Abstract

Persistent key value stores are an important component of many distributed data serving solutions with innovations targeted at taking advantage of growing flash speeds. Unfortunately their performance is hampered by the need to maintain and replicate a write ahead log to guarantee availability in the face of machine and storage failures. Cyclone is a replicated log plug-in for key value stores that systematically addresses various sources of this bottleneck. It uses a small amount of non-volatile memory directly addressable by the CPU - such as in the form of NVDIMMs or Intel 3DXPoint - to remove block oriented IO devices such as SSDs from the critical path for appending to the log. This enables it to address network overheads using an implementation of the RAFT consensus protocol that is designed around a userspace network stack to relieve the CPU of the burden of data copies. Finally, it provides a way to exploit the parallelism available in commodity NICs. Cyclone is able to replicate millions of small updates per second using only commodity 10 gigabit ethernet adapters. As a practical application, we use it to improve the performance (and availability) of RocksDB, a popular persistent key value store by an order of magnitude when compared to its own write ahead log without replication.

1 Introduction

Persistent key value stores are an important component of datacenter scale storage services. Key value stores such as Rocksdb [2], LevelDB [3] and FloDB [12] represent significant efforts on both engineering and research fronts. These key value stores include sophisticated in-memory data structures built around Log Structured Merge (LSM) trees [28] and are heavily tuned to extract maximum performance from flash-based solid state drives (SSDs).

These key value stores however tend to ignore an important component: the write ahead log. A machine or storage failure leading to total loss or temporary unavailability of data is unacceptable in services where high availability and revenue are interconnected. Key value stores therefore usually incorporate support for a write ahead log that if replicated and kept durable for every appended update provides the necessary high availability. Unfortunately, the write ahead log is a performance achilles heel for these systems, eclipsing much of the work on improving the performance of the LSM component. To illustrate the impact of the write ahead log, consider Figure 1. The line marked 'rocksdb' shows the performance of Rocksdb without the write ahead log. The performance when persisting the log three ways without replicating it is shown as the line marked 'rocksdb/WAL'. The line marked 'rocksdb/3 way rep.' is for simply replicating the log three ways without persisting it, using RAFT [29] running over TCP/IP. Either persisting every update to the log or replicating it using TCP/IP causes performance to drop by an order of magnitude (note the log scale on the x-axis). It is therefore no surprise that deployments of Rocksdb often turn off the write ahead log [4], depending on upper layers to provide availability by co-ordinating replicas. On the other side of the spectrum, key value store research prototypes such as FloDB [12] turn off the write ahead
log to be able to showcase benefits of sophisticated extensions to LSM data structures.

These two performance bottlenecks illustrated in Figure 1 are not independent, they cannot be addressed in isolation. In particular, durability semantics mean that the key-value store cannot respond to the client until the operation has been persisted to the log at a majority of replicas, since it must be completed even on a crash and subsequent recovery. Therefore, addressing the network bottleneck is pointless without also addressing the storage bottleneck. Cyclone shows how a small amount of non-volatile memory can be used to address both bottlenecks.

Cyclone is a high speed strongly consistent replicated write ahead logging service specialized for key value stores such as Rocksdb. Cyclone entirely closes the performance gap due to both the storage and the network shown in Figure 1. We show that Cyclone achieves performance transparent replication in that it can provide both a persistent write ahead log and replication without compromising on RocksDB’s performance.

The first key contribution of Cyclone is demonstrating the benefit of a small amount of non-volatile memory when combined with the flash SSD based persistent logs. The primary cause of slowdown when turning on a write ahead log on a single machine in Figure 1 is the need to do synchronous block IO for every update regardless of the size of the update. SSDs provide the maximum throughput when writing large chunks (usually more than 4KB) of data. This is due to the fixed cost of a round trip to the SSD through the IO interface (NVMe in our case), regardless of the volume of data being synchronously persisted. Small updates (sum of key and value sizes) are surprisingly common in observed workloads for key value pairs. For example, Facebook [10] reports that 90% of the space allocated in key value stores is for data items under 500 bytes in size.

Cyclone avoids this overhead by making use of a small amount of directly attached non-volatile memory (NVM), also called persistent memory, on the server. This can be in the form of NVDIMMs (DIMMs with an added ultracapacitor to dump state to a small amount of attached flash) -or- newer and potentially cheaper (but slower) forms of persistent memory [16]. In cases where the log does not entirely fit in NVM, we periodically drain the NVM log into a log placed on a standard SSD on the system.

The second key contribution of this work is in showing that the throughput bottlenecks in the network stack can be mitigated entirely in software, once block IO is removed from the critical path. Existing work on log replication using state machine replication protocols such as Paxos [22] and RAFT [29] has not - thus far - addressed high performance replication in the local area network of a datacenter using commodity networks. Research focusing on addressing network latencies by reducing the number of network hops with new protocols such as Fast Paxos [24] or network switch modifications such as No Paxos [26] do not address throughput bottlenecks due to network stack related inefficiencies in the participating nodes of the quorum – a more urgent problem with local area replication. On the other hand, work done to address network related inefficiencies start with the assumption that the bottleneck to good throughput on the network is the CPU and therefore one must either resort to network offload mechanisms such as RDMA [30, 15, 20] or offload the protocol entirely to an FPGA [19]. We demonstrate in this paper that this is not the case. Rather, once persistence is provided by directly attached non-volatile memory, thereby eliminating block IO from the persistence
step in replication protocols, the problem becomes akin to multicasting the same log entry from the leader to all followers. We design Cyclone’s network stack around well known principles in the software packet switching community. In particular, a careful implementation of a consensus protocol that relieves the CPU of the responsibility of data movement permits a high performance implementation entirely in software that addresses the order of magnitude network related performance gap in Figure 1 using only commodity 10 Gigabit ethernet.

Both the storage (NVM, SSD) as well as the NIC expose significant parallelism that is left unused when Cyclone is used to replicate a single log. The third key contribution of this work is to show how one can exploit this parallelism in Cyclone automatically creates and manages multiple logs, mapping them to the available parallelism in the system via multiple instances of the same consensus protocol.

The rest of the paper is organized as follows. We describe Cyclone’s system architecture in Section 2. We describe the two level log structure in Section 3. The set of optimizations to the network stack is described in Section 4. We show how Cyclone can be scaled to make use of available parallelism on the system in Section 5. A detailed evaluation of Cyclone’s replication performance is provided in the context of RocksDB - a popular persistent key value store - in Section 6. We then discuss related work before concluding.

2 System Architecture

A persistent key value store durably stores key-value mappings accessible through a simple interface:

- GET(K): returns value corresponding to key K
- PUT(K, V): sets the value of key K to value V
- DELETE(K): deletes the key K

Key value stores such as RocksDB also support atomic writes (PUT operations) to multiple keys, called batched writes, and the ability to take snapshots.

Cyclone integrates with key value stores as both a client and server side library. Cyclone replicates the key value store across a set of replica servers. The client side library sends all requests - reads and updates - to a distinguished leader replica. On the server side Cyclone accepts requests from clients, calls into the key value store, and returns a response to the client. Before executing any PUT or DELETE request, Cyclone appends it to a durable log and replicates the request to the logs of follower replicas. The request is considered replicated once acknowledged by a majority of replicas. Follower replicas apply updates from the log in order.

Cyclone uses the RAFT consensus protocol [29] to keep the logs in sync across the replicas. On failure of the leader replica, a new leader is automatically elected – RAFT ensures that the new leader has the most up to date log. The Cyclone client library automatically locates the new leader on a failover, resulting in only a brief interruption in service for clients. Cyclone guarantees that the order of operations to any particular key are linearizable. A key sees the exact same sequence of update operations (including deletes) on all replicas. These per-key guarantees follow immediately from the properties of the RAFT log and by requiring clients to perform a quorum read (logged as an entry in the RAFT log).

In addition, Cyclone also provides clients with a weak read that does not require a quorum read thereby requiring only one round trip to a server. A weak read of a key sees a prefix of the linearized sequence of updates to a key that includes all successful update operations made by the client before it issues the weak read. To do a weak read, clients maintain the last known term of the RAFT leader locally and ensure they always talk to a RAFT leader that has at least the same term. This ensures that clients see their own writes avoiding split brain problems where a network partition allows clients to talk to old RAFT leaders after having committed changes to a new RAFT leader. In addition, a weak read waits until all pending RAFT log entries have been committed and ap-


plied before executing. This ensures that in the event of a failover, any previous committed updates from the same client have been applied and are visible to the weak read. A weak read is not linearizable as the RAFT leader responding to the weak read might actually no longer be the leader - a new one having been elected without it realizing, perhaps due to a network partition. This means that while a weak read from a client sees its own writes, in some rare cases it might not see later writes by other clients.

Finally, Cyclone allows operations to multiple keys in an atomic batch, where either all updates in the batch are applied or no operation in the batch is applied - a property that holds at all replicas, regardless of failures. Batched operations are supported in Rocksdb to allow referential integrity between keys - where the value associated with a key is a reference to another key. We also use a lightweight batched operation to support snapshots - that can be viewed as an atomic no-op to all keys. We discuss how batched operations are supported by Cyclone later in the paper.

3 Storage

Storage devices such as flash-based SSDs export a block IO interface. Appending a small update to the write-ahead log requires a synchronous access to the SSD. Even with write coalescing using a write cache on the SSD, the round trip time to a current generation NVMe SSD such as the one we use in this paper [5], is of the order of 20 us, limiting the throughput to under 50K ops/sec and resulting in a high baseline latency at even low load (as shown in Figure 1). This problem leads many system designers to under-provision key-value store shards ensuring that it operates at moderate to high load, using group-commit to batch additions to the log. They therefore pay a price in latency to ensure the bandwidth to storage is fully utilized.

Cyclone adopts a different strategy by making use of novel memory technologies to obviate the need to make this tradeoff in the first place. We assume a small amount of non-volatile memory directly addressable by the CPU, rather than being placed behind a block oriented IO interface. Log appendes are done to the “NVM log” placed in this non-volatile memory. However, directly attached persistent memory in the form of NVDIMMs today or new memory technologies in the future [10] will be of lesser capacity than traditional (NAND based) flash available through an SSD. Providing the same capacity as existing flash based logs for key value stores therefore requires us to provide a second level of the log placed on a flash SSD (called flashlog). Entries are drained from the NVM log to this flashlog in conveniently large units that are a multiple of 4KB – the optimum IO unit for flash SSDs. This ensures we get the best possible throughput from a flash device without paying the price of synchronous IO for small key-value pairs. At the same time, the amount of non-volatile memory required is small enough to not add undue cost to the server. This is in contrast to systems like FARM [15] that require both the key value store and write ahead log to be held entirely in non-volatile memory.

The flashlog is written out in segments of configurable size (we use 128KB segments). A segment buffer is prepared in memory (volatile DRAM) using the layout shown in Figure 2. We do not allow objects in the flashlog to cross a 4KB boundary - linking multiple objects together with a special flag encoded into the size if necessary. We flush log segments out to the log file using asynchronous direct IO, and therefore we continue to fill log segment buffers while keeping IO to previously filled buffers outstanding to the flash drive. We allocate enough buffers to keep a maximum of 32 outstanding requests to the SSD. To avoid having to do a synchronous metadata flush, we preallocate (using the posix_fallocate call) a gigabyte worth of zero filled disk pages at the end of the log file whenever we hit its end.

In order to recover from a crash, we make two important assumptions about the underlying SSD. First, we assume that 4KB is the minimum atomic unit for updating pages on the SSD even under power failure i.e. there are no shorn writes (otherwise known as torn writes) on a 4KB page [32]. We also assume that the SSD has power loss data protection mean-
We move log entries from the head of the NVM log to the flashlog buffers in FIFO order. The NVM log entry is only actually removed when the IO for the corresponding flashlog page is complete. This means that during recovery we can have the same log entry both in the NVM log and the flashlog, a condition that can be detected by examining the log sequence number that we embed in each log entry.

In this section we demonstrated how Cyclone uses a small amount of non-volatile memory to improve storage bottlenecks when maintaining a durable log on a single machine. In the next section, we deal with replicating this log efficiently across multiple machines.

4 Network

Cyclone uses the RAFT [29] consensus protocol to replicate the log of operations across machines. Cyclone provides guarantee to the client that any operation responded to is durable and its results available as long as a majority of replicas continue to function. Cyclone’s failure model is fail-recovery, where nodes that can recover from failure simply continue to participate in the protocol. This requires RAFT to persist every log entry before it sends it out for replication and before a follower replica responds to the leader. Storage overheads are therefore not independent of network overheads, and we must deal with both storage and networking overheads simultaneously to improve the performance of replication.

We leverage the two level log from the previous section to remove storage bottlenecks from the critical path of replication in much the same way we did for logging on a single machine. RAFT is only aware of and replicates the top level NVM log. Each replica independently drains committed (in terms of RAFT consensus) entries from the NVM log to the flashlog. Block IO therefore is no longer a consideration when optimizing data movement over the network, unlike systems that need to deal with such problems [21]. The task of replication reduces to that of efficiently sending a block of data already present in directly attached memory over the network.

The core network operation in replication is to receive a request from the client at the leader replica and send that exact same request (as a log entry) to all follower replicas. The leader therefore multicasts a received request packet to follower replicas, a problem well studied in the networking community when building software packet switches. Software packet switches reach impressive speeds of millions of packets forwarded per second [6], a number far in excess of the few thousands of packets we manage in Figure 1. The key insight in removing network overheads in Cyclone is therefore to approximate a software packet switch for the networking component of Cyclone. We do this by implementing Cyclone’s network stack on top of the Data Plane Development Kit (DPDK) [7], that provides low latency userspace access to an ethernet NIC. We discuss Cyclone’s network protocol in Section 4.1.

However, the flow of packets through a software packet switch is usually very simple: the packet enters through an ethernet port and after a simple (usu-
ally stateless) decision is sent out through a set of chosen ports. In contrast, log replication requires a complex protocol state machine to decide what to do with the packet. In addition, unlike software switches we cannot simply forget a packet after transmitting it. We must append it to the log and act on it after consensus is reached by a majority quorum. In Section 4.2 we cover the techniques we use in Cyclone to ameliorate these overheads.

4.1 DPDK

The Data Plane Development Kit [7] provides low latency userspace access to an ethernet NIC, permitting the application to directly send and receive raw ethernet frames via the transmit and receive queues on the NIC. DPDK is often used by developers of software packet switches and therefore we leverage DPDK as a library for building Cyclone.

DPDK does not by itself provide a TCP stack. But this is not a problem, since RAFT (and indeed most consensus protocols) tolerate network losses and reordering by design due to the need to support asynchronous communication. In addition, most datacenter networks rarely drop or reorder packets and provide full bisection bandwidth between servers that might serve as Cyclone replicas. We therefore jettisoned TCP and chose to send raw IP packets encapsulated in ethernet frames. Cyclone takes complete control of an ethernet interface, receiving all packets directed to it, while the IP and ethernet addresses provide sufficient information to route the packet if necessary through multiple switches. We currently follow this communication model both for server to server communication between replicas as well as client to server communication for requests and responses. Although a detailed evaluation is made later, switching from the kernel TCP/IP stack to DPDK reduces the latency between machines in our testbed from 18 us to as low as 5 us, providing a significant boost to performance.

```c
    event_receive_client_req()
    {
        if(!check_is_leader()) {
            drop_msg
            return
        }
        Prepend raft log term and index
        Persist to local log
        Transmit to follower replicas
    }
```

Figure 3: Event handling

4.2 Addressing Overheads

Software packet switches built on DPDK try to touch as little of the packet data as possible, minimizing movement of data up and down the cache and memory hierarchy. Log replication looks like multicast that does not require deep packet inspection. Software packet switches implementing multicast therefore simply manipulate packet headers to produce new packets to send on the output ports. We designed our implementation of the RAFT protocol based on the same principle.

The pseudocode in Figure 3 describes part of the packet handling code in Cyclone organized as event handlers triggered on receiving a packet at the leader. We focus on only one key event for brevity: the event where a request is received from a client. The first step is to check that this replica is indeed the RAFT leader in the current view (term). If not, the message is simply dropped (a timeout causes the client to try a different server). It then prepends RAFT related information to the packet - this includes the current term and log index for this entry. Next, it appends a pointer to the log in Figure 5 effectively appending the packet to the persistent log. Finally, it transmits the packet to follower replicas.

This entire process is done without making any copies of the received packet. Figure 4 illustrates how Cyclone manipulates packet layouts across the two steps of prepending a RAFT header and transmitting to follower replicas. DPDK describes packets using an “mbuf” data structure. Roughly speaking,
an “mbuf” consists of a flat array of bytes actually containing the packet and a fixed size piece of external metadata that describes various aspects of the packet, most crucially a pointer to the start and end of the packet in the byte array. DPDK’s userspace drivers receive packets from the NIC such that they are offset in the byte array by a configurable amount referred to as “headroom”. We strip off the existing network headers in the packet and prepend RAFT related information specific to each log entry in the headroom by shifting the start pointer appropriately. These operations are standard enough for software packet switches that DPDK provides convenient library calls for it. For the final step, we need to prepare the packet for transmission to the various follower replicas. To do this we prepare a different packet containing a network header for each targeted replica and “chain” the data packet to each of these headers. Each header is then separately handed off to the driver for transmission via the NIC, carrying the data packet with it by association.

We direct DPDK to use pages backed by NVM for packet buffers. DPDK uses a concurrent memory allocator based on reference counting - used by both the NIC driver and CPU cores. This means that packet allocation and deallocation does not happen in the same order as their corresponding position in the replicated RAFT log. To deal with this, we use a level of indirection as shown in Figure 5. The NVM log is maintained as a circular log of fixed sized pointers to the actual packets. Adding a level of indirection in the NVM log allows us to separate the FIFO ordered circular log being manipulated by RAFT from packet data being managed by the memory allocator of DPDK. Both the circular log and packet data are in
NVM. An advantage of this scheme is that it makes recovery from NVM easy – appends to the circular pointer log are atomic and we can use the pointer log to recover allocator state i.e. what pieces of NVM are currently in use by the log.

RAFT requires that the log entry be persisted before it is multicast out to follower replicas. DPDK userspace NIC drivers operate in DDIO mode \cite{8} where the packet is directly written into the CPU cache rather than first being DMAed into DRAM and then fetched by the CPU on demand. We need to persist the packet to directly attached NVM by executing a cacheline flush (ciflush) instruction for every cacheline in the packet and the pointer in the pointer buffer to persist these via the memory bus. This is not too onerous a burden because we can use the newly introduced clflush-opt \cite{1} instruction specifically intended to efficiently flush to persistent memory without the overhead of the serialization normally introduced by clflush. This allows us to hit full memory bandwidth on current generation platforms, a quantity in excess of 200 Gb/s per core which is well above the near term speeds of commodity NICs. We execute a single serializing sfence before the sequence of clflushes to make sure any dirty cachelines due to header manipulation related writes from the CPU are sent to cache.

Although RAFT is an efficient consensus protocol in the common case, the protocol state machine still adds significant overhead to each packet, relative to the time for the packet to flow in from the NIC and back out to the replicas. We address this problem for the loaded case using batching - treating a whole sequence of client commands as a single RAFT log entry, while avoiding any copies to group these packets together. Figure 6 illustrates how this is done. We use a burst receive call available in the DPDK userspace driver to receive a burst of client packets at a time. We then chain these packets together and treat them as a single log entry from the perspective of RAFT, amortizing the control plane overheads over the packets (at most 32 at a time due to current driver limitations). Crucially, batching in Cyclone does not involve a latency-throughput tradeoff like in many other systems \cite{13}. The batch receive call we use in DPDK returns immediately with whatever number of packets is available, including zero. We always flush the transmit buffer after every call to DPDK to transmit packets to replicas. Therefore, we never tradeoff latency for throughput when batching. We also receive log entries in batches at follower replicas and return a single acknowledgment for the entire batch, speeding up the progress of the protocol.

Our choice of RAFT as a consensus protocol is driven by the need to efficiently maintain the log datastructure. Unlike alternatives such as MultiPaxos \cite{23} or Quorum based replication \cite{17}, the leader is guaranteed to have the most up to date logs. There is therefore no case where a leader needs to receive log entries to “fill” holes in its logs from follower replicas, simplifying the protocol state machine we need to implement. A leader can immediately reject any responses that are not at least as current as its view (term). In turn, the persistent log operates as a double ended queue, with entries either being appended (or possibly deleted at followers) at the end and being deleted from the front (after commit). This is critical to efficient operation of Cyclone, as it allows a simple top level structure (a circular buffer of pointers) to represent the log.
5 Parallelism

Although the work described in the previous section significantly boosts the network performance of replication in Cyclone, it still does not come close to saturating the capabilities of even the commodity NICs that we use. This is because NICs today encapsulate significant parallelism in terms of multiple send and receive queue pairs. Exploiting this capability to improve throughput requires us to remove the bottleneck of a single sequential log in RAFT. To this end, we extend the implementation described thus far to run multiple copies of the RAFT consensus protocol each maintaining and replicating its own two level log. We refer to these logs as physical logs. All these instances however exist in the same process address space as the key value store application itself and therefore manipulate the same application. The number of instances is a fixed property of the Cyclone service and cannot be changed after startup.

The first question we deal with is – how do Cyclone clients decide which physical log to send a request to? The guarantees from Cyclone (except batched writes) cover ordering of updates to a single key (Section 2). They can be satisfied by ensuring that all reads and writes to a key go to the same physical log (i.e. RAFT instance). We achieve this by hashing the key to select the physical log.

Multiple physical logs in Cyclone operate in a shared nothing manner by partitioning the NVM and SSD space evenly between them and by allocating dedicated NIC queue pairs to each instance of RAFT. This works well because the memory hierarchy including the NVM and the SSD efficiently support concurrent operations. The only synchronization necessary is when doing reads or writes to the single shared key value store. The level of concurrency therefore is constrained only by the concurrency available in the software architecture of the persistent key value store itself, for which good designs exist [12].

5.1 Ganged Operations

Using multiple instances of RAFT leads to a serious problem with batched operations, since we need to split up the batch into a mini-batch for each of the physical logs. There is however no guarantee that the request for a mini-batch will succeed breaking the atomicity requirement for batched updates. The obvious and simple solution is to do two phase commit across the logs, ensuring all or nothing semantics. However this was unacceptable to some customers who pointed out that ensuring that an external co-ordinator implementing two phase commit does not itself fail requires running a separate replicated service - with its attendant resource and reliability headaches. We were therefore challenged to come up with a solution that did not require two phase commit.

Our final solution is based on two observations. First, we do not require that either all mini-batches commit to their raft logs or none do. What we actually requires is that either all are applied to Rocksdb or none of them are. Put another way we should not apply a mini-batch from a ganged operation if any of the other mini-batches have failed to commit to their RAFT log. This means that the client can be stateless. The second observation is that checking whether the other minibatches have committed is easy because the different RAFT instances can communicate through shared memory on the same machines unlike the more general case of distributed participants in two phase commit.

We now describe our solution called “ganged operations” in Cyclone. The first key problem we need to deal with is that the leaders for the different RAFT instances to which the keys map can be located on different machines. To avoid having a client co-ordinate different machines for a single operation, we constrain the RAFT leader election algorithm for the different RAFT instances to converge to the same machine. We do this by triggering re-elections for a RAFT instance other than that of the first physical log until it is on the same machine as the first physical log. This process is therefore resilient to failed ma-
RAFT requires that the leader have the most up to date log. To ensure that the process converges we therefore ensure that the currently elected leader brings a majority quorum up to date before triggering a reelection. We also do not accept any requests from clients until all leaders are co-located. We assume that no network partitions occur within a machine i.e. some RAFT instances are able to send and receive packets, while others are not, a possibility we discount due to our single process design.

Next, we need to simultaneously inject the ganged operation into all participating physical logs on the machine hosting the leaders. Clients always dispatch batched writes to a fixed co-ordinating physical log/RAFT instance (henceforth called the co-ordinator), which is then responsible for forwarding the request to the participating logs. We make use of packet cloning primitives to avoid making physical copies of the packet, generating indirect references instead. The co-ordinator also adds a “nonce” - a unique timestamp to the packet. In addition, the co-ordinator adds a unique view number to the packet containing the term numbers of all the participating RAFT instances (read from shared memory of the co-located leaders). The event that applies a ganged operation is described in the pseudocode of Figure 7. We defer the discussion of how we generate the nonce to later in this section. We also assume that a unique barrier is allocated in shared memory for each ganged operation. We discuss later how this is done without using dynamic allocation.

The complexity in Figure 7 arises from the need to handle both shared memory concurrency and failure during replication. Without failure, Figure 7 is straightforward. A barrier is executed on all RAFT instances. Once replication is complete on all participating physical logs, a state indicated by all necessary bits being set in the barrier mask, the RAFT instances simultaneously execute the ganged operation.

A failure causes a new leader to be elected for the affected physical log, moving forward the term. If the participants of a ganged operation do not detect this case, they could be left waiting forever. We detect failure on any RAFT instance by having each instance publish its current term and continuously comparing the view in the ganged operation to it. If any RAFT instance has moved past that term, the ganged operation is then terminated.

The assumption in Figure 7 is that each ganged operation is mapped to a unique barrier. We achieve this by using a fixed piece of memory owned by the co-ordinator to hold the barrier and write the nonce to it in order to indicate that the barrier is active for the corresponding ganged operation. Participants watch for the nonce to know when to execute the ganged operation barrier in Figure 7 while also monitoring the leader’s published view to detect the case where the ganged operation fails to replicate on the co-ordinator’s physical log.

Finally, we describe how we generate the nonce. The nonce is generated on the co-ordinator RAFT instance by concatenating the ethernet MAC ID of the first NIC on the system with a 64 bit value that is the number of CPU timestamp counter cycles since epoch time (read from the real time clock at startup plus the number of cycles from the CPU rdtsc instruction). The nonce can only be repeated if the same machine manages to fail and come back up in less time than the real time clock drift (controlled with NTP), a possibility that we discount.

Ganged operations possibly constitute the most complex part of Cyclone but the code weighs in at well under a couple of hundred lines. We believe that this additional complexity is still small compared to distributed transactions using two-phase commit - especially when taking into account failure recovery - as used in systems such as FARM [15].

6 Evaluation

We evaluate Cyclone on a 12 node x86 Xeon cluster connected via a 10 GigE switch. Three of the machines are equipped with 1.6TB Intel DC P3600 SSDs and 4*10 GigE ports. The remaining nine machines do not have SSDs and have only one 10 GigE port,
/ Apply ganged operation
event_apply_ganged_op (packet, barrier)
{
    if(co-ordinator)
        atomic set bit me in barrier.mask
    do
        for each participant p in operation
            if public_data[p].view > packet.view
                barrier.failed = true
                atomic set bit for p in barrier.mask
        while barrier.mask != mask of all participants
            if barrier.failed
                send retry to client
            else
                execute operation
                send response
    else
        wait until
            public_data[co-ordinator].view > packet.view OR
            barrier.mask == mask of participating cores
        if public_data[co-ordinator].view > packet.view OR
            barrier.failed
                send retry to client
        else
            execute operation
}

Figure 7: Ganged Operation
serving as clients for most of the experiments. We turn on jumbo frame support in the 10 GigE switch to enable maximum use of batching in Cyclone. As with other work [20], we use DRAM on the machines to proxy for NVDIMMs where necessary - the NVM needed never exceeds 64 MB regardless of the size of the key value store or second level log on flash. We divide the evaluation into three parts.

First, we evaluate Cyclone’s performance with a single level log as a pure software packet switch. For this purpose, Cyclone uses a dummy server stub that simply echoes the client request back to it. Next, we evaluate performance with the dummy stub, but with the addition of the second level of log on flash. Finally, we evaluate performance when integrated with Rocksdb [2] as an alternative to Rocksdb’s write ahead log.

Unless otherwise mentioned, we use a 60 byte header followed by an optional payload for experiments. We log both the header and payload. Also, unless otherwise mentioned we use 8 physical logs (and associated RAFT instances) each mapped to a dedicated core. The remaining cores are dedicated to the stub server or Rocksdb, as the case may be.

We begin by systematically evaluating network stack related optimizations applied in Cyclone to replicate the NVM log in Figure 8 - with no payload. The y-axis reports latency seen at the client (which means two network round trips with replication). Using TCP/IP to replicate a RAFT log tops out at around 30K entries/s. Switching to DPDK (the line marked +DPDK) improves the throughput by an order of magnitude to around 500K entries/s. Using batching (the line marked +batching) improves the performance further bringing us close to a million entries/s. Scaling to 8 physical logs (+8 phy logs) improves performance to close to 2M entries/s. Finally using all 4 ethernet ports on the machine to replicate entries improves performance considerably to 6M entries/s. In all, performance improves by 200X over the TCP/IP single log baseline. Cyclone also considerably improves the latency for replication, from close to 100us with TCP/IP to around 30us at peak throughput.

One can draw three important conclusions from Figure 8. First, one can indeed treat log replication as a software packet switching problem provided the persistent log can be held in directly attached memory eliminating the block interface from the critical path. Second, relieving the CPU from the overhead of data copies has a significant positive effect on performance.

Second, using multiple physical logs is essential to exploiting the concurrency available at the level of the NIC (even a single one!) that would otherwise go wasted due to the serializing abstraction of a single log. Finally, we note that Cyclone achieves about 50% of the line rate across the four ethernet ports. This is essentially the cost of running a consensus protocol in software.

Both the replica count and payload size can have significant impact on Cyclone’s network performance. First, the number of replicas dictates the outgoing message rate from the leader replica and therefore increasing the replication factor can decrease Cyclone’s performance. Figure 9 shows the impact of varying replica count. Using only a single replica cuts out a network round trip and shows the best unloaded latency (10 us) and peak throughput (near 10M entries/s). Adding replicas decreases the peak throughput down to around 2M entries/s with 5 replicas. We note that a number of previous pieces of work [20, 15] use three replicas and therefore we focus on three replicas for the replicated cases we consider below. The second factor that dictates Cyclone’s per-
performance is the size of the log entry being replicated. Figure 10 shows the effect of increasing the payload size from zero to 512 bytes. Peak throughput drops from 6M entries/s to approximately 2M entries/s. At this replication rate, the leader replica needs to transmit data at approximately 30 Gbit/s. Coupled with the cost of network headers all four 10 GigE ports are now saturated and therefore Cyclone hits the network line rate bottleneck at this point. It is worthwhile to compare this to the case with small updates, where running the consensus protocol was a bottleneck to reaching line rate.

We now turn our attention from the network component of Cyclone to the storage one by adding the second level flashlog. We evaluate the impact of adding the flashlog in Figures 11 and 12. The benefit of the second level flashlog is that it lets us keep the same amount of log space as with the flash based implementation, and not limit it to the amount of NVM available in the system. The hypothesis was that batching the movement of data from the NVM log to the flashlog would be sufficient to hide the latency of the block IO device from network speed replication. The results confirm that in terms of latency for the low to moderate load cases, our two level log arrangement is effective at hiding the latency of the NVMe SSD. The picture however is different for peak throughput. For small updates there is no impact on throughput when we add the SSD. On the other hand Figure 12 shows that using a 512 byte payload has a significant impact on peak throughput - it drops to approximately 350K ops/sec. This corresponds to around 50K 4KB IOPS to the SSD to write out the flashlog pages. This is in fact the expected IOPS limit with the 32 outstanding requests to the drive that we maintain (Section 3). A final observation on Figure 12 is that once we are past the storage bottleneck the latency spike is dramatic and large enough to trigger Cyclone’s failure detector and repeated retries from the clients. There are therefore no points on the “knee” of the curve as in the pure packet switched one-level log case.

One can therefore conclude that using a small amount of directly attached NVM is effective at hiding the latency of a background block storage device from the critical path of replication. Further, for small updates the bottleneck is the capability of the software to run...
the consensus protocol, but the bottleneck shifts to the secondary storage device for larger request sizes.

We now evaluate ganged operations. The primary purpose of ganged operations is to avoid the need for distributed transactions to manipulate what is a single shared memory image and therefore we were most concerned about unloaded latency given the complexity of synchronizing different replication quorums as well executing our rendezvous protocol on multiple cores. We therefore setup an experiment where a single client – reflecting the unloaded case – made ganged requests to the replicas. We varied the number of physical logs participating in the request from one to the full complement of 8. Figure 13 shows the results. Unloaded latency increases slowly as we increase the number of active physical logs - to around 32 us from the baseline of 21 us. The reason for this increase is that the DPDK userspace NIC driver pipelines request processing for communication between the CPU core and the NIC. Simultaneous replication on multiple physical logs represents a worst case for this arrangement as all eight cores try to send replication messages to their replicas, adding about a microsecond of serial latency each, to dispatch requests to the NIC. Regardless, the experiment underlines the value of our ganged operation design over a distributed transaction that would need 8 network hops for the two phase commit (and replication) using an external co-ordinator, a minimum of 80us.

Next, we evaluate Cyclone integrated with the
Rocksdb persistent key value store. Rocksdb is a complex commercial grade persistent key value store and an important target for practical use of Cyclone. Rocksdb is accompanied by a complex array of performance tuning knobs to get the best performance from flash. Designing LSM tree based key value stores to extract good performance from flash and make best use of DRAM on the machine is an area of active research [12, 11]. One of our main goals is to demonstrate that our conclusions will apply even as Rocksdb performance continues to improve with the integration of new ideas and better SSDs. Keeping this in mind, we configured RocksDB to place all files for the key value store (SSTables) on a RAMdisk, which presumably represents the limit in performance for both software enhancements as well as improvements to flash-based SSDs. However, both Rocksdb’s own write ahead log and the alternative of Cyclone’s second level flashlog are placed on the SSDs. In effect we make availability a harder problem in this setting to ensure that our design is future-proof.

For the first experiment with Rocksdb we use 8 byte keys with either 8 byte values or 256 byte values. Since our focus is replication and only update requests are replicated, we use a 100% update workload to test the capability of the system. This involves loading 100 million key value pairs and during the test updating the value associated with a key picked at random.

Before evaluating with Rocksdb, we measure the baseline performance of replicating the log with Cyclone for the given request sizes - Rocksdb performs a no-op. We note that in addition to the key and value, we are also logging RocksDB specific request data such as operation type and the request header, making this different from the previous experiments. Figure [14] shows the baseline performance for the chosen request sizes. With the smaller request size, Cyclone can conservatively sustain close to a million requests a second at a latency of just under 25us. With the larger request size, Cyclone can sustain around 350K requests a second, again at a latency of just under 25 us. Armed with these baseline numbers we now examine how well Cyclone performs with Rocksdb.

The performance of Rocksdb with Cyclone for the small update workload is shown in Figure [15]—essentially presenting the solution to the problem demonstrated in Figure [1]. We consider four different setups. The line labeled ‘rocksdb’ is the key value store running with no logging whatsoever - a system crash would lead to data loss. The line labeled ‘rocksdb/wal’ is for Rocksdb running with its write ahead logging turned on. The large gap between these two is the overhead of the existing Rocksdb WAL solution. The line labeled ‘rocksdb/Cyclone 1 way’ is a two level Cyclone log but without any replication. The line almost exactly tracks the performance of Rocksdb. Cyclone is able to provide a write ahead log with no overhead to Rocksdb. The line labeled ‘rocksdb/Cyclone 3 way’ is with 3-way replication turned on. Other than a 20us delta due to the extra network round trip, the line almost exactly tracks Rocksdb performance with no logging. Cyclone therefore provides high availability to Rocksdb at a fraction of the cost of its existing single machine write ahead log. We also repeat the experiment for the larger update size in Figure [16]. The conclusions are identical: Cyclone solves Rocksdb’s write ahead logging problem.

Next, we consider the problem of supporting Rocksdb’s write-batch operation that atomically writes a set of key-value pairs into the KV store. This is a practical application of ganged operations in Cyclone. In order to perform the operation with Cyclone...
managing the log, the client must issue a ganged operation across physical logs owning the keys in the write batch. A key concern here was whether Cyclone would add any latency to the operation due to the extra synchronization needed across replication quorums (shown in a previous experiment). We examine the problem for the unloaded case and small updates in Figure 17 for a single client with increasing number of keys in the batch (up to 32 keys). The line labeled Rocksdb is with no write ahead logging. We note an increasing latency for this baseline indicating Rocksdb itself takes longer with larger key batches. The existing option of Rocksdb/wal has considerably larger latency. Cyclone does an effective job of cutting down on this latency even as it needs to pay a price for synchronizing multiple physical logs. Cyclone therefore provides effective replicated logging for batched operations using the idea of ganged operations, while scaling the performance of single operations using its multiple physical logs.

Our evaluation has, thus far, focused on synthetic write heavy workloads. To illustrate that Cyclone can also be useful for real-world read-heavy workloads, we configured our clients to generate key value requests that mimic the distribution of value sizes in Facebook’s ETCD trace [10, 27] and are read heavy (95% reads). We use weak reads in Cyclone to avoid the extra round trip for quorum reads. Figure 18 illustrates that even with a read dominated workload, Cyclone is effective at providing a write ahead log with 3 way replication with a lower performance overhead than Rocksdb’s own write ahead logging. We consider the case of another real-world workload that is more write intensive (at 80%) and with a smaller range of value sizes – derived from Facebook’s VAR trace [10, 27], in Figure 19. One can similarly conclude that Cyclone provides more functionality (replicated write ahead log) at a far lower performance penalty that Rocksdb’s existing single machine write ahead log solution.

Finally, we showcase the benefit of using Cyclone beyond pure performance as compared to the existing single machine Rocksdb write ahead log. Cyclone brings multi-machine availability with the ability to automatically failover. We demonstrate this in Fig-
Cyclone takes a software only approach to improving replication performance using commodity network hardware. In contrast, Mojim [31] pairs directly attached persistent memory with RDMA to replicate persistent data structures. None of the evaluated modes of Mojim provide any means to keep more than two replicas in strong synchronization and therefore its guarantees are weak compared to Cyclone. Further, Mojim’s claim that “Paxos-like protocols” require two networking round trips and are therefore somehow inefficient compared to mirroring is not true. For instance, we have demonstrated with Cyclone, where the leader responds as soon as it hears back from a majority quorum, that the critical path to replication is just one network round trip. We can compare Mojim’s replication performance to Cyclone for the case where we use only the NVM log in Cyclone. On 40Gbps Infiniband, Mojim reported being able to mirror data at 4GB/s. In contrast, Cyclone can replicate data three ways using 4*10 Gbps commodity ethernet NICs at roughly 3.7 GB/s. Note that this result is with Cyclone running the provable RAFT consensus protocol, while Mojim is doing simple mirroring of main memory. One can conclude that network offload via RDMA and Infiniband is not an a-priori requirement for high throughput replication. This is made possible by Cyclone’s approach that relieves the CPU from the burden of data copies. On the other hand, the latency of a hop on commodity ethernet at 5 us with our DPDK stack is larger than the close to 2us latency with Infiniband. Depending on the use case for the key value store application the extra 6us with ethernet for the round trip to the replica might be a concern for some. We note that mapping the commutativity of key value store
interfaces to multiple logs in Cyclone is a technique that can also be applied to RDMA. Mojim confirms that concurrency is a significant determinant of performance when replicating over RDMA.

Consensus in a box [19] implements the Zookeeper atomic broadcast protocol together with a NIC on an FPGA. That work ignored durability, focusing purely on network performance for replication. Latency is excellent due to the fact that FPGA cuts out the path from CPU caches to the NIC. The authors report latency as low as 3us for a round trip from leader to follower replica, compared to the 6us we observe with DPDK. Notably however they reported 7us when using TCP/IP from the FPGA rather than their own connection oriented network protocol. On the other hand their peak replication throughput is 4M replications/sec on 66 Gbps of aggregate network bandwidth for small messages, comparable to the 6M replications/sec mark obtained by Cyclone on an aggregate 40 Gbps of network bandwidth when also persisting the log on the SSD. We believe the general applicability afforded by our software only approach together with the fact that we provide persistence by design makes it a compelling alternative to an FPGA based solution, even given the larger latency. Also, these results demonstrate that a general purpose CPU core can be as efficient as an FPGA in running a consensus protocol using the techniques described in this paper.

DARE [30] implements state machine replication over RDMA, using a custom replication protocol. DARE does not consider persistence in its design. It is worthwhile to point out that since DARE allows any replica to become the leader it requires a log adjustment protocol for the leader to bring its logs up to date, a situation we avoid by using RAFT as described in Section 4.2. Using 40 Gb/s speeds, and 3-way replication DARE reported being able to replicate 500K requests/sec. This is without persisting the log of updates. In contrast, Cyclone replicates upwards of 6 million similarly sized requests per second with 4*10 Gbps ethernet (without the second level flashlog). DARE reports an unloaded write latency of 15us, which is lower than the unloaded write latency of Cyclone at 20us, thanks to Infiniband. The conclusions we can draw are similar to the comparison with Mojim: a carefully implemented log replication system obviates the need for network offload when doing replication.

CRANE [14] is a system for replicating multithreaded programs using Paxos. It uses deterministic multithreading to ensure replicas converge to the same state as opposed to semantic equivalence in Cyclone using API commutativity. CRANE reports around a 2X slowdown for MySQL, likely rendering it unsuitable as a replacement for the write ahead log in key value stores.

Database practitioners have considered the utility of byte addressable non-volatile memory in improving logging for databases [18]. However, that work proposes placing the entire log in NVM, presuming sufficient availability of such memory. It also does not consider replication.

Cyclone does not provide exactly once semantics as we believe that exactly once semantics are better provided by the key value store itself by persisting necessary request markers - as done in systems such as Kafka [9]. A possible direction of future work however is to add exactly once semantics to Cyclone’s client-server protocol to serve as a building block for distributed transactions across key-value shards, each running Cyclone, in a manner similar to other systems [25].

8 Conclusion

Cyclone shows how one can leverage a small amount of non-volatile memory to address two fundamental difficulties in adding high availability to persistent key value stores. First, Cyclone avoids paying the cost of the block IO interface for every update operation. This removes block IO latency from the task of appending updates to the log as well as sending it out over the network for replication. In turn, this enables us to apply software packet switching techniques and concurrency to improve the performance of replication, and making full use of available re-
sources when replicating log entries over the network. By optimizing the storage and network components simultaneously, Cyclone enables high availability to persistent key value stores without compromising on their performance.

Cyclone is available as open source software at: https://github.com/sdulloor/cyclone/

References

[1] http://www.snia.org/sites/default/files/AndyRudoff_Processor_Support_NVM.pdf 2015.

[2] http://rocksdb.org/ 2017.

[3] http://leveldb.org/ 2017.

[4] https://issues.apache.org/jira/browse/SAMZA-543 2017.

[5] http://www.intel.com/content/www/us/en/solid-state-drives/ssd-dc-p3600-spec.html 2017.

[6] http://fast.dpdk.org/doc/perf/DPDK_16_11_Intel_NIC_performance_report.pdf 2017.

[7] http://dpdk.org 2017.

[8] http://www.intel.com/content/www/us/en/io/data-direct-i-o-technology.html 2017.

[9] https://www.confluent.io/ 2017.

[10] Berk Atikoglu, Yuehai Xu, Eitan Frachtenberg, Song Jiang, and Mike Paleczny. Workload Analysis of a Large-scale Key-value Store. In Proceedings of the 12th ACM SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems, SIGMETRICS ’12, 2012.

[11] Oana Balmau, Diego Didona, Rachid Guerraoui, Willy Zwaenepoel, Huapeng Yuan, Aashray Arora, Karan Gupta, and Pavan Konka. TRIAD: Creating synergies between memory, disk and log in log structured key-value stores. In Annual Technical Conference, pages 363–375, 2017.

[12] Oana Balmau, Rachid Guerraoui, Vasileios Trigonakis, and Igor Zablotsky. Flodb: Unlocking memory in persistent key-value stores. In Proceedings of the Twelfth European Conference on Computer Systems, pages 80–94. ACM, 2017.

[13] Adam Belay, George Prekas, Ana Klimovic, Samuel Grossman, Christos Kozyrakis, and Edouard Bugnion. Ix: A protected dataplane operating system for high throughput and low latency. In Proceedings of the Conference on Operating Systems Design and Implementation, pages 49–65. USENIX Association, 2014.

[14] Heming Cui, Rui Gu, Cheng Liu, Tianyu Chen, and Junfeng Yang. Paxos made transparent. In Proceedings of the Symposium on Operating Systems Principles, pages 105–120. ACM, 2015.

[15] Aleksandar Dragojević, Dushyanth Narayanan, Edmund B. Nightingale, Matthew Renzelaar, Alex Shamis, Anirudh Badam, and Miguel Castro. No compromises: Distributed transactions with consistency, availability, and performance. In Proceedings of the Symposium on Operating Systems Principles, pages 54–70. ACM, 2015.

[16] Subramanya R. Dulloor, Sanjay Kumar, Anil Keshavamurthy, Philip Lantz, Dheeraj Reddy, Rajesh Sankaran, and Jeff Jackson. System software for Persistent Memory. In Proceedings of the Ninth European Conference on Computer Systems, EuroSys ’14, 2014.

[17] David K. Gifford. Weighted voting for replicated data. In Proceedings of the Seventh ACM Symposium on Operating Systems Principles, pages 150–162. ACM, 1979.

[18] Jian Huang, Karsten Schwan, and Moinuddin K. Qureshi. Nvram-aware logging in transaction systems. Proc. VLDB Endow., 8(4):389–400, 2014.

[19] Zsolt István, David Sidler, Gustavo Alonso, and Marko Vukolic. Consensus in a box: Inexpensive
coordination in hardware. In Proceedings of the Conference on Networked Systems Design and Implementation, pages 425–438. USENIX Association, 2016.

[20] Anuj Kalia, Michael Kaminsky, and David G. Andersen. Fasst: Fast, scalable and simple distributed transactions with two-sided (rdma) datagram rpcs. In Proceedings of the Conference on Operating Systems Design and Implementation, pages 185–201. USENIX Association, 2016.

[21] Ana Klimovic, Heiner Litz, and Christos Kozyrakis. Reflex: Remote flash $\approx$ local flash. In Proceedings of the Twenty-Second International Conference on Architectural Support for Programming Languages and Operating Systems. ACM, 2017.

[22] Leslie Lamport. The part-time parliament. ACM Transactions in Computer Systems, 16(2), 1998.

[23] Leslie Lamport. Paxos made simple. Technical report, December 2001.

[24] Leslie Lamport. Fast paxos. Distributed Computing, 19:79–103, 2006.

[25] Collin Lee, Seo Jin Park, Ankita Kejriwal, Satoshi Matsushita, and John Ousterhout. Implementing linearizability at large scale and low latency. In Proceedings of the Symposium on Operating Systems Principles, pages 71–86. ACM, 2015.

[26] Jialin Li, Ellis Michael, Naveen Kr. Sharma, Adriana Szekeres, and Dan R. K. Ports. Just say no to paxos overhead: Replacing consensus with network ordering. In Proceedings of the Conference on Operating Systems Design and Implementation, pages 467–483. USENIX Association, 2016.

[27] Rajesh Nishtala, Hans Fugal, Steven Grimm, Marc Kwiatkowski, Herman Lee, Harry C. Li, Ryan McElroy, Mike Paleczny, Daniel Peek, Paul Saab, David Stafford, Tony Tung, and Venkateshwaran Venkataramani. Scaling Memcache at Facebook. In Proceedings of the Conference on Networked Systems Design and Implementation, 2013.

[28] Patrick O’Neil, Edward Cheng, Dieter Gawlick, and Elizabeth O’Neil. The log-structured merge-tree (lsn-tree). Acta Inf., 33(4):351–385, 1996.

[29] Diego Ongaro and John Ousterhout. In search of an understandable consensus algorithm. In Proceedings of the Annual Technical Conference, pages 305–320. USENIX Association, 2014.

[30] Marius Poke and Torsten Hoefler. Dare: High-performance state machine replication on rdma networks. In Proceedings of the Symposium on High-Performance Parallel and Distributed Computing, pages 107–118. ACM, 2015.

[31] Yijing Zhang, Jian Yang, Amirsaman Memariipour, and Steven Swanson. Mojim: A reliable and highly-available non-volatile memory system. In Proceedings of the Conference on Architectural Support for Programming Languages and Operating Systems, pages 3–18. ACM, 2015.

[32] Mai Zheng, Joseph Tucek, Feng Qin, and Mark Lillibridge. Understanding the robustness of ssds under power fault. In Proceedings of the Conference on File and Storage Technologies, pages 271–284. USENIX Association, 2013.