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Network Hardware-Accelerated Consensus

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Abstract

Consensus protocols are the foundation for building many fault-tolerant distributed systems and services. This paper posits that there are significant performance benefits to be gained by offering consensus as a network service (CAANS). CAANS leverages recent advances in commodity networking hardware design and programmability to implement consensus protocol logic in network devices. CAANS provides a complete Paxos protocol, is a drop-in replacement for software-based implementations of Paxos, makes no restrictions on network topologies, and is implemented in a higher-level, data-plane programming language, allowing for portability across a range of target devices. At the same time, CAANS significantly increases throughput and reduces latency for consensus operations. Consensus logic executing in hardware can transmit consensus messages at line speed, with latency only slightly higher than simply forwarding packets.

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1 Introduction

Consensus is a fundamental problem for distributed systems. It consists of getting a group of participants to reliably agree on some value used for computation (e.g., the next valid application state). Several protocols have been proposed to solve the consensus problem [27, 39, 40, 12], and these protocols are the foundation for building fault-tolerant systems, including the core infrastructure of data centers. For example, consensus protocols are the basis for state machine replication [26, 55], which is used to implement key services, such as OpenReplica [42], Ceph [10], and Chubby [9]. Moreover, several important distributed problems can be reduced to consensus, such as atomic broadcast [12] and atomic commit [19].

Given the key role that consensus protocols play in reliable computing, it is unsurprising that there is significant interest in optimizing their performance. Prior efforts towards this goal span a range of approaches, including exploiting application semantics (e.g., EPaxos [37], Generalized Paxos [28], Generic Broadcast [45]), strengthening assumptions about the network (e.g., FastPaxos [29], Speculative Paxos [49]), restricting the protocol (e.g., Zookeeper atomic broadcast [51]), or careful engineering (e.g., Gaios [5]).

This paper presents CAANS, an alternative approach to increasing the performance of consensus protocols. Rather than implementing consensus logic in software running on servers, CAANS allows the network to offer consensus as a service, just as point-to-point communication is provided today. The CAANS approach provides two specific benefits. First, since the logic traditionally performed at servers is executed directly in the network, consensus messages travel fewer hops, resulting in decreased latency. Second, rather than executing server logic in software, which adds overhead for passing packets up the protocol stack and involves expensive message broadcast operations, the same operations are realized “on the wire” by specialized hardware, improving both latency and throughput.

CAANS is possible because of recent trends in commodity networking hardware. Switches and NICs are becoming more powerful, and several devices are on the horizon that offer flexible hardware with customizable packet processing pipelines, including Protocol Independent Switch Architecture (PISA) chips from Barefoot networks [7], FlexPipe from Intel [23], NFP-6xxx from Netronome [38], and Xpliant from Cavium [61].

At the same time, importantly, these devices are becoming easier to program. Several vendors and consortia have developed high-level programming languages that are specifically designed to support network customization. Notable language examples include Huawei's POF (protocol-oblivious forwarding) [57], Xilinx's PX [8], and the P4 Consortium's P4 (programming protocol-independent packet processors) [6]. Such languages significantly lower the barrier for implementing new dataplane functionality and network protocols. Moreover, they offer the possibility for co-designing the network and consensus protocols to optimize performance, as suggested by NetPaxos [16].

Recently, István et al. [20] implemented Zookeeper atomic broadcast in a Xilinx VC709 FPGA. Their work clearly demonstrates the performance benefits achievable by implementing consensus logic in hardware. However, their system suffers from several significant limitations: (i) The FPGA implementation does not provide an application-level API. Thus, any application that wishes to use consensus must also be implemented inside of the FPGA. Developing an application more complex than a key-value store (such as Zookeeper itself) might prove a daunting task. (ii) The implementation is platform-specific, and is not portable to other network devices, such as programmable ASICs, Network Processor Units (NPUs), or other FPGA boards. (iii) Zookeeper atomic broadcast is a restricted version of Paxos that has not been used in storage systems other than Zookeeper.

In contrast, CAANS implements a complete Paxos protocol and is a *drop-in* replacement for software-based implementations. Moreover, CAANS is implemented in a higher-level, data-plane programming language, P4 [6], allowing for portability across a range of target devices.

We have evaluated CAANS on a variety of target architectures, including three different FPGAs, an NPU, and in simulation. Because CAANS offers the same API as a software-based Paxos, we were able to directly compare their performance. Our evaluation shows that CAANS significantly increases throughput and reduces latency for consensus operations. Consensus logic executing in hardware can transmit consensus messages at line speed, with latency only slightly higher than simply forwarding packets. Overall, this paper makes the following contributions:

- It describes the design and implementation of a system offering consensus as a network service that is a drop-in replacement for software-based consensus libraries.
- It provides a complex use-case for data-plane programming languages, and evaluates their performance across a range of target devices.
- It presents experiments demonstrating the performance improvements gained by moving consensus logic into the network.

The rest of this paper is organized as follows. We first provide short summaries of the Paxos protocol (§2). We then discuss the design (§3) and implementation (§4) of CAANS. Next, we provide a thorough evaluation (§6) of our prototype. Finally, we discuss related work (§7), and conclude (§8).

2 Background and Motivation

Before detailing the design of CAANS, we briefly describe the Paxos protocol, and present experiments that motivate moving consensus logic into the network.

2.1 The Paxos Consensus Protocol

Paxos is a fault-tolerant consensus protocol with important characteristics: it has been proven safe under asynchronous assumptions (i.e., when there are no timing bounds on message propagation and process execution), live under weak synchronous assumptions, and resilience-optimum [27].

Paxos distinguishes the following roles that a process can play: *proposers*, *acceptors* and *learners*. Clients of a replicated service are typically proposers, and propose commands that need to be ordered by Paxos before they are learned and executed by the replicated state machines. These replicas typically play the roles of acceptors (i.e., the processes that actually agree on a value) and learners. Paxos is resilience-optimum in the sense that it tolerates the failure of up to f acceptors from a total of $2f+1$ acceptors—to ensure progress—where a quorum of $f+1$

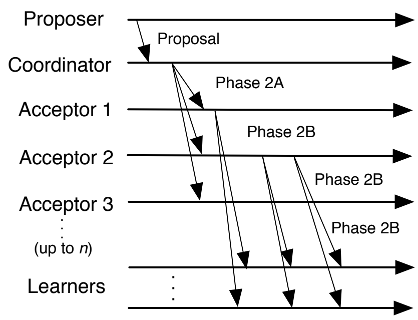


Figure 1: The Paxos Phase 2 communication pattern.

acceptors must be non-faulty [30]. In practice, replicated services run multiple executions of the Paxos protocol to achieve consensus on a sequence of values [11]. An execution of Paxos is called an instance.

An instance of Paxos proceeds in two phases. During the first phase, a proposer that wants to submit a value selects a unique round number and sends a prepare request to a group of acceptors (at least a quorum). 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 prepare requests with smaller round numbers. If the acceptor already accepted a request for the current instance (explained next), 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, it proceeds to the second phase of the protocol.

The communication pattern for Phase 2 of the protocol is illustrated in Figure 1. The proposer selects a value according to the following rule. If no acceptor in the quorum of responses accepted a value, 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 chooses the value with the highest round number. The proposer then sends an accept request with the round number used in the first phase and the value chosen to at least a quorum of acceptors. When receiving such a request, the acceptors acknowledge it by sending a message to the learners, unless the acceptors have already acknowledged another request with a higher round number. Some implementations extend the protocol such that the acceptor also sends an acknowledge to the proposer. When a quorum of acceptors accepts a value consensus is reached.

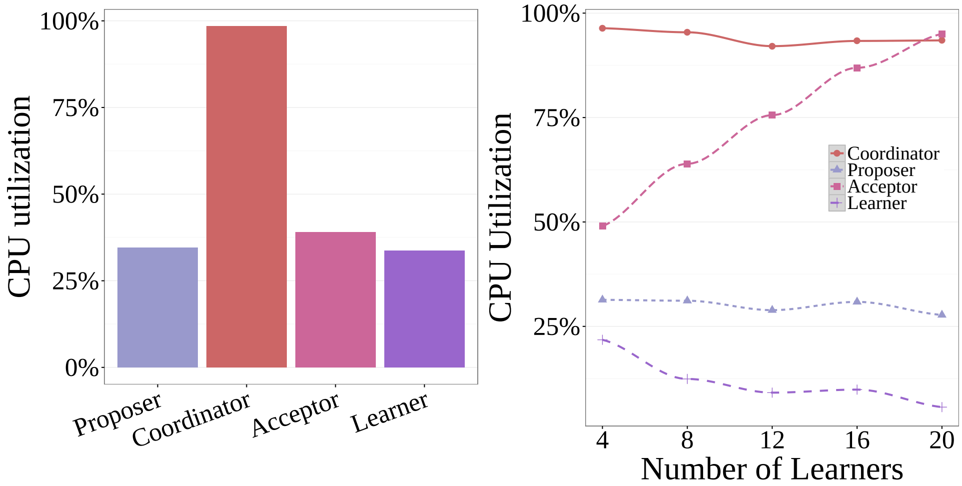
If multiple proposers simultaneously execute the procedure above for the same instance, then no proposer may be able to execute the two phases of the protocol and reach consensus. To avoid scenarios in which proposers compete indefinitely in the same instance, a *coordinator* process can be chosen. In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

If the coordinator identity does not change between instances, then the protocol can be optimized by pre-initializing acceptor state with previously agreed upon instance and round numbers, avoiding the need to send phase 1 messages [27]. This is possible because only the coordinator sends values in the second phase of the protocol. With this optimization, consensus can reached in three communication steps: the message from the proposer to the coordinator, the accept request from the coordinator to the acceptors, and the response to this request from the acceptors to the coordinator and learners.

2.2 Motivation

To investigate the performance bottleneck for a typical Paxos deployment, we measured the CPU utilization for each of the Paxos participants when transmitting messages at peak throughput. As a representative implementation of Paxos, we used the open-source `libpaxos` library [32]. There are, of course, many Paxos implementations, so it is difficult to make generalizations about their collective behavior. However, `libpaxos` is a faithful implementation of Paxos that distinguishes all the Paxos roles. It has been extensively tested and is often used as a reference Paxos implementation (e.g., [20, 21, 48, 56]). Moreover, `libpaxos` performs better than all the other available Paxos libraries we are aware of under similar conditions [37].

In the initial configuration, there are seven processes spread across three machines running on separate cores:



(a) Coordinator bottleneck **(b) Acceptor bottleneck**

Figure 2: The coordinator and acceptor processes are the bottleneck in a software-based Paxos deployment. Acceptor utilization scales with the degree of replication.

one proposer that generates load, one proposer that is designated the coordinator, three acceptors, and two learners. The processes were distributed as follows:

- *Server 1:* 1 proposer, 1 acceptor, 1 learner
- *Server 2:* 1 coordinator, 1 acceptor
- *Server 3:* 1 acceptor, 1 learner

The details of the hardware are explained in Section 6. For brevity, we do not repeat them here.

The client application sends 64-byte messages to the proposer at a peak throughput rate of 69,185 values/sec. The results, which show the average utilization per role, are plotted in Figure 2a. They show that the coordinator is the bottleneck, as it becomes CPU bound.

We then extended the experiment to measure the CPU utilization for each Paxos role as we increased the degree of replication by adding additional learners. The learners were assigned to one of three servers in round-robin fashion, such that multiple learners ran on each machine.

The results, plotted in Figure 2b, show that as we increase the degree of replication, the CPU utilization for acceptors increases. In contrast, the utilization of the learners decreases. This is because as the number of learners increases, the throughput of the acceptor decreases, resulting in fewer messages sent to the learners, and lower ultimately, lower learner utilization.

Overall, these experiments clearly show that the coordinator and acceptor are performance bottlenecks for Paxos. To address these bottlenecks, CAANS moves coordinator and acceptor logic into network hardware. Intuitively, this involves: (i) mapping Paxos messages into a format that can be processed by network devices, and (ii) modifying network devices to execute consensus logic. The next section presents the details of the CAANS design.

3 Design

At a high-level, CAANS is similar to any other Paxos implementation, in that there are four roles that participants in the protocol play: proposers, coordinators, acceptors, and learners.

An instance of consensus is initiated when one of the proposers sends a message to the coordinator. The protocol then follows the communication pattern shown in Figure 1. While executing an instance of consensus, the various roles provide the following functionality:

Proposer. Proposers provide an API to the application to *submit* a value, and initiate an instance of consensus.

Coordinator. A coordinator brokers requests on behalf of proposers. The coordinator ensures that proposers will not compete for a particular instance (thus ensuring that every instance terminates), and imposes an ordering of messages. The coordinator implements a monotonically increasing sequence number, binding messages that come from proposers to consensus instances.

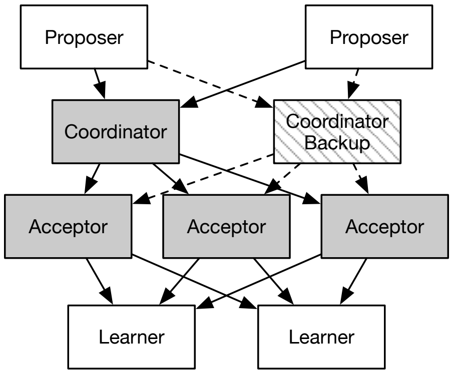


Figure 3: A switch-based deployment of CAANS. Switch hardware is shaded grey, and commodity servers are colored white. The arrows represent communication. The coordinator backup may be deployed on either switch hardware of a commodity server. The dashed-arrows represent backup communication.

Acceptor. Acceptors are responsible for choosing a single value for a particular instance. For every instance of consensus, each acceptor must "vote" for a value. The value can later be delivered if a quorum of acceptors vote the same way. Acceptors represent the "memory" of the protocol and must maintain 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.
Learner. Learners are responsible for replicating a value for a given consensus instance. Learners receive votes from the acceptors, and *deliver* a value if a majority of votes are the same (i.e., there is a quorum).
As per the discussion in Section 2, our design assumes that a single coordinator is used by the proposers. Therefore, CAANS acceptors can initialize their history of messages by implicitly assuming an a priori execution of Phase 1, without the need for the coordinator to actually execute Phase 1 [19]. In other words, acceptors initialize the round numbers in their history to the same initial value used by the coordinator. This is a well-known protocol optimization. We note that Paxos does not require that only one participant act as coordinator at a time. As we will explain later in details, if the coordinator fails, the system can elect a new coordinator.

3.1 Key Issues

CAANS differs from typical Paxos deployments in that it moves some of the consensus logic described above directly into the network. Intuitively, this means (i) mapping Paxos messages into a format that can be processed by network devices, and (ii) modifying network devices to execute consensus logic. However, implementing this design raises several key issues, including:

- What is the interface between the application and the Paxos implementation?
- What logic should be implemented in hardware, and what logic should be implemented in software?
- What is the format for Paxos messages?
- How do memory constraints impact the protocol?
- How should failures be handled?

We discuss each of these topics in detail below.
Application interface. One of the primary design goals for CAANS is to provide a drop-in replacement for software-based implementations of consensus. Therefore, the CAANS implementation of Paxos provides the exact same API as a Paxos software library. The API consists of three key functions, shown in Figure 4.

The `submit` function is called when the application using Paxos sends a value. The application simply passes a character buffer containing the value, and the buffer size. The `paxos_ctx` struct maintains Paxos-related state across invocations (e.g., socket file descriptors).

The application must also register a callback function with the type signature of `deliver`. To register the function, the application sets a function pointer in the `paxos_ctx` struct. When a learner learns a value, it calls

```c
void submit(struct paxos_ctx * ctx,
            char * value,
            int size);

void (*deliver)(struct paxos_ctx* ctx,
                int instance,
                char * value,
                int size);

void recover(struct paxos_ctx * ctx,
             int instance,
             char * value,
             int size);
```

Figure 4: CAANS application level API.

```c
struct paxos_t {
  uint8_t msgtype;
  uint8_t inst[INST_SIZE];
  uint8_t rnd;
  uint8_t vrnd;
  uint8_t swid[8]
  uint8_t value[VALUE_SIZE];
};
```

Figure 5: Paxos packet header.

the application-specific `deliver` function. The `deliver` function returns a buffer containing the learned value, the size of the buffer, and the instance number for the learned value.

The `recover` function is used by the application to discover a previously agreed upon value for a particular instance of consensus. The recover function results in the same sequence of Paxos messages as the `submit` function. The difference in the API, though, is that the application must pass the consensus instance number as a parameter, as well as an application-specific no-op value. The resulting `deliver` callback will either return the accepted value, or the no-op value if no value had been previously accepted for the particular instance number.

Hardware/Software divide. An important question for offering consensus as a network service is: *exactly what logic should be implemented in network hardware, and what logic should be implemented in software?*

In the CAANS architecture, network hardware executes the logic of *coordinators* and *acceptors*. This choice allows CAANS to address the bottlenecks identified in Section 2. Moreover, since the proposer and learner code are implemented in software, the design facilitates the simple application-level interface described above. The logic of each of the roles is neatly encapsulated by communication boundaries.

Figure 3 illustrates the CAANS architecture for a switch-based deployment. In the figure, switch hardware is shaded grey, and commodity servers are colored white. Note that a backup coordinator can execute on either a second switch, or a commodity server, as we'll discuss below. We should also point out that CAANS could be deployed on other devices, such as the programmable NICs that we use in the evaluation.

Paxos header. Network hardware is optimized to process packet headers. Since CAANS targets network hardware, it is a natural choice to map Paxos messages into a Paxos-protocol header. The Paxos header follows the transport protocol header (e.g., UDP), allowing CAANS messages to co-exist with standard network hardware.

In a traditional Paxos implementation, each participant receives messages of a particular type (e.g., Phase 1A, 2A), executes some processing logic, and then synthesizes a new message that it sends to the next participant in the protocol.

However, network hardware, in general, cannot craft new messages; they can only modify fields in the header of the packet that they are currently processing. Therefore, a network-based Paxos needs to map participant logic into forwarding and header rewriting decisions (e.g., the message from proposer to coordinator is transformed into a message from coordinator to each acceptor by rewriting certain fields). Because the message size cannot be changed at the switch, each packet must contain the union of all fields in all Paxos messages, which fortunately are still a small set.

Figure 5 shows the CAANS packet header for Paxos messages, written as a C struct. To keep the header small, the semantics of some of the fields change depending on which participant sends the message. The fields are as follows: (i) `msgtype` distinguishes the various Paxos messages (e.g., phase 1A, 2A); (ii) `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; and (v) `value` contains the request from the proposer or the value for which an acceptor has cast a vote.

A CAANS proposer differs from a standard Paxos proposer because before forwarding messages to the coordinator, it must first encapsulate the message in a Paxos header. Through standard sockets, the Paxos header is then encapsulated inside a UDP datagram and we rely on the UDP checksum to ensure data integrity.

Memory limitations. CAANS aims to support practical systems that use Paxos as a building block to achieve fault tolerance. A prominent example of these are services that rely on a replicated log to persistently record the sequence of all consensus values. The Paxos algorithm does not specify how to handle the ever-growing, replicated log that is stored at acceptors. On any system, this can cause problems, as the log would require unbounded disk space, and recovering replicas might need unbounded recovery time to replay the log. The problem is potentially more acute for CAANS, since the target hardware (e.g., switches and NICs) has limited memory available. This imposes a practical concern: *how is the protocol impacted by memory constraints?*

A main issue to consider is what happens in case certain learners are slow and have not participated in recent Paxos instances. A mechanism is needed for these lagging learners to catch-up with leading learners. Following the design of Google's Paxos [11], we believe that an application using CAANS must checkpoint its state to ensure that past consensus instances will not be needed. As part of the checkpoint process, $f+1$ learners would need to inform the acceptors that they can trim their log up to a particular instance number. However, the decisions of when and how to checkpoint are application-specific, and we therefore do not include these as part of the CAANS implementation. In ongoing work, we are exploring appropriate application-level checkpoint mechanisms that are orthogonal to the work described in this paper.

We note that there are a few CAANS-specific issues for applications to consider. First, occasionally slow learners might need the ability to find out what the value of a certain instance Paxos instance was. This could happen for instance if a learner observes gaps in Paxos instances and suspects that it is lagging behind but a fresh checkpoint is not (yet) available. CAANS provides a *recover* API to applications that can be used to discover what value was accepted for a given consensus instance. We cover this in more details when discussing failure handling.

Second, the number of instances that can be tracked is bounded by the memory available to CAANS acceptors to store the consensus history, which is addressed by the `inst` field of the Paxos header. On the one hand, setting the field too big could potentially impact performance since the coordinator and acceptor code must reserve sufficient memory and make comparisons on this value. On the other hand, if the `inst` field is too small, then the coordinator and acceptors could run out of available instances in a short time. For example, at a rate of 150,000 consensus instances executed per second with 64-byte values, acceptors would fill a 1GB buffer in less than two minutes. Reusing the acceptor's storage buffer means that past instances in the buffer will no longer be available. Over time, we expect that this limitation will become less of a concern, as the amount of memory available on devices continues to increase.

Failure handling. The Paxos protocol does not provide guarantees against message loss. Again, the details of how to cope with message loss depend on the application and the deployment. We therefore do not include this functionality in CAANS.

In general, to cope with message loss, an application must provide a way to (i) identify that a message was lost, and (ii) re-transmit the message. One common approach is to use timeouts. A proposer that is also a learner should deliver its submitted value. If the proposer times out before delivering the value, it assumes that a message was lost (e.g., its request to the coordinator, the coordinator's prepare message to the acceptors) and resubmits the value. This mechanism requires learners to detect and discard duplicated delivered values, a situation that may happen if proposers use timeouts that are too aggressive.

Learners that miss the decision of a consensus instance can find out the value decided by contacting the acceptors through the *recover* API. To find out the value decided in some instance k, this API performs a new execution of the Paxos protocol (phase 1+2) while proposing a no-op value in consensus k and waits for the result. If a value was decided in k, the learner will receive the value, assuming a quorum of acceptors; otherwise, no-op will be decided in k and discarded by the application.

A faulty switch coordinator can be replaced by either another switch or a coordinator in software running on a server that temporarily assumes the role. If a software coordinator is chosen, then it can be co-located with any of the proposers. The most important information the new coordinator needs is the last consensus instance used. This information does not need to be accurate though. If the next instance the new coordinator uses is smaller than the last instance used by the failed switch coordinator, then new values will not be accepted until the new coordinator catches up with the last instance used. If the next instance used is greater than the last instance used, the learners will see gaps in the sequence of learned values and will fill in these gaps using the recover procedure described above.

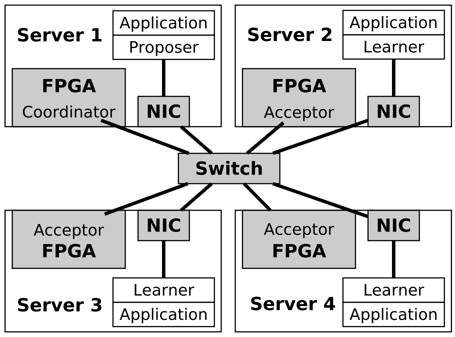


Figure 6: An implementation of CAANS using FPGAs.

Finally, we note that Paxos usually requires that acceptor storage is persistent. In other words, if the acceptor fails, and then restarts, it should be able to recover its durable state. Like prior work [20], we assume that memory on network devices could be made persistent through a variety of techniques, including using battery-backed memory or newer NVRAM technology.

3.2 Discussion

The Paxos protocol does not guarantee or impose an ordering on consensus instances. Rather, it guarantees that for a given instance, a majority of participants agree on a value. So, for example, the i-th instance of consensus need not complete before the $(i+1)$-th instance.

Many applications may require stronger properties. For example, an application might want to know if a given instance has not reached consensus. The process of detecting a missing instance and re-initiating consensus depends on the details of the particular application and deployment. For example, if proposers and learners are co-located, then a proposer can observe if an instance has reached consensus. If they are deployed on separate machines, then proposers would have to employ some other process (e.g., using acknowledgments and timeouts).

This observation begs the natural question: *why not implement functionality beyond consensus in the network?* For example, one could imagine implementing state-machine replication, or like István et al. [20], implement a replicated key-value store.

Certainly, this is a topic that will require further research. However, we believe that CAANS occupies a sweet-spot amongst the issues raised by the end-to-end principle [54]: consensus is widely-applicable to a large class of applications; the implementation provides significant performance improvements; and it avoids implementing application-specific logic in the network.

4 Implementation

We have implemented a prototype of CAANS. The proposer and learner code are written in C, and the coordinator and acceptor are written in P4 [6]. All code, including a demo that runs in a simulated environment, is publicly available with an open-source license[1].

P4 is a high-level, data-plane programming language that can be compiled to several hardware backends including FPGAs and network processors. The P4 implementation of CAANS follows the design of Dang et al. [15].

We have experimented with four different P4 platforms: P4FPGA [59], Netronome's Open-NFP [41], Xilinx's SDNet [60], and P4.org's compiler [44] which targets a simulated environment (i.e., Mininet [36] and P4 Behavioral Model switch [43]). Since P4 is relatively new and rapidly changing, our experiments and results push the state-of-the-art of P4 environments. Specifically, none of the compilers could generate a complete P4 source-to-target solution. Each of the compilers required some additional implementation effort, which we describe below.

P4FPGA. P4FPGA [59] is an open-source framework that compiles and runs high-level P4 programs to various FPGA targets such as Xilinx and Altera FPGAs. P4FPGA first transforms P4 programs into a data-plane pipeline expressed as a sequence of hardware modules written in Bluespec Verilog [4]. P4FPGA then compiles these

[1] https://github.com/anonymous

Bluespec modules to FPGA firmware. The acceptor and coordinator pipelines include a parser, match table and/or action block, then deparser. Since the P4FPGA compiler is a work-in-progress and is not fully automated yet, we modified P4FPGA to implement any missing functionality and optimized it with hand-written Bluespec code. For example, P4FPGA generated six match/action stages for the acceptor pipeline, and three of those stages were not necessary, since the match operations were hit on every incoming packet.

An FPGA has a limited number of on-chip block ram (BRAM) and registers. As a result, the CAANS implementation is constrained by the amount of BRAMs available, which is the primary resource for logging consensus values. To scale to the large number of consensus instances required for CAANS, we could leverage off-chip SRAM and DRAM. Of course, accessing off-chip memory in general leads to longer processing delays. Our current implementation uses on-chip memory only.

Open-NFP. The Open-NFP [41] organization provides a set of tools for developing network function processing logic in server networking hardware. These tools include a P4 compiler that targets 10, 40 and 100GbE Intelligent Server Adapters (ISAs) manufactured by Netronome.

The Open-NFP compiler currently does not support register related operations and cannot parse header fields larger than 32 bits. Moreover, while P4 version 1.0.2 allows users to define actions for handling packets, the Open-NFP compiler supports a custom P4 syntax that declares actions with the `primitive_action` keyword, and implements actions in MicroC code external to the P4 program. The MicroC primitive actions can be used to extract packet headers and to read or write header fields. The Open-NFP primitive actions are similar to "external actions" in the proposed P4 version 1.2 specification.

Therefore, to target the Netronome hardware devices, our P4 implementation of Paxos needed to be modified to gather all actions and register declarations in a MicroC sandbox. Because the coordinator and acceptor code require different register sizes, we had to explicitly assign memory locations for registers. Additionally, we used MicroC code to access hardware counters to compute the operation latency.

Xilinx SDNet. Xilinx SDNet [60] is a development environment for data plane programmability that allows for scalability across the range of Xilinx FPGAs. SDNet compiles programs from the high-level PX [8] language to a data plane implementation on a Xilinx FPGA target, at selectable line rates from 1G to 100G without program changes.

A Xilinx Labs prototype P4 compiler works by translating from P4 to PX, and then using SDNet to map this PX to a target FPGA. A future version in progress will compile P4 directly, rather than cross-translating. The SDNet-generated hardware IP blocks can then be imported into a standard Xilinx Vivado project, in which they can be connected to other hardware IP blocks. The resulting system is then synthesized using the Vivado toolchain. For NetFPGA SUME [62], we needed to write a Verilog wrapper around the SDNet standard interfaces to match them up with the expected interfaces in the NetFPGA SUME reference switch design. One challenge in this development effort was synchronizing packet metadata with the packets that flow through the data plane pipeline.

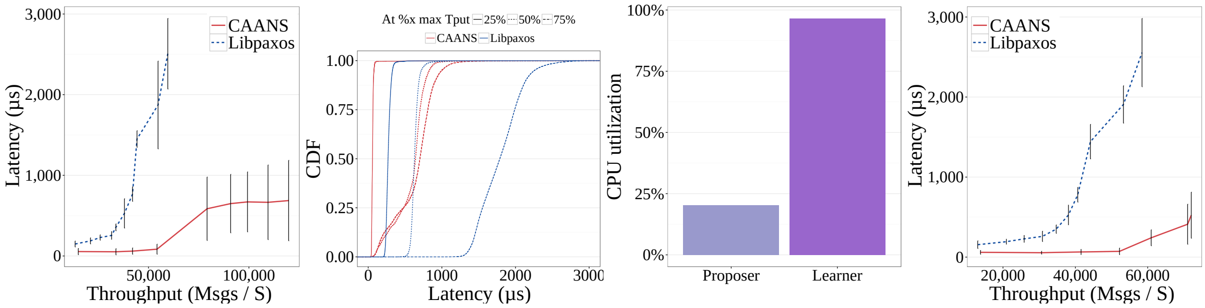
The Xilinx Labs P4 compiler is currently under active development, and evolving towards the future P4 version 1.2 specification. To use the compiler, we needed to modify our P4 version 1.0 implementation to adopt expected version 1.2 features. The biggest difference was the use of "external methods" to replace stateful register operations.

P4.org and P4 Behavioral Model In addition to the compilers described above, we also have used the P4.org compiler [44] which targets a simulated environment (i.e., Mininet [36] and P4 Behavioral Model switch [43]). As a software demo, we deploy one coordinator and three acceptors as switches running CAANS, with a proposer and learners running as Mininet hosts. An HTTP server runs on top of the proposer, and a simple key-value store is deployed on each learner. Users connect to the system using a web-interface to put and get values to the replicated key-value store. Users can experiment with failure scenarios using mininet commands to add and remove hosts or connections.

5 Case Study: Replicated LevelDB

As an example application of CAANS, we have used it to create a distributed storage system backed by LevelDB [31]. LevelDB is a popular open-source, on-disk, key-value store implemented as a library, rather than a server. LevelDB is used by a number of applications, including Google's Chrome to store client-side data, and BitCoin to store blockchain metadata [3]. Our own implementation is inspired by Riak [52], which uses LevelDB as one of its storage back-ends and Paxos for consensus.

Our application consists of two components: a client and a server. The client code links against the CAANS



(a) Throughput vs. latency **(b) Latency CDF.** **(c) CPU Utilization.** **(d) Throughput vs. latency (w/ LevelDB).**

Figure 7: The end-to-end performance of CAANS compared to libpaxos: (a) throughput vs. latency without, (b) latency CDF, (c) CAANS CPU Utilization, and (d) throughput vs. latency with LevelDB. CAANS demonstrates higher throughput, lower latency, and more predicable latency. Moreover, CAANS moves the processing bottleneck to the learner component, suggesting that even better performance should be possible.

proposer library. Users of the client submit get, put, and delete operations, which are then serialized, and submitted to the storage servers via calls to `submit`. The proposer library crafts the CAANS message with the Paxos packet header, and sends the message to the coordinator.

Multiple servers run in parallel, each with their own instance of LevelDB. The storage is replicated. The server code links against the CAANS learner library. When the learner delivers a value, it invokes the application-specific callback function. The function returns the accepted value, which contains the serialized request for the LevelDB instance. The server side code is responsible for de-serializing the request, and invoking the appropriate method from the LevelDB API. CAANS ensures that all replicas are consistent.

It is worth emphasizing that the client and server components need only interact with the consensus service via the small API described in Section 3. The CAANS API is the same as any other software-based implementation of Paxos. No code from LevelDB needed to be modified. Thus, users of CAANS need only link against a different library.

6 Evaluation

Our evaluation of CAANS explores three questions: (i) What is the absolute performance of individual CAANS components? (ii) What is the end-to-end performance of CAANS as a system for providing consensus? And, (iii) What is the performance under failure?

Overall, the results are promising. CAANS dramatically increases throughput and reduces latency for end-to-end performance when compared to software-only implementations. Our experiments show that CAANS shifts the processing bottleneck from coordinators and acceptors to learners and the application itself. The absolute performance of the hardware-based coordinators and acceptors suggests that further performance gains would be possible with improvements in learners and application design, pointing to future areas of research. Moreover, we have evaluated CAANS on four different target devices using three different compilers and toolchains[2]. This demonstrates that CAANS is portable across a diversity of network devices.

6.1 Hardware Configuration

We ran our end-to-end experiments on a testbed with four Supermicro 6018U-TRTP+ servers and a Pica8 P-3922 10G Ethernet switch, connected in the topology shown in Figure 6. 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. We installed one NetFPGA SUME [62] board in each server through a PCIe x8 slot, though NetFGPAs behave as stand-alone systems in our testbed. Two of the four SFP+ interfaces of the NetFPGA SUME board and one of the four SFP+ interfaces provided by the 10G NICs are connected to Pica8 switch with a total of 12 SFP+ copper cables. The servers were running Ubuntu 14.04 with Linux kernel version 3.19.0.

[2]We don't use the P4.org compiler for performance measurements because it targets a simulated environment.

	P4FPGA	SDNet	Netronome
Forwarding	0.37 μs	0.73 μs	-
Acceptor	0.79 μs	1.44 μs	0.81±0.01 μs
Coordinator	0.72 μs	1.21 μs	0.33±0.01 μs

Table 1: Measured latency for acceptors and coordinators on NetFPGA SUME with P4FPGA @ 250MHz, NetFPGA SUME with SDNet @ 200MHz, and Netronome.

In addition to the above hardware testbed, we also compiled CAANS coordinator and acceptor P4 programs on the following target devices:

- A Netronome AgilIO-CX 1x40GbE Intelligent Server, with a Netronome NFP-4000 processor, and 2GB of DDR3 DRAM memory
- An Alpha Data ADM-PCIE-KU3: 2x40G NIC
- A Xilinx VCU109: 4x100G line card

6.2 Performance of CAANS components

The first set of experiments explores the performance of CAANS coordinator and acceptor logic. We focus on measuring throughput and latency for a diverse set of hardware. Overall, the experiments show that CAANS coordinators and acceptors can saturate a 10Gbps link, and that the latency overhead for Paxos logic is little more than forwarding delay.

Max achievable throughput. To measure the maximum rate at which coordinators and acceptors can process consensus messages, we benchmarked their implementations on the NetFPGA SUME using P4FPGA. We configured a P4FPGA-based hardware packet generator and capturer to send 102 bytes[3] consensus messages to each of acceptor and coordinator, then captured and timestamped each message measuring maximum receiving rate.

The results show that both acceptor and coordinator can process over 9 million consensus messages per second, which is close to the line-rate of 102 byte packets ($\approx$ 9.3M). We performed the same benchmark with the Netronome card and measured the maximum throughput at 2 million consensus messages per second. We suspect that a higher throughput rate is possible with the Netronome card, but that performance is limited by our software license, which only provided evaluation access.

Hardware latency. To quantify the processing overhead added by executing Paxos in network hardware, we measured the pipeline latency of forwarding with and without Paxos. In particular, we computed the difference between two timestamps, one when the first word of a consensus message entered the pipeline and the other when the first word of the message left the pipeline.

Table 1 shows the results. The first row shows the results for forwarding without Paxos logic. The latency was measured between the parser and deparser stages of the forwarding pipeline. The results show that the latency for forwarding was 0.37 and 0.73 us for P4FPGA and SDNet, respectively. We were not able to measure the forwarding latency for Netronome, as we do not have access to parser or deparser timestamps in Netronome. The second and third rows show the pipeline latency for an acceptor and a coordinator. Acceptors of P4FPGA and SDNet represent a modest increase in latency of 0.42 and 0.71 us over forwarding. The difference in latency between a coordinator and acceptor was due to the complexity of operations of consensus messages: acceptors do more work per message, hence the higher latency. Lastly, we observed that the latency of the FPGA based targets were constant due to their pipelines being a constant number of stages; whereas the NPU-based Netronome target had some measurable variance, which is due to the internal architecture and scheduling of threads in NPU.

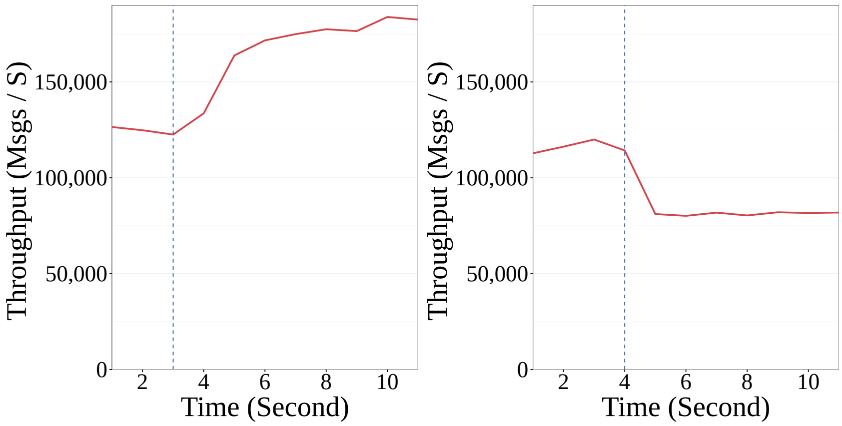
Computed throughput and latency. In addition to the above measured latencies, we also computed throughput and latency for three different target devices when compiling with SDNet. SDNet can report precisely how many clock cycles it takes a packet to go through from input to output. One can then just multiply this by the clock rate of the target board, and have reliable latency numbers. For throughput, one can take the chosen bus width and the clock rate, and adjust for end-of-packet fragmentation. The computed throughputs and latencies are shown in Table 2. The latency differences here result predominantly from increasing clock rates on the three platforms, and are not due to significant differences in pipeline length.

Resource utilization. To evaluate the cost of implementing Paxos logic on FPGAs, we report resource utilization on NetFPGA SUME using P4FPGA. An FPGA contains a large number of programmable logic blocks: look-up

[3] Ethernet header (14B), IP header (20B), UDP header (8B), Paxos header (44B), and Paxos payload (16B)

Device	Coordinator latency	Acceptor latency	Throughput	Clock rate
Digilent NetFPGA SUME: 4x10G port switch	1.280 μs	1.515 μs	60M packets/s	200MHz
Alpha Data ADM-PCIE-KU3: 2x40G NIC	1.024 μs	1.212 μs	60M packets/s	250MHz
Xilinx VCU109: 4x100G line card	0.867 μs	1.023 μs	150M packets/s	300MHz

Table 2: Computed latencies and throughput for code generated from Xilinx SDNet.



(a) Acceptor failure **(b) Coordinator failure**

Figure 8: The performance of CAANS when (a) an acceptor fails, and (b) when the hardware coordinator fails and is replaced by a software coordinator.

tables (LUTs), registers and block rams (BRAMs). In NetFPGA SUME, we implemented P4 stateful memory with on-chip BRAM to store the consensus history. As shown in Table 3, current implementation uses 54% of available BRAMs, out of which 35% are used for stateful memory. As mentioned in Section 4, we could scale up the current implementation in NetFPGA SUME by using large, off-chip DRAM at a cost of higher memory access latency. It is possible to hide DRAM access latency without significant affect overall throughput [20]. We note that cost may differ with other compilers and targets.

6.3 End-to-End Performance

To evaluate the end-to-end performance, we compare the throughput and latency for transmitting consensus messages when using CAANS and the software-based `libpaxos` mentioned in Section 2.

Figure 6 shows the deployment for CAANS. As an application, we used a simple echo server. Server 1 runs a multi-threaded client process and a single proposer process. Servers 2, 3, and 4 run learner processes and the echo server. The deployment for `libpaxos` is similar, except that the coordinator and acceptor processes run in software on their servers, instead of running on the FPGA boards.

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 learner as the number of deliver invocations over time.

To push the system towards higher message throughputs, we increased the number of threads running in parallel at the client. The number of threads, N, ranged from 1 to 22 by increments of 1. We stopped measuring at 22 threads because the CPU utilization on the learners reached 100%. For each value of N, the client sent a total of 2 million messages (i.e., unique instances). We repeat this for three runs, and report the mean latency and throughput over the three runs.

Throughput and latency. The results are shown in Figure 7a. The experiment shows that CAANS results in dramatic improvements in throughput and latency. While `libpaxos` is only able to achieve a maximum throughput of 59,604 messages per second, CAANS reaches 134,094 messages per second, a 2.24x improvement. The lowest latency for `libpaxos` occurs at the lowest throughput rate, and is 157μs. However, the latency increases significantly as the throughput increases, reaching 2,510μs. In contrast, the latency for CAANS starts at

LUTs	84674 / 433200 (19.5%)
Registers	103921 / 866400 (11.9%)
BRAMs	801 / 1470 (54.4%)

Table 3: Resource utilization on NetFPGA SUME with P4FPGA with 65,535 Paxos instance numbers.

	% max Tput	avg latency (μs)	std latency (μs)
CAANS	25%	60.8	38.4
CAANS	50%	582.5	389.2
CAANS	75%	653.9	385.1
libpaxos	25%	275.9	92.7
libpaxos	50%	637.4	145.4
libpaxos	75%	1800.1	465.0

Table 4: The mean latency and standard deviation for CAANS and libpaxos.

only 52μs, and is never higher than 686μs.

Predictability. CAANS messages also demonstrate more predictability than `libpaxos`. Since applications typically do not run at maximum throughput, we report the results for when the application is sending traffic at 25, 50, and 75% of the maximum throughput rates. Note that the maximum throughput rates for CAANS and `libpaxos` are very different. Figure 7b shows the latency distribution. Table 4 shows the average and standard deviation for latencies for both CAANS and `libpaxos`. We see that the latency measurements are much more stable for CAANS.

Utilization. In Section 2, we showed that in a typical software deployment, the coordinator and acceptors become bottlenecks for consensus. We repeated the experiment with CAANS, measuring the CPU Utilization at the proposer and learners when sending at maximum throughput. The results are shown in Figure 7c. With CAANS, we measured close to 100% utilization on the learner. This explains the limit on maximum throughput for CAANS, as the performance bottleneck is moved to the learner.

Application overhead. As a final end-to-end performance experiment, we measured the throughput and latency for consensus messages for our replicated LevelDB example application. The LevelDB instances were deployed on the three servers running the learners. We followed the same methodology as described above, but rather than sending dummy values, we sent an equal mix of get and put requests.

The results are shown in Figure 7d. The maximum achievable throughput for CAANS is reduced to 75,825 messages per second. This shows that the replicated application itself adds significant overhead, and in fact, becomes the bottleneck when run with CAANS. In contrast, there is no throughput change for the `libpaxos` deployment, where we measured a maximum throughput of 58,427 messages per second. There is no difference from the previous experiment, because with `libpaxos`, the coordinator is the bottleneck.

6.4 Performance Under Failure

As a final set of experiments, we repeated the throughput and latency measurements from Section 6.3 under two different failure scenarios. In the first, one of the three acceptors fails. In the second, the hardware coordinator fails, and the coordinator is temporarily replaced with a software coordinator. Note that in the second scenario, acceptor logic remains in hardware. In both the graphs in Figure 8, the blue, vertical line indicates the failure point.

Figure 8a shows that the throughput of CAANS increases after the loss of one acceptor. This is expected, since the learner is the bottleneck, and it processes fewer messages after the failure.

To handle the loss of a coordinator, we re-route traffic to a software coordinator. Figure 8b shows that CAANS is resilient to the failure, although the software-coordinator adds additional processing overhead. We note that CAANS could use a backup hardware-based coordinator. Unfortunately, we did not have access to an additional FPGA. However, we expect that performance would not decrease with a hardware coordinator.

7 Related Work

Dang et al. [16] proposed the idea of moving consensus logic in to network devices. Their work suggested two possible approaches: (i) implementing Paxos in switches, and (ii) using a modified protocol, named *NetPaxos*, which solves consensus without switch-based computation by making assumptions about packet ordering. Their Paxos Made Switch-y paper [15] makes the implementation of a switch-based Paxos concrete, by presenting a detailed discussion of the source code written in P4 [6]. This paper builds on their work, both by providing a complete system, and by presenting a thorough of the performance benefits of network-based consensus.

The work of István et al. [20] describes an implementation of Zookeeper's atomic broadcast written in Verilog. As mentioned in the introduction, CAANS differs from their work on several key design points: (i) CAANS implements a complete Paxos protocol, as opposed to the simplified ZAB protocol, (ii) CAANS provides an general API exposed to software applications, while István et al. require that applications be implemented inside of the FPGA, and (iii) CAANS is portable across a range of target devices.

Network support for applications. Several recent projects have investigated leveraging network programmability for improved application performance, focusing especially on large-scale, data processing systems, such as Hadoop. For example, PANE [17], EyeQ [22], and Merlin [58] all use resource scheduling to improve the job performance , while NetAgg [33] leverages user-defined *combiner* functions to reduce network congestion. These projects have largely focused on improving application performance through traffic management. In contrast, this paper argues for moving application logic into network devices.

Speculative Paxos [50] uses predictable network behavior to improve the performance of Paxos. It uses a combination of techniques to eliminate packet reordering in a data center, including IP multicast, fixed length network topologies, and a single top-of-rack switch acting as a serializer.

Replication protocols. Research on replication protocols for high availability is quite mature. Existing approaches for replication-transparent protocols, notably protocols that implement some form of strong consistency (e.g., linearizability, serializability) can be roughly divided into three classes [13]: (a) state-machine replication [26, 55], (b) primary-backup replication [39], and (c) deferred update replication [13].

Despite the long history of research in replication protocols, there exist very few examples of protocols that leverage network behavior to improve performance. The one exception of which we are aware are systems that exploit *spontaneous message ordering*, [29, 46, 47]. The idea is to check whether messages reach their destination in order, instead of assuming that order must be always constructed by the protocol and incurring additional message steps to achieve it. This paper differs in that it implements a standard Paxos protocol that does not make ordering assumptions.

8 Conclusion

Performance has long been a concern for consensus protocols. Twenty years ago, researchers observed that you might not use consensus in-band for systems with high demand [18]. Since that time, there have been many proposals made to optimize the performance of consensus protocols (e.g., [37, 1, 28, 45, 29, 49, 34, 51]). But still, as recently as five years ago, Bolosky et al. [5] wrote that "Conventional wisdom holds that Paxos is too expensive to use for high-volume, high-throughput, data-intensive applications."

The performance benefits provided by CAANS can have a dramatic impact for local-area and data-center deployments. The CAANS approach means that coordinators and acceptors can fully saturate 10G links, and the latency for transmitting consensus traffic is little more than simply forwarding.

With CAANS, the bottleneck for consensus becomes the learners and the application itself. We believe that this changes the landscape for future replication research. The focus of future work should be on investigating how applications can handle data at such high rates.

There have been some initial efforts in this direction already. For example, some approaches explore how to leverage the parallelism of multi-core machines to improve the performance of replication [2, 35, 25, 24, 14]. Bolosky et al. [5] focuses on avoiding disk latency. NetMap [53] investigate ways to avoid overhead for reading packets. These techniques are complimentary to CAANS, and we expect efforts like this will become increasingly important.

In summary, the advent of flexible hardware and expressive dataplane programming languages will have a profound impact on networks. One possible use of this emerging technology is to move logic traditionally associated with the application layer into the network itself. In the case of Paxos, and similar consensus protocols, this change could dramatically improve the performance of data center infrastructure, and open the door for new research challenges in the design of consensus protocols.

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