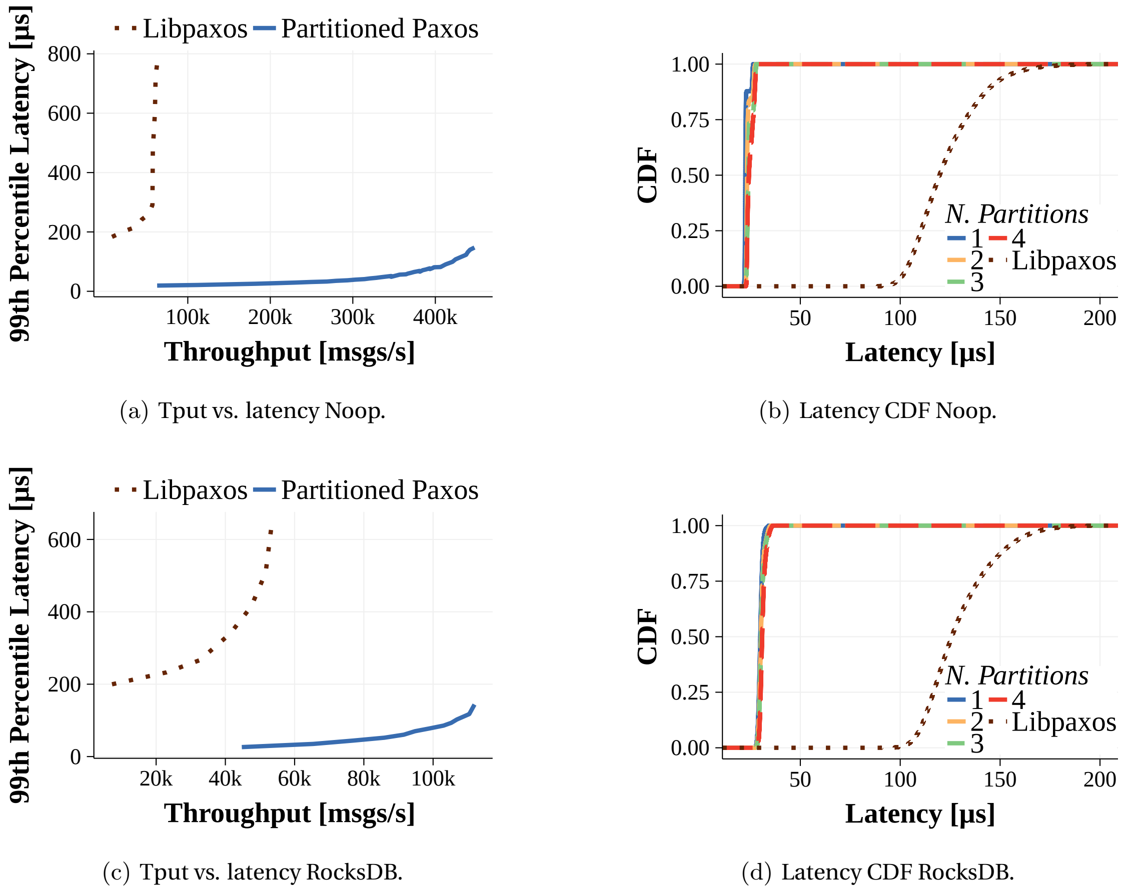
5.2 Resource Overhead

The next set of experiments evaluates the resource overhead and cost of running Partitioned Paxos on network hardware.

Resources and coexisting with other traffic. We note that our implementation combines Partitioned Paxos logic with L2 forwarding. The Partitioned Paxos pipeline uses less than 5% of the available SRAM on Tofino, and no TCAM. Thus, adding Partitioned Paxos to an existing switch pipeline on a re-configurable ASIC would have a minimal effect on other switch functionality (e.g., storing forwarding rules in tables).

Moreover, the absolute performance experiment demonstrates how in-network computing can coexist with standard networking operation, without affecting standard network functionality, without cost overhead or additional hardware. Because the peak throughput is measured while the device runs traffic at full line rate of 6.5Tbps, there is a clear indication that the device can be used more efficiently, implementing consensus services parallel to network operations.

Power consumption A common criticism of in-network computing is that its power consumption overweights it performance benefits. To evaluate Partitioned Paxos power overhead, we compare the power consumption of Tofino running layer 2 forwarding, and layer 2 forwarding combined with Partitioned Paxos.



(a) Tput vs. latency Noop.

(b) Latency CDF Noop.

(c) Tput vs. latency RocksDB.

(d) Latency CDF RocksDB.

Figure 8: The throughput vs. 99 percentile latency for a single partition of the No-op application (a) and RocksDB (c). The latency at 50 percent of peak throughput for No-op application (b) and RocksDB (d).

Due to the large variance in power between different ASICs and ASIC vendors [35], we only report normalized power consumption. Transceiver power consumption is not accounted for (accounting for it would benefit Partitioned Paxos). We again used a "snake" connectivity, which exercises all ports and enables testing Tofino at full capacity.

First, we measure the power consumption of both designs in idle, and find that it is the same, meaning that the Paxos program alone does not increase the power consumption. (i.e. activity is the one leading to additional power consumption). We then sent traffic at increasing rates. The difference between the idle power consumption and maximum power consumption is only 2%. While 2% may sound like a significant number in a data center, we note that the diagnostic program supplied with Tofino (diag.p4) takes 4.8% more power than the layer 2 forwarding program under full load.

5.3 End-to-end Experiments

Partitioned Paxos provides not only superior performance within the network, but also performance improvement on the application level, as we exemplify using two experiments. In the first, the replicated application generates reply packets, without doing any computation or saving state. This experiment evaluates the theoretical upper limit for end-to-end performance taking into account the network stack, but not other I/O (memory, storage) or the file system. In the second experiment, we use Partition Paxos to replicate RocksDB [49], a popular key-value store. RocksDB was configured with write-ahead logging (WAL) enabled.

As a baseline, both experiments compare Partitioned Paxos to `libpaxos`. For the libpaxos deployment, the three replica servers in Figure 7 also ran acceptor processes. One of the servers ran a leader process.

No-op application   In the first experiment, Server 1 runs a multi-threaded client process written using the DPDK libraries. Each client thread submits a message with the current timestamp written in the value. When the value is delivered by the learner, a server program retrieves the message via a deliver callback function, and then returns the message back to the client. When the client gets a response, it immediately submits another message. The latency is measured at the client as the round-trip time for each message. Throughput is measured at the replica as the number of deliver invocations over time.

To push the system towards higher a message throughput, we increased the number of threads running in parallel at the client. The number of threads, N, ranged from 1 to 12 by increments of 1. We stopped measuring at 12 threads because the CPU utilization on the application reached 100%. For each value of N, the client sent a total of 10 million messages. We repeat this for three runs, and report the 99^{th}-ile latency and mean throughput.

Figure 8a shows the throughput vs. 99^{th}-ile latency for Partitioned Paxos run on a single partition. The deployment with libpaxos reaches a maximum throughput of 63K. Partitioned Paxos can achieve a significantly higher throughput at 447K, a ×7 improvement. As well will see later, the throughput of Partitioned Paxos increases even further as we add more partitions. Moreover, the latency reduction is also notable. For Libpaxos, the latency at minimum throughput is 183μs and at maximum throughput is 773μs. The latency of Partition Paxos is only 19μs at 63K and 147μs at maximum throughput.

We measure the latency and predictability for Partitioned Paxos, and show the latency distribution in Figure 8b. Since applications typically do not run at maximum throughput, we report the results for when the application is sending traffic at a rate of 50% of the maximum. Note that this rate is different for libpaxos and Partitioned Paxos: 32K vs. 230K, respectively. Partitioned Paxos shows lower latency and exhibits better predictability than `libpaxos`: it's median latency is 22 μs, compared with 120 μs, and the difference between 25% and 75% quantiles is less than 1 μs, compared with 23 μs in `libpaxos`. To add additional context, we performed the same experiment with an increasing number of partitions, from 1 to 4. We see that the latency for Partitioned Paxos has very little dependence on the number of partitions.

RocksDB   To evaluate how Partitioned Paxos can accelerate a real-world database, we repeated the end-to-end experiment above for the no-op experiment, but using RocksDB instead as the application. The RocksDB instances were deployed on the three servers running the replicas. We followed the same methodology as described above, but rather than sending dummy values, we sent put requests to insert into the key-value store. We enabled write-ahead logging for RocksDB, so that the write operations could be recovered in the event of a server failure. It is important to note that RocksDB was *unmodified*, i.e., there were no changes that we needed to make to the application.

Figure 8c shows the results. For libpaxos, the maximum achievable throughput was 53K message / second. For Partitioned Paxos—again, using a single partition—the maximum throughput was 112K message / second. The latencies were also significantly reduced. For libpaxos, the latency at minimum throughput is 200μs and at maximum throughput is 645μs. The latency of Partitioned Paxos is only 26μs at 44K messages/second, and 143μs at maximum throughput.

We measure the latency and predictability for Partitioned Paxos with replicated RocksDB, and show the latency distribution in Figure 8d. As with the no-op server, we sent traffic at a rate of 50% of the maximum for each system. The rates were 23K for libpaxos and 65K for Partitioned Paxos. Again, we see that Partitioned Paxos shows lower latency and exhibits better predictability than `libpaxos`: it's median latency is 30 μs, compared with 126 μs, and the difference between 25% and 75% quantiles is less than 1 μs, compared with 23 μs in `libpaxos`. As before, we repeated the experiment with 1, 2, 3, and 4 partitions. The latency has very little dependence on the number of partitions.

Increasing number of partitions   Figures 8a and 8c show the throughput for Partitioned Paxos on a single partition. However, a key aspect of the design of Partitioned Paxos is that one can scale the replica throughput by increasing the number of partitions.

Figure 9 shows the throughput of RocksDB with an increasing number of partitions, ranging from 1 to 4. The figure shows results for different types of storage media. For now, we focus on the results for SSD.

As we increase the number of partitions, the throughput increases linearly. When running on 4 partitions, Partitioned Paxos reaches a throughput of 576K messages / second, almost × 11 the maximum throughput for libpaxos.

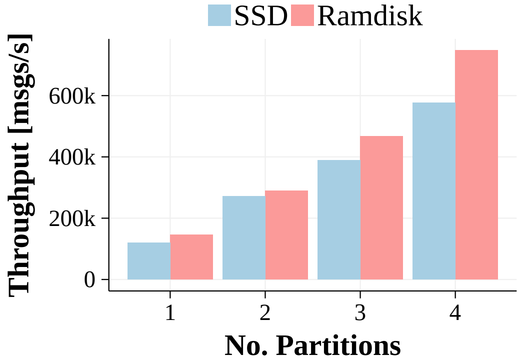


Figure 9: Performance of Partitioned Paxos with RocksDB on Ramdisk and SSD.

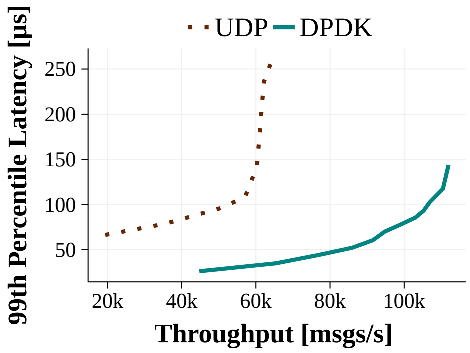


Figure 10: Comparing throughput of replicated RocksDB using UDP socket vs. DPDK.

Storage medium To evaluate how the choice of storage medium impacts performance, we repeated the above experiment using Ramdisk instead of an SSD. Ramdisk uses system memory as a disk drive, i.e., it uses RAM instead of SSD. As can be seen in Figure 9, the throughput increases linearly with the number of partitions. But, the maximum throughput is much higher, reaching 747K messages / second. This experiment eliminates the disk I/O bottleneck, and shows that improving storage I/O can provide a 30% performance improvement. It also shows that solving the storage bottleneck alone will not solve all performance issues, i.e., it will not allow 1B packets at the host.

DPDK To evaluate how much of the performance gains for Partitioned Paxos can be attributed simply to the use of DPDK, we performed the following experiment. We ran Partitioned Paxos on a single partition, and replaced the DPDK library with a normal UDP socket. In both cases, the replicas delivered requests to RocksDB for execution. The workload consisted entirely of put requests.

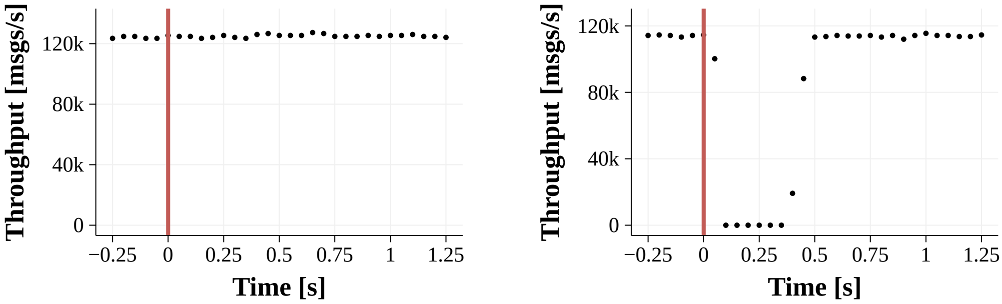
Figure 10 shows the results. We can see that DPDK doubles the throughput and halves the latency. For UDP, the latency at minimum throughput (19K messages/second) is 66μs and at maximum throughput (64K messages/second) is 261μs. The latency of DPDK is only 26μs at 44K messages/second and 143μs at maximum throughput (112K messages/second).

5.4 Failure Experiments

To evaluate the performance of Partitioned Paxos after failures, we repeated the latency and throughput measurements under two different scenarios. In the first, one of the three Partitioned Paxos acceptors fails. In the second, the leader fails, and the leader is replaced with a backup running in software. In both the graphs in Figure 11, the vertical line indicates the failure point. In both experiments, measurements were taken every 50ms.

Acceptor failure To simulate the failure of an acceptor, we disabled the port between the leader and one acceptor. Partitioned Paxos continued to deliver messages at the same throughput, as shown in Figure 11a. In this single-partition configuration, the bottleneck is the application.

Leader failure To simulate the failure of a leader, we disabled the leader logic on the Tofino switch. After 3 consecutive retries, the proposer sends traffic to a backup leader. In this experiment, the backup leader was implemented in software using DPDK, and ran on one of the replicas. The backup leader actively learns the chosen values from the primary leader, so it knows the highest chosen Paxos instance. The results, appearing in Figure 11b, show that the throughput drops to 0 during the retry period. Again, because the application is the bottleneck in the single-partition configuration. the system returns to the peak throughput when the traffic is routed to the backup leader. A DPDK-based implementation of a leader can reach a throughput of ~250K msgs/s.



(a) Acceptor failure

(b) Leader failure

Figure 11: Throughput when (a) an acceptor fails, and (b) when FPGA leader is replaced by DPDK backup. The read line indicates the point of failure.

6 Related Work

Consensus is a well studied problem [24, 39, 40, 8]. Many have proposed consensus optimizations, including exploiting application semantics (e.g., EPaxos [38], Generalized Paxos [27], Generic Broadcast [42]), restricting the protocol (e.g., Zookeeper atomic broadcast [48]), or careful engineering (e.g., Gaios [3]).

Recent work on optimizing consensus protocols rely on two approaches: either they increase the strength of the assumptions that a protocol makes about network behavior (e.g., reliable delivery, ordered delivery, etc.). Or, they rely on increased support from network hardware (e.g., quality-of-service queues, support for adding sequence numbers, maintaining persistent state, etc.).

Lamport's basic Paxos protocol only assumes packet delivery in point-to-point fashion and election of a non-faulty leader. It also requires no modification to network forwarding devices. Fast Paxos [28] optimizes the protocol by optimistically assuming a spontaneous message ordering [28, 43, 44]. However, if that assumption is violated, Fast Paxos reverts to the basic Paxos protocol.

NetPaxos [12] assumes ordered delivery, without enforcing the assumption, which is likely unrealistic. Speculative Paxos [47] and NoPaxos [30] use programmable hardware to increase the likelihood of in-order delivery, and leverage that assumption to optimize consensus à la Fast Paxos [28]. In contrast, Partitioned Paxos makes few assumptions about the network behavior, and uses the programmable data plane to provide high-performance.

Partitioned Paxos differs from Paxos made Switch-y [11] in several important ways. First, Partitioned Paxos implements both Phase 1 and Phase 2 of the Paxos protocol in the switch. Second, it provides techniques for optimized Paxos replicas (i.e., execution). Third, Partitioned Paxos targets an ASIC deployment, which imposes new constraints on the implementation. And, finally, Partitioned Paxos includes a quantitative evaluation of in-network consensus.

István et al. [19] implement Zookeeper Atomic Broadcast (ZAB) in an FPGA. ZAB uses TCP for reliable delivery. They also require that the replicated application itself be implemented in the FPGA. In contrast, Partitioned Paxos provides consensus for unmodified applications.

None of these prior systems address the problem of how an application can take advantage of an accelerated consensus. Partitioned Paxos builds on the idea of using the network data plane to accelerate agreement, but also optimizes execution via state partitioning and parallel execution.

In a separate, but related line of research, Eris [29] and NOCC [20] use programmable switches to accelerate transaction processing.

7 Conclusion

Partitioned Paxos significantly improves the performance of agreement without additional hardware. Moreover, it allows unmodified applications to leverage the performance gains by sharding state and performing execution in parallel. This is a first step towards a more holistic approach to designing distributed systems, in which the network can accelerate services traditionally running on the host.

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