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Building Reliable and Secure Replication Service in Distributed Systems

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Abstract

By allowing multiple servers to be consolidated on fewer physical hosts, virtualization technologies are widely used. Nevertheless, consolidation exacerbates the consequence of unexpected host failures. Replication is an attractive way of providing high-availability for virtual machines (VMs). State machine replication (SMR) is an efficient and mainstream approach for replication. It regards the VMs as deterministic state machines that are kept identical by starting them from initial state and ensuring the same requests are applied in the same order.

Our group have implemented a RDMA-based SMR protocol for providing fault-tolerant applications, based on the approach of replicating the execution of the leader application. The main target of dissertation is to embed FALCON into KVM (Kernel-based Virtual Machine) for providing high availability virtual machines. The critical applications running in the virtual machine can be guaranteed available all the time even in the case of hardware failure. Evaluation on three widely used open-sourced databases (e.g. MySQL and MongoDB) shows that this solution has moderate overhead.

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Declarations

I declare that this thesis represents my own work, expect where due acknowledgment is made, and that it has not been previously included in a thesis, dissertation or report submitted to this University or to any other institution for a degree, diploma or other qualifications.

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I also appreciate my friends in Main Building Office 110 and 112. With the accompany of them, the study life seems relaxing and interesting. We create a comfortable working environment, and communicating with them in my leisure time delight me.

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Chapter 1

Introduction

Recently, there has been a wide interest in server virtualization. With more than a decade's development, server virtualization has emerged as a powerful technique in data centers, yet many users still consider it as a new technology. But experts in this area have grown to believe it changes people's life.

Virtualization is used to create one or more Virtual Machines (VMs) that act like real machines in a physical host. Nevertheless, it provides some features which are impossible when constrained within a physical world. While server virtualization has continued to mature and advance itself, industrial corporations are not fully taking full advantages of the virtualized resources.

1.1 Virtualization benefits

There are many benefits adopting a virtualization strategy in data centers. Virtualization facilitates flexible partitioning and dynamic allocation of computing resources. For each VM running in the host, it is just like a resource container who could schedule and execute the tasks by itself.

Multiple resource containers can be consolidated in a single physical server. Running applications in separate VMs on a single physical server cuts down on server waste by making full use of the resources in host. By allocating appropriate amount of CPU, memory resources the VM needs, it reduces various costs including power, space, etc. Since applications are running in an application virtualized environment instead of a native machine, it also becomes possible to run incompatible applications side-by-side.

Virtualization provides isolation which contributes to the security of applications. If one VM contains a buggy operating system, that OS can start scribbling all over physical memory, it is definitely an intolerable disaster. No doubt, virtualization provides the feature of fault isolation by containing these kinds of bugs within the VM boundaries. Furthermore, VM are naturally isolated for each other by running in separate software environments. As most of the issues with computers are complex software configurations such as library versions and viruses, software isolation could enhance the security of these critical applications.

1.2 High availability for VM

Unfortunately, consolidation exacerbates the consequence of unexpected host failures. When VMs are consolidated, failure of a single host may bring down multiple VMs on the host and all applications running inside, resulting in an unacceptable aggregate loss.

Thus, high availability (HA) becomes an essential feature which should be provided by the VM. It requires that VMs build redundancy into architecture layers to mitigate against disasters. Generally, commercial systems tend to use specialized hardware or customized software to realize HA. But surviving failure is notoriously hard and complex no matter which method is adopted. As host failures are inevitable, developing a highly available VM protocol has become a crucial task.

1.3 Primary-and-backup approach

A common approach to provide high availability is the primary-and-backup approach, where the backup server can take over immediately if the primary server fails. As the name suggests, there are always two servers deploying in two different physical machines. Primary is responsible for receiving all the requests from the external network and executing corresponding commands while the backup one is a copy of the primary. The state of the backup server must be guaranteed to be identical with the primary server at all times, so the external requests could be executed in the backup server quickly once the primary crashes. Only in this way the failures are hidden to the outside world and the state remains consistency.

One typical method for replicating VM is to transmit all the changed state of the primary, including CPU, memory and I/O devices, to the backup nearly continuously. Although this approach is straightforward, it may be slow due to the large amount of state needs to be synchronized between the primary and the backup servers. What is worse, it may suffer from inconsistent primary. If the old primary fails and comes back while the backup becomes new primary, it is difficult to determine which one is more up-to-date. It would lead to inconsistency between primary and backup.

1.4 State machine replication approach

Another approach to achieve high availability is state machine replication (SMR). SMR regards the programs as deterministic state machines that are kept identical by starting them from initial state and ensuring the same requests are applied in the same order. It replicates a service on multiple physical servers so that the programs remain available even if one or more nodes fails. As long as the majority of the nodes is running normally, the system can still offer high-performance services.

Compared with primary and backup approach, SMR approach is more efficient. As the programs get exact same input in same order, they can execute same commands and reach to the same state. Therefore, there is no need to transfer the changed state, less network communication is enough to guarantee consistency. In addition, SMR guarantees consistent primary with the mechanism of leader election. There would be only one primary at all times in SMR.

1.5 Challenges of using SMR

Although SMR has many strengths in replication in comparison with primary and backup approach. But it still exists some challenges to use this technique in VM replication.

A naive approach for realizing highly available services is to integrate SMR into all applications running inside the VM. In other words, we can guarantee the high availability of VM by replicating all the server programs. In this way, critical applications' states are all identical with the counterpart in other replicas. VM's consistency can be guaranteed by the consistency of these program servers.

However, SMR is notoriously difficult to understand and implement as integrating SMR into every application involves the modification of source code. No doubt, it would lead to huge workloads for every application requiring replication. Furthermore, for some applications whose source codes are not open-sourced, such as Oracle database and SQL server, it becomes much harder to replicate them.

Overall, the greatest challenge of using SMR approach becomes how to achieve high availability of VM efficiently and conveniently.

1.6 Dissertation contributions

The network device of VM is always emulated by the software rather than the hardware. As the number of hardware network devices in host machine is limited, network device cannot be allocated to every VM. In this case, the network device of VM which is used for sending and receiving network packets is always implemented by the software. They use specific virtual devices to get the packets from the same network interface card (NIC) and forward the packets to the internal VMs. It just seems like every VM has its own hardware NIC but not shared with others.

Our key insight is that SMR can overcome primary and backup's limitation of synchronizing large amount of state. Low bandwidth is enough to transmit the input requests in this process. Meanwhile, intercepting the network packets becomes easy in VM since its network device is implemented with software. Replicating the VM in networking layer seems much more reliable and convenient rather than in application layer.

Leveraging this insight, we present an efficient high availability solution for Kernel-based Virtual Machine (KVM) virtualized environment by using SMR approach in networking layer. With SMR, a virtual machine just runs as is, and SMR helps keep the consistent state across replicas. We intercept the network inputs from the I/O device emulator of KVM and invokes the input coordination component of an SMR system called FALCON to efficiently enforce same sequence on inputs across replicas.

We evaluated replicated VM on three widely used server programs in KVM virtualized environment, including a NoSQL database MongoDB, a key-value store Memcached, and a SQL server MySQL. Our initial results on popular benchmarks show that the proposed replicated VM's performance overhead is moderate (14.7%

overhead on throughput and 17.9% on response time on average). Compared with another VM replication system Remus, the response time is much faster.

The main contributions of dissertation are as follows:

1. The idea of using SMR approach in networking layer for providing high availability to virtual machines.
2. The method of parsing network packets and getting the payload of critical applications in virtual machines.

1.7 Organization of the dissertation

The remaining of this dissertation is organized as follows.

Chapter 2 discusses some related work to achieve high availability of virtual machine, and presents the limitations of these methods.

Chapter 3 introduces the background of KVM and the FALCON SMR system.

Chapter 4 gives an overview of the whole replication system, the architecture of KVM replication.

Chapter 5 describes the implementation details of the replication protocol and the method to integrate the protocol into KVM.

Chapter 6 reports the experiment results of my dissertation. It includes the analytical model, and the performance comparison between normal case and the replication method.

Chapter 7 draws the conclusions of my dissertation and suggests some future works on virtual machine replication.

Chapter 2

Review of literature

Research of Virtual machine replication has been studied for many years both in industrial and academic circle. High availability system that aims to replicate the virtual machine could be implemented by using special hardware or some customized software. Either hardware or software implementation method requires expensive and complex redundant servers. The system could transparently survive failure and provide fault-tolerant servers.

Currently there are three main approaches to implementing virtual machine replication.

The first method for replication is the primary-and-backup approach (It also can be called state transfer approach as it needs to transfer the state of virtual machine.) where the backup server could take over and recover all the tasks when the primary server fails. And the state of the primary server and backup server are identical at all times.

The second one is the record replay. It is supposed that two virtual machines are started at the same initial state and they will receive the same requests at the same order in the coming time. For the deterministic state machines, this approach is viable.

The third method is the lightweight state synchronization approach, in fact, it is the combination of state transfer and record replay. These two approaches actually complement each other and can collaborate get a better result.

In this chapter, I will discuss these three approaches in detail.

2.1 State transfer

Remus is a typical state transfer approach which has been developed for many years. In this section, §2.1.1 introduces the basic algorithm of Remus and §2.1.2 discusses the limitations of this approach. §2.1.3 shows some improvements on the basis of state transfer.

2.1.1 Algorithm of Remus

Remus is a software system that provides high availability for applications or operating systems on commodity hardware. It takes advantage of the method in live migration for virtual machine [1, 11]. Live migration is a feature provided by the virtual machine to migrate a running guest operating system from one host to that of another. Remus extends VM's support for live migration to provide fine-grained checkpoints.

Remus runs VM in an active-passive mode. Paired VMs are deployed in two different physical hosts in local area network (LAN). The active primary VM is responsible for receiving the network requests from the clients while the backup VM remains silent to the external world. By propagating frequent checkpoints of the primary VM to the backup physical host, Remus achieve high availability for virtual machines.

The basic stages of operation in Remus are given in Figure 2.1. This procedure can be divided into six steps: (1) A client established a reliable connection with the primary VM and sends requests to it. (2) Without directly responding to the client, the primary VM buffers these output. (3) After an epoch, pause the running primary and collect all the changed state, including memory, CPU and I/O devices, into a buffer. (4) After that, the primary server resumes itself to forward progress and accept following requests from the clients. Replication engine in host operating system is responsible for sending these changed state to the backup. (5) The backup physical host who receives these buffered state information begins to synchronize immediately. (6) Finally, when a complete, the backup server sends an acknowledgement to the primary which demands it to release the buffered output to the clients.

Different from the network traffic which is visible by external clients, the disk state is invisible. However, as an essential part of virtual machine replication, the disk state must be propagated to backup server just like the memory. In virtual machine, the dirty page memory is recorded by capturing the page fault. Through analyzing the information in fault, the dirty page can be clearly recorded. To maintain disk replication, all writes to the primary disks would be forwarded to backup server, where these writes are stored in memory first. After the changed state has been synchronized to the backup server and the backup responds with an acknowledgement. The primary server releases the output and send a signal to backup. It means the backup server could apply the writes to the disk right away.

The servers can hide the internal issues to the outside world when applying this technique in critical VMs. If the primary fails in this process, to the sight of the external, the state is consistent as no output is made externally visible. The senders just think that previous operations are not well performed in virtual machine and resend them to new primary again.

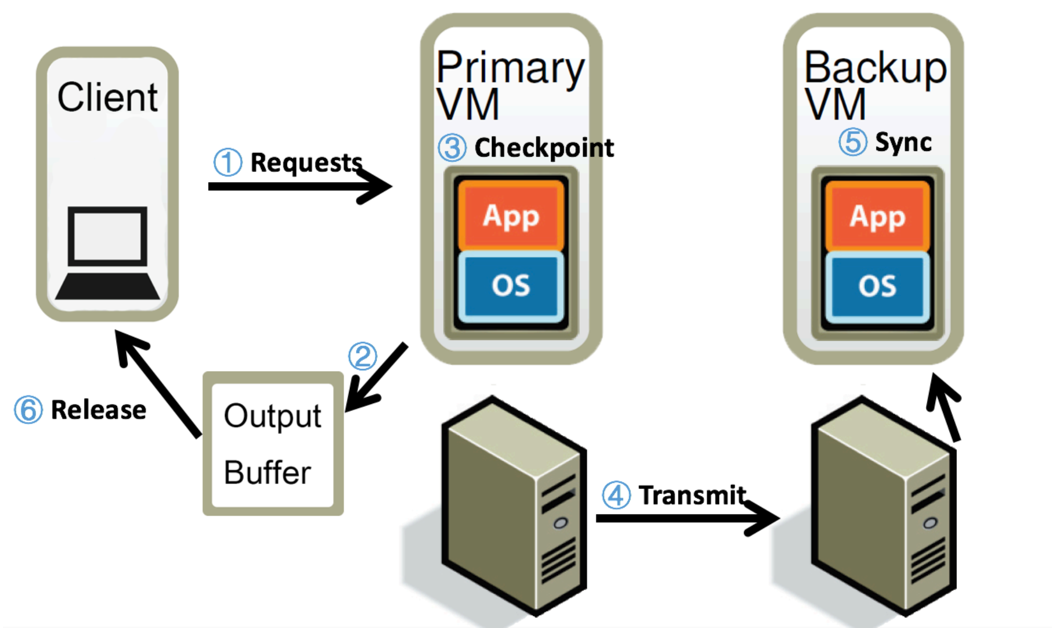

Figure 2.1: Virtual machine replication in Remus

2.1.2 Limitations of state transfer

The primary and backup approach in Remus could effectively replicate the virtual machine and provide fault tolerant VMs. However, this model entails a potentially steep performance cost.

Most importantly, it needs to consume large amount of resources to propagate associated changed state to the backup nearly continuously, especially the dirty page memory. The state synchronization is working with the page-by-page basis and a small change within a page leads to the whole page transfer. No doubt, large changed memory would burden the host machine with state transmission. The underlying flow control is based on a stop-and-go model which is sensitive to the round-trip delay. If the network bandwidth between two host machines is not large enough, it directly affects the frequency of checkpoint.

Furthermore, suspending the virtual machine too frequently reduces the service time of the primary, and in the suspension period, the resources cannot be allocated to other applications, which contributes to the low CPU usage. The suspension will lead to the degradation of performance.

2.1.3 Improvements based on state transfer

The main bottleneck for this approach is the state synchronization of memory. Many optimization techniques have been proposed to reduce the performance overhead associated with transferring modified memory.

Maohua Lu and Tzi-cker Chiueh [24] introduced three optimization methods, namely *fine-grained dirty region tracking (FDRT), speculative transfer* and *active slave*.

FDRT technique is trying to decrease the size of dirty unit. Since the primary needs to transfer the whole memory page in Remus, an obvious method is to accurately identity the regions of modified memory and propagate these regions to backup. The minimum unit in FDRT is dramatically smaller than the memory page size. And the smaller of the dirty block region is, the smaller amount of memory requiring forwarding. The whole procedure involves the calculation of block's hash value, hash value comparison and block memory transfer.

The idea of *speculative transfer* is that a dirty page can be sent to backup as soon as it is modified. There is no need waiting for the suspension of primary and the colleting dirty memory operation can be done at any time. However, it is possible that this method generates many redundant pages when many modifications are acting on a single memory page. A tradeoff between the risk of generating too many unnecessary memory and the benefit of speculative transfer should be balanced.

Active slave proposes the idea to run backup concurrently with the primary. For typical state transfer approach, the backup is passive and never consumes any CPU resources. However, for the active slave approach, both of them receive the same requests and execute the the operations. After a period of time, suspending these two virtual machines and computing the hash value of memory page. In this way, the difference between memory states can be tiny.

For the other improvements, Jun Zhu et al. [34] improved the performance by adding read fault reduction, write fault prediction and software-superpage to the Xen hypervisor. However, the problem of bandwidth occupation is still outstanding. Kemari [30] reduced the bandwidth usage by only triggering synchronization by I/O requests. However, the use case only favors storage services and it uses shared storage, which needs additional effort to avoid one point of failure.

2.2 Record replay

2.2.1 Replica-coordination protocol

Replica-coordination protocol was introduced in 1995, which provided a ground for later work of record replay. The difficulties of implementing replica coordination in the hardware, the operating system and the application programs caused the researchers to explore alternatives to replace them. Use of a hypervisor to implement replica coordination becomes attractive since it addresses all the problems caused by the hardware, operating system and programs. At the same time, hypervisor is a software layer implemented to serve virtual machines. In this way, replica coordination protocol based on hypervisor becomes a replication protocol which is used for achieving high availability virtual machines.

In this protocol, it is assumed that a set of given instructions must have the same effect whether it is executed by the primary server or the backup server. This protocol laid a solid foundation for record replay virtual machine replication.

2.2.2 VMware vSphere replication

VMware corporation embed the replication into virtual machine with the deterministic record replay approach [17]. Like Remus, for the virtual machine which we desire to replicate, we place another backup server on a different physical host. Nevertheless, VMware runs VM in an active-active configuration. It means that both primary and backup receive the input and produce the output in the process of execution. Therefore, the input-output model is extremely different from that of state transfer approach. The basic configuration is displayed in Figure 2.2.

For the input part of the replicated VM, the backup server executes the same input as the primary server with a small time lag. Of course, only the primary server sends and receives network packets. The backup server remains silent all the time and only communicates with the primary server. The communication here means the logging channel in vSphere. To guarantee the backup server executes identically to the primary, we should ensure all the operations must be deterministic. For those non-deterministic operations, they must be executed in the same way.

Apart from the deterministic events in the operating system, there are still many non-deterministic operations requiring synchronization. How to correctly capture all the non-determinism to ensure the execution deterministic is the biggest challenge in this technique. The vSphere provides a log file to record all the non-determinism. When the input is captured by the vSphere, it makes a judgment immediately whether this operation is deterministic. If not, it means the primary needs to provide sufficient information to allow the backup server could reproduce the same state. During replay, the event is delivered at the same point in the instruction stream. VMware deterministic log-replay implements an efficient event recording and event delivery mechanism that employs various techniques, including the use of hardware performance counters developed in conjunction with AMD and Intel.

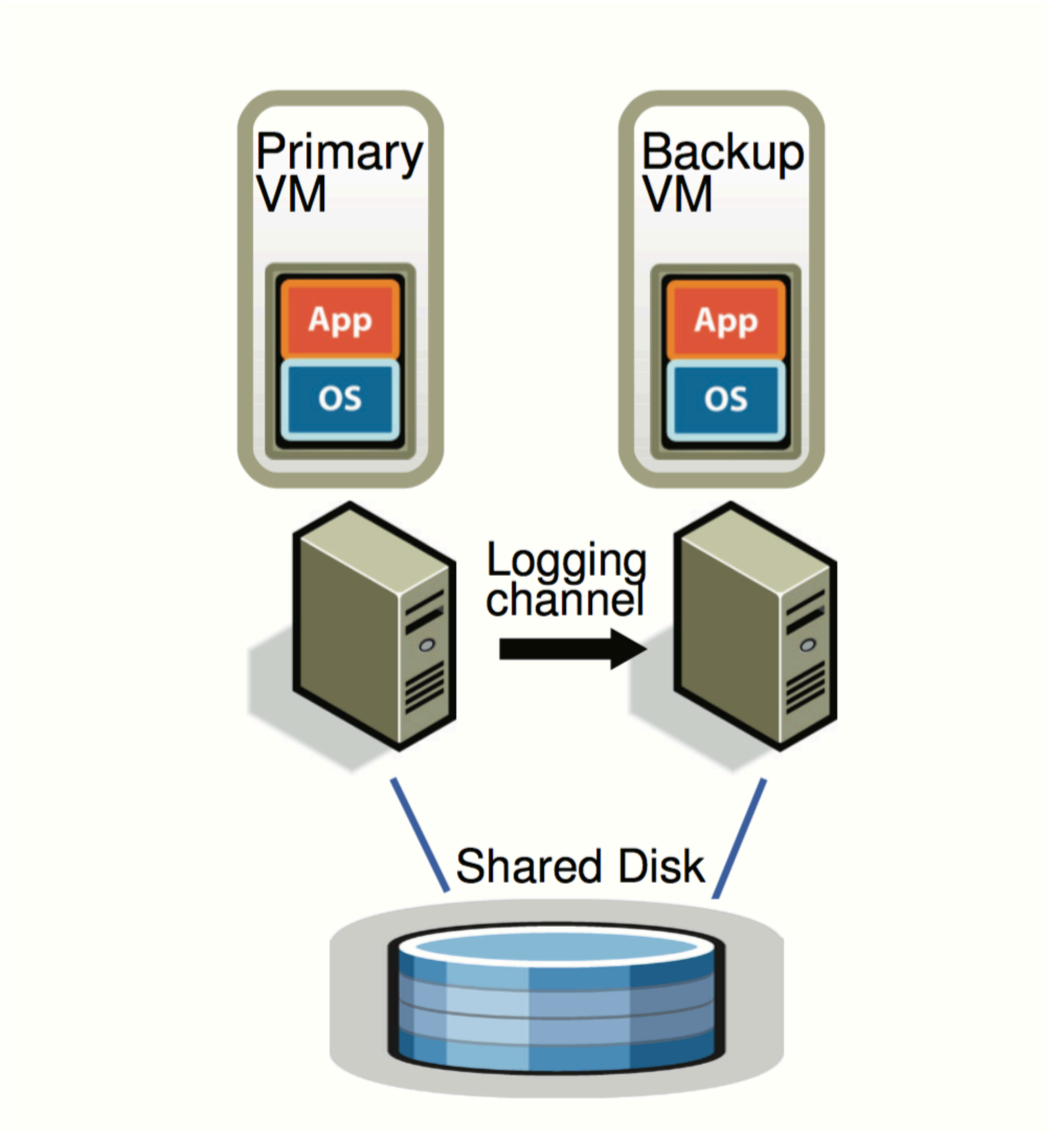

Figure 2.2: Basic fault tolerant servers in vSphere

The output includes write operations to the memory and disk. In order to simplify the output part, VMware utilizes the shared storage to store the disk. Both the primary and backup could read the information in shared disk but only the primary has the privilege to write to it. The primary's output would first be buffered until the backup virtual machine has received and acknowledged the log entry associated with the operation producing the output. The backup's output which should be sent to the clients will be dropped as the primary has already sent to the client side. The architecture of the fault-tolerant virtual machine and the protocol are displayed in Figure 2.3.

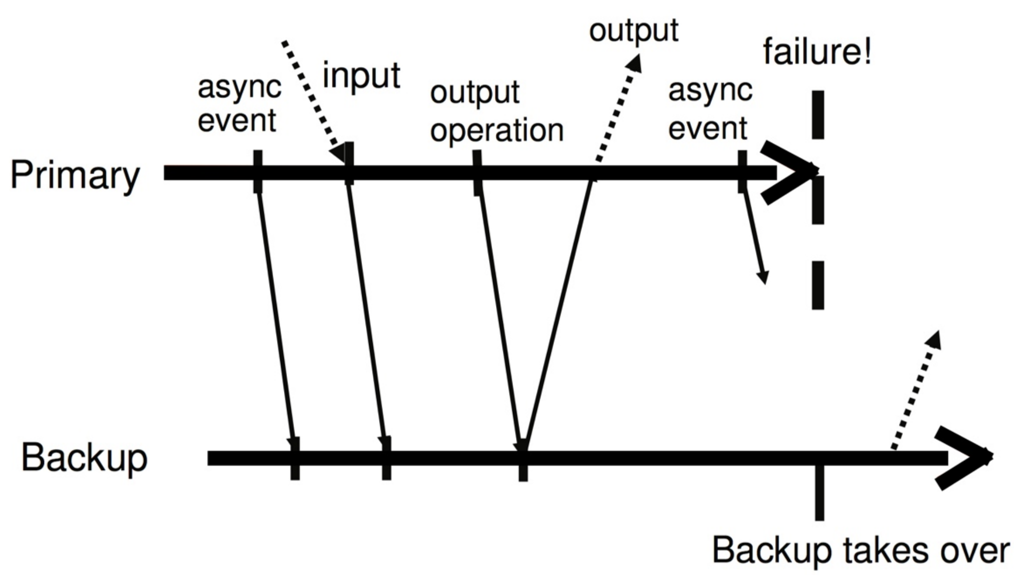

Figure 2.3: VMware replication protocol

2.2.3 Limitations of record replay

It is obvious that compared with the state transfer, the record replay approach is more convenient as it only needs to send small amount of log information. With this log file, the state between two virtual machines are identical with each other.

There is no need to ship all the changed memory which consuming large amount of network bandwidth resources.

However, there are still some limitations for this approach, first of all, as I mentioned above, the record replay approach cannot efficiently resolve the problem of non-deterministic operations. For the non-deterministic operations like clock functions, the primary server must collect enough data to reproduce the same state in backup server. In this way, the developer must know all the non-deterministic operations in advance. Otherwise, the primary server may lose sight of some non-deterministic operations which contribute to the inconsistent between two machines.

Secondly, it cannot support multi-thread in guest operating system. The multi-thread application would produce some concurrency bugs if some codes are not locked when executing. In the virtual machine, multi-thread would account for the inconsistency between virtual machines. The developer cannot ensure the operations in multi-thread applications are executed in the same order. So the results of execution may vary.

Thirdly, this approach has the split-brain problem. It cannot effectively determine which virtual machine is more up-to-date when the old primary fails and comes back while the backup server becomes the new primary. Although it proposes a good method to determine who is the primary by using the shared disk. The shared disk is just like the third party to judge who is the primary like the SMR protocol. However, if the record replay approach is running in two different virtual machines who are not willing to share the disk, the third party decider becomes difficult to find.

2.3 Lightweight state synchronization

Lightweight state synchronization is proposed by our group with the idea of hybrid migration.

The key insight of lightweight state synchronization is that SMR and state transfer approach actually complement each other. SMR can help state transfer approach overcome the limitation of synchronizing large amount of state while state transfer approach can benefit SMR by repairing the divergence of execution states. Leveraging this insight, it is possible to implement high availability KVM by combing SMR and a lightweight state-transfer approach. It could effectively resolve the practical problem of non-determinism.

To detect and repair divergence, it leverages an efficient network output checking mechanism provided by FALCON. It could be implemented by calculating an accumulated hash value by interposing on the server programs' network outputs and the periodically invoking the output checking mechanism of FALCON. If divergence of execution states between replicas is detected, the replicated virtual machine triggers a lightweight state transfer process. This process works by first computing hashes of the changed states, then making an efficient comparison to identity the divergent states and finally transferring them.

To do this, each replica maintains a Merkle tree kept updating from the dirty pages. By "dirty", we mean the memory the memory page has been modified since last synchronization. One problem here is that each VM may have dirtied different pages. This leads to different structures of Merkle trees and they are not comparable. This approach addresses this problem using a fast method as follows (It uses A to denote the diverged replica; it will fetch state from replica B).

1. A sends its dirty page bitmap $M_B$to B.
2. B does a bitwise or calculation $M_{union} = M_A|M_B$, and sends M_{union} back to A.
3. A and B both update their own Merkle tree according to M_{union}. A sends its updated Merkle tree to B.
4. B dose a comparison on both Merkle trees to find the differences, as illustared in Figure 2.5.

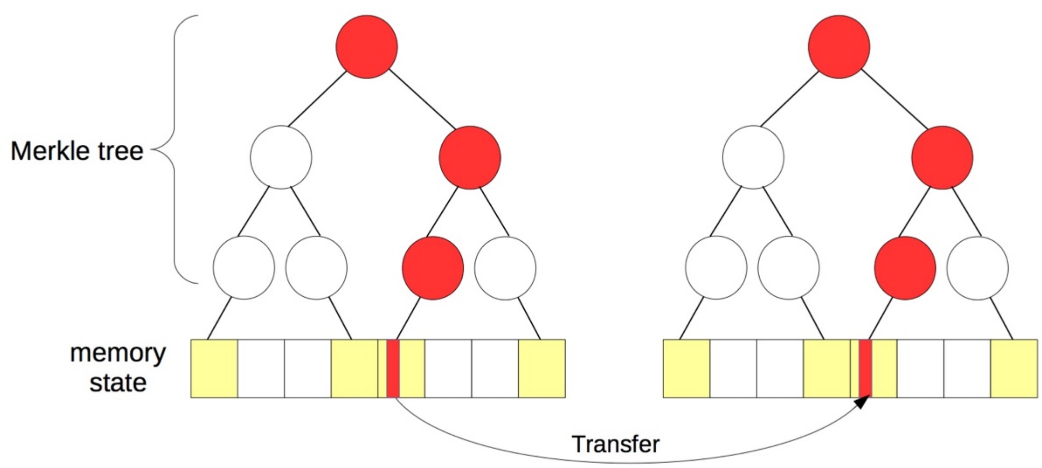

Figure 2.5: Identifying divergent states using Merkle tree. Blcoks in yellow are dirtied memory. Diverged memory state are shared in red. Divergent states can be located by traversing the red nodes of the Merkle tree.

This method is efficient for two reasons. First, it only transfers the different pages between replicas. Because it has made consensus on inputs and it can turn off

Address made consensus Randomization to trade for correctness, the difference rate will be really small. Second, the use of Merkle tree optimizes the time complexity of comparison between memory states to *O(logn)*.

2.4 Summary

In this chapter, we studied the related work on the virtual machine replication. Overall, the research on virtual machine replication is mature. The two types of replication, record replay and state transfer, both has its own pros and cons.

As we mentioned above, VMware integrated the record replay approach into its product vSphere together with several performance optimizations. However, recording the interleaving of multi-core processors and replaying them deterministically still shows large overhead.

State transfer checkpoints the state of the primary periodically and propagates the state updates to the backup. However, the frequent checkpoints may bring in large performance overhead. The propagation of states may take up precious network bandwidth and increase latency to incoming requests.

The lightweight state synchronization approach, which is proposed by our group, although performed better than the other two ones. But the detailed algorithm still needs improving.

Chapter 3

Architecture

This section introduces the architectures of two key techniques used in this dissertation, Kernel-based Virtual Machine, with reference to its network I/O architecture in QEMU-KVM [9] and the FALCON SMR system.

3.1 FALCON

FALCON is a typical kind of Paxos protocol implemented with RDMA library. We run replicas in our cluster where all servers are connected to a switch. Every replica registers a memory for itself and connects with each other using RDMA QPs. And every replica has the privilege to access the memory in other nodes.

We chose FALCON because it is fast and robust. In a FALCON-replicated system, a set of 2f+1 machines (nodes) are connected through an interconnect with support for RDMA. Once the FALCON system starts, each replica would try to establish reliable connections with others. After all the connections are created among replicas, it would elect a leader which proposes the order of requests to execute. An arbitrary number of clients in LAN or WAN send network requests to the leader and then get responses from it.

FALCON is a strong consensus algorithm consisting of four main steps. On receiving network request from a client, the leader node would first intercept the requests and get the real data from relevant packets. The second step is local preparation, add the viewstamp information for this consensus log and write it to a local parallel logging storage on SSD. It would invoke a RDMA-based distributed consensus protocol on this request to enforce that all the replicas see the same input. The last step is the leader collecting the ACKs from the replicas, once it reaches Quorum, it means the consensus is completed. Benefiting from RDMA and FALCON's fast protocol, each consensus process takes less than 10us. Compared with TCP/IP-based Paxos protocol, whose latency was always over 600us, FALCON has the advantage of lower performance overhead.

3.2 KVM

We use Kernel-based Virtual Machine as the platform of our study mainly because of the full capacity of user-space tools in its I/O device emulator process.

KVM [20] is a full virtualization or hardware-assisted virtualization solution for Linux on x86 hardware containing virtualization extensions (Intel VT or AMD-V). It consists of two modules, namely, kvm.ko and an architecture dependent kvm-amd.ko or kvm-intel.ko module. Under KVM, every virtual machine is a regular Linux process handled by the standard Linux scheduler by adding a guest mode execution which has its own kernel and user modes.

KVM becomes the new industry standard in virtualization with multiple operating system support. Its source code has been merged into Linux kernel after version 2.6.20 and a wide variety of guest operating systems could be run in the KVM such as Linux, OpenBSD, Windows and FreeBSD benefit from the full virtualization technique. By comparing KVM with other products such as VMware and Xen, it is easy for us to find KVM could support in more situations and has better performance.

KVM is a kind of hardware-assisted virtualization. From its name, we could know only specific hardware could support this feature. By default, this feature is disabled in the physical machine. As a result, enabling this function needs to reboot and reset the machine. Of course, in the operating system, the relative module should be loaded into the kernel.

3.3 QEMU-KVM

KVM is responsible for the CPU and memory virtualization in physical machine. However, a virtual machine is not only a process possessing the CPU or memory resources. As a matter of fact, KVM also requires a modified QEMU which is located in the user space to provide emulated I/O devices and we call this application QEMU-KVM.

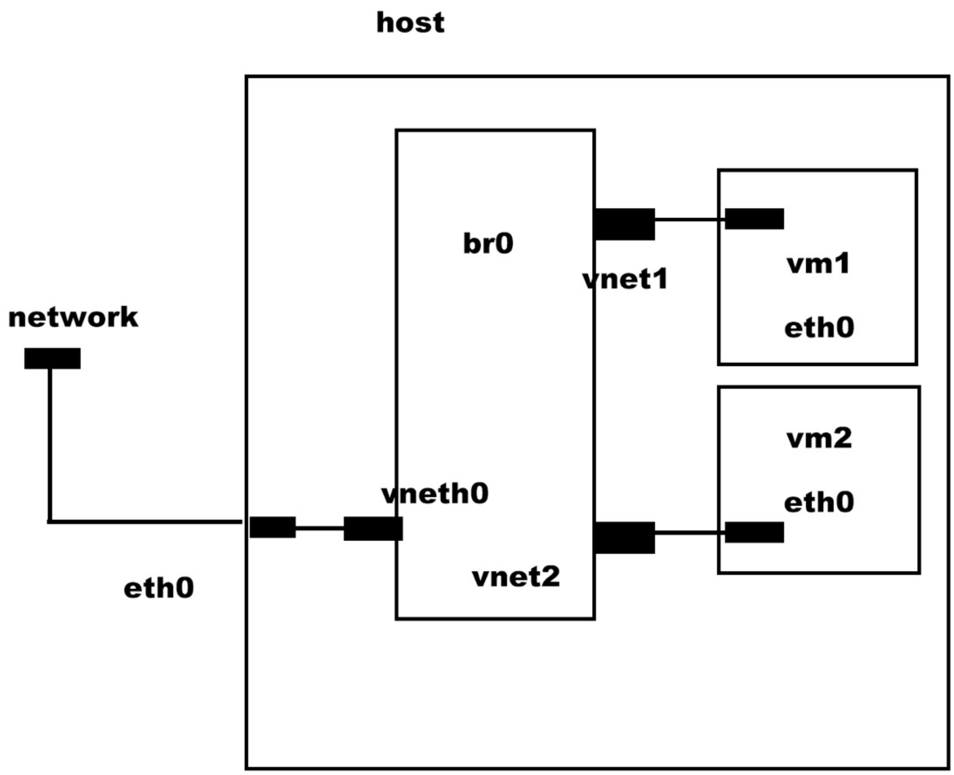

Figure 3.1: The architecture of virtual bridge

In order to make the applications running inside the virtual machine can be accessed by the clients outside the host machine, we install a virtual Ethernet bridge in our host machines. Through binding the host machine's network interface with the virtual bridge, binding bridge with virtual machine's network interface, and allocating a static IP address for the virtual machine, the clients in other hosts could access this virtual machine easily. What is more, when binding an interface with the bridge, the bridge would also require a virtual front end interface to connect with the back end interface in the virtual machine. Figure 3.1 shows the architecture of the virtual Ethernet bridge.

The networking in KVM is implemented in the user space QEMU-KVM application. A typical packet flows through the KVM virtualization host in the following way. When a packet arrives at the physical NIC in the host, interrupts generated by NIC are handled by the physical driver. Then the physical NIC device driver handles the interrupts by transferring the packet to the virtual Ethernet bridge, which forwards the packet to the appropriate virtual machine's front end interface. The front end interface we used in QEMU-KVM is the TAP device which is entirely supported in software. It simulates an Ethernet link layer device which operates the Ethernet frame. The TAP device would create a file descriptor in host machine when we start it. And this file descriptor is responsible for receiving all the frames from the local area network. When the network packet arrives at the TAP device, the TAP device sends a signal to the KVM driver which sends a virtual interrupt to the QEMU in the guest notifying it of the new packet. Once receiving the virtual interrupt, QEMU-KVM delivers the packet to the guest operating system's network stack. The architecture of the whole network flow can be seen in Figure 3.2.

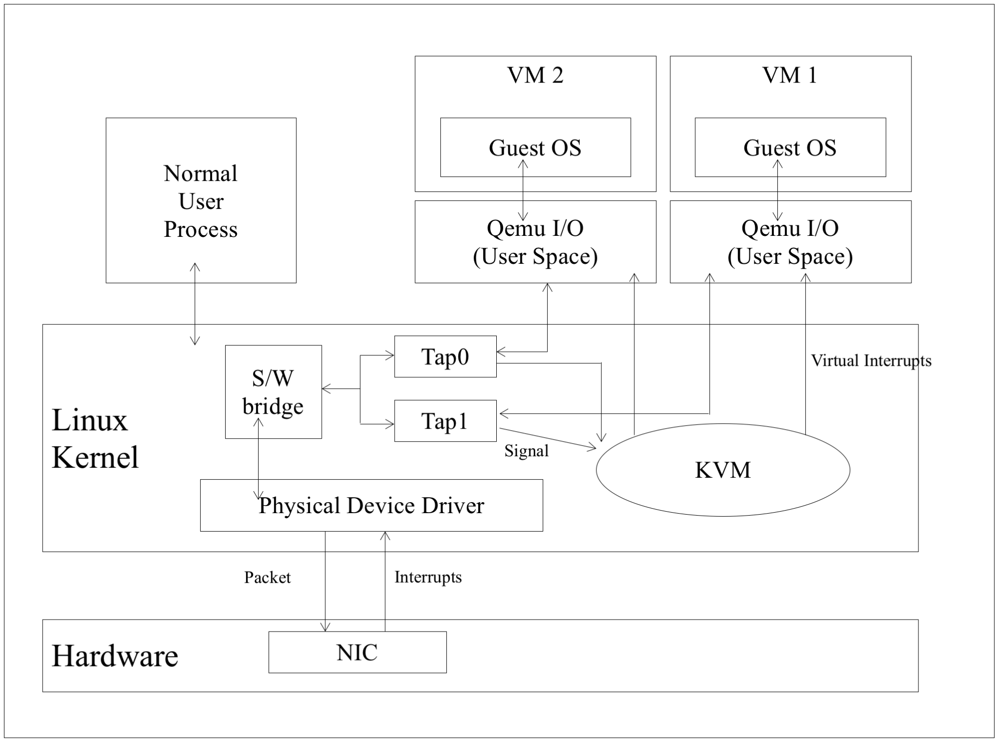

Figure 3.2: The architecture of KVM network

3.4 Overall architecture

Figure 3.3 shows the overall architecture of my dissertation, The QEMU-KVM is responsible for sending and receiving network message including critical applications' network packets. FALCON, the SMR system running in the user space of physical host, plays a major role in VM replication. It intercepts the network packets and forwards them to its counterpart in other machines. The replica's FALCON would send these packets to replica's virtual machine.

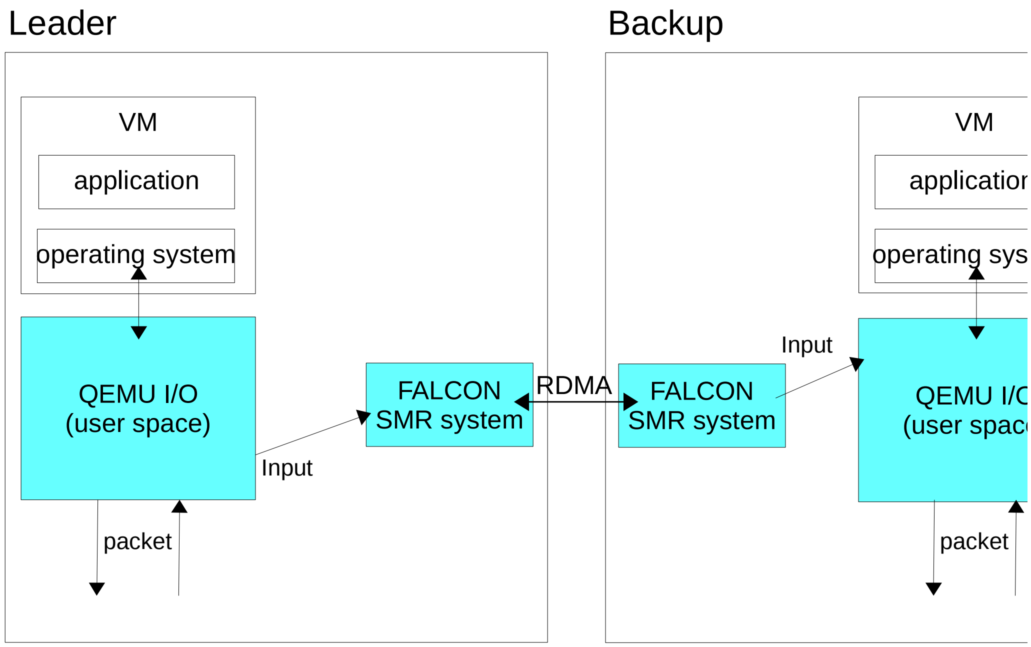

Figure 3.3: Overall architecture of replicated VM

3.5 Summary

In this chapter, we introduce the architecture of this dissertation. FALCON is a RDMA-based Paxos protocol responsible for the input log replication and log replay in replicas. KVM is the platform for us to achieve virtual machine replication while QEMU-KVM is used for emulating I/O devices in the virtual machine.

Through installing a virtual bridge in host and creating a virtual software-based network device TAP for every virtual machine, the network packet can be easily obtained and replicated to other replicas.

Chapter 4

Implementation

In this chapter, we describe the implementation details of the virtual machine replication. We first discuss the process of getting the network packet from the QEMU-KVM. Then, we turn our attention to the steps to get our needed packet the its real data part. Finally, the replication process achieved in FALCON.

4.1 Intercept the network packet

As we mentioned above, we use the TAP virtual network device as the front end interface to receive the network packet from the virtual bridge. So, how can we get the network packet from this virtual network device becomes the most urgent question.

The tap_send() function in QEMU-KVM is called to check whether there is any frame received by the TAP device. And the tap_receive() function is used for receiving frame from the virtual machine. These two functions are jointly concerned with a file descriptor. The details of interception process could be described as follows. The file descriptor is created before the activation of virtual machine. It is responsible for receiving the packet outside the virtual machine. The system call read() would be invoked and return a non-zero value when there is any packet received by this file descriptor. The information of the packet would be written into the memory and read() function would return the length of the packet. Then, the tap_send() function would judge if the length of packet is not zero. If so, it would forward this packet to the virtual machine asynchronously. With adding some code in the tap_send() function, it is easy for us to intercept all the network packet sending from the clients.

4.2 Preprocessing of the packet

As the TAP device is an Ethernet device running in the data link layer, the packet we intercepted contains the information of the Ethernet header, IP header and TCP [36]. The real data part is followed after these headers. To get the real data of the packet, we should understand the structure of Ethernet packet.

Furthermore, not all the packets we intercepted are critical applications' packet. It contains other network packet including ARP, RARP, ICMP and IGMP. It is necessary to distinguish the critical applications' packet from others.

Through printing out the information in the packet, we find the initial 10 bytes of the packet is used for judging the type of the packet for the QEMU-KVM. We call the initial 10 bytes qemu header. So, deleting the qemu header, the rest is a whole Ethernet frame.

The Ethernet header is followed after the qemu header. All the network packet intercepted by the TAP device have an Ethernet packet. So, we could directly get the information from this header without any judgment. The first 6 bytes is the mac address of the destination, destination here, is the virtual machine. The next 6 bytes is the mac address of the source. For the critical applications' network packet, the source means the clients. The following 2 bytes presents the Ethernet type. As critical applications' network packet must have the IP header, we should judge the type of this frame fist. The code Ox0800 in Ethernet type means it is an Internet Protocol, in other words, it is followed by a IP header. We could drop all the other frames except the Internet Protocol's. The structure of the Ethernet frame is displayed below (Figure 4.1).

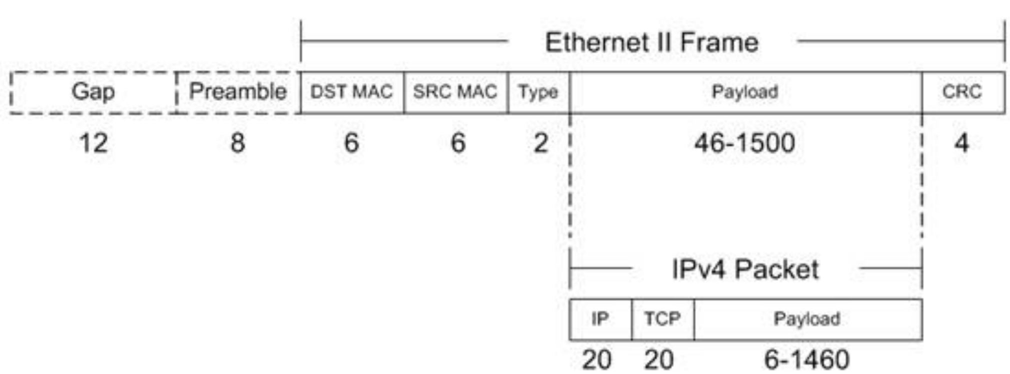

Figure 4.1: Structure of Ethernet header

IP header is much more complex than the Ethernet header (Figure 4.2). It contains lots of essential messages such as IP version, source IP address, destination IP address and time-to-live, etc. Although there are two types of IP headers defined, the virtual machine only includes the IPv4 address. There is no need to consider the IPv6 header. In the IPv4 header, the information we need to get include source IP address, destination IP address protocol and the length of the IP header. For the other information like service type and header checksum, as we cannot get useful information from them, we did not take them into account. First, with the

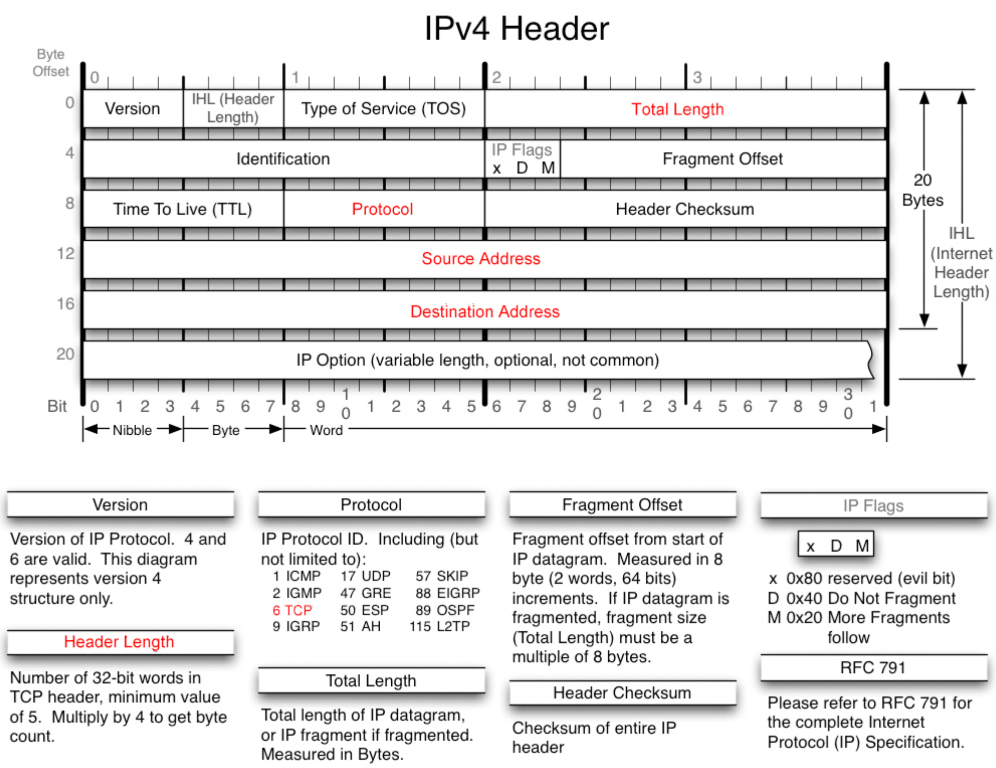

Figure 4.2: Structure of IP header

destination IP address, we could judge if the virtual machine is the single destination of this packet. For the broadcast or multicast message, the destination

IP address would not equal to the IP address of the virtual machine. These packets obviously are not critical applications' packets. Then, the protocol information in the 13 bytes offset of the IP header represents the IP protocol. Here, only the TCP message with the number 0x06 is acceptable. Finally, the IP header may include some options, the length of the header is not constant. It is necessary to get the length of IP header and calculate the first byte address of the TCP header header. The structure of the IP header is displayed in Figure 4.2.

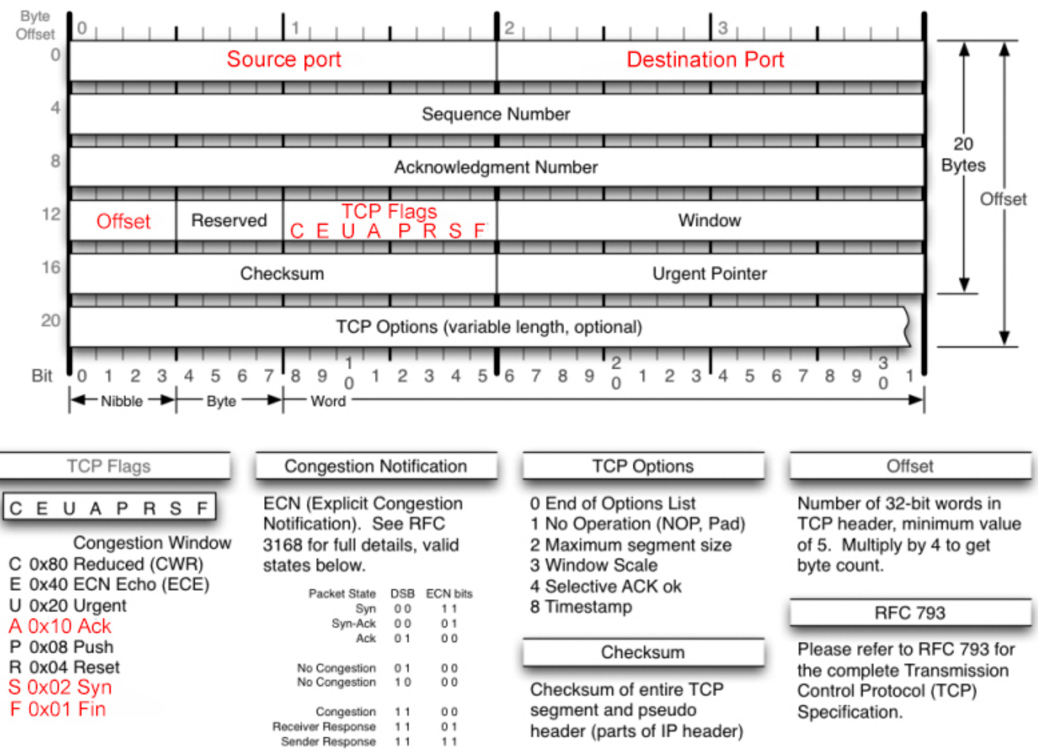

Figure 4.3: Structure of TCP header

TCP is considered as a reliable protocol (Figure 4.3). It checks to see if everything that was transmitted was delivered at the receiving end. And it also allows for the retransmission of lost packets, thereby making sure all data transmitted is eventually received. Due to its reliability, most critical applications prefer to use the TCP protocol to create reliable connections with the clients to exchange the information. Here, we would discuss the structure of the TCP header in detail below, thus, get the information we need for replication.

From the figure, it is shown clearly that the TCP header has 10 mandatory parts, plus a TCP option field. The real data part follows this header. The important fields contain source port, destination port, offset and TCP flags. We should first record the critical applications' ports, only the packets with these ports could be replicated in other virtual machines. As for the source port, it is a good field to distinguish the clients so as to support concurrent connections. The size of the TCP flags is 8 bits. It represents 8 different flags in TCP header. From left to right, they are CRW, ECE, URG, ACK, PSH, RST, SYN and FIN. To make preprocessing simple, we only consider the flag ACK, SYN and FIN. SYN flag means the client wants to synchronize sequence number with the server. This TCP segment is the beginning of connection establishment. ACK flag indicates the acknowledgement field is effective, and the acknowledgement number is set in this TCP segment. This flag has to be set in every packet after the connections between the client and server has been established. Otherwise, this packet would be dropped by the operating system of the virtual machine as it is not a significant packet. The FIN flag is the symbol of disconnection. It means there is no data from the client anymore. These three flags are corresponding to three relative operations in FALCON. The detail will be discussed in the next section. Finally, the offset here is similar with the length of the TCP header. With the offset, we could easily get the first byte address of the real data part. Of course, not all the network packet includes data part, before transporting the data part to the FALCON, we also have to calculate the length of this part. As long as the length is larger than zero, we would forward the address of the data to FALCON.

4.3 Embed FALCON into KVM

To make the whole process simple, Embedding FALCON into KVM could be completed in two steps. Firstly, add the preprocessing codes into FALCON, compile the whole codes and produce a shared library. Then, add this shared library into QEMU-KVM, rewrite the function in it.

4.3.1 Add preprocessing codes into FALCON

As the functions in preprocessing codes would be called frequently, we directly add the codes into FALCON. The three TCP flags are corresponding to three different operations in FALCON. When the SYN symbol is marked in network packet, it indicates a reliable connection is established for the leader. FALCON would forward this message to the replicas and demand the host machine create an identical connection for replicas. When the ACK symbol is marked in network packet, the real data, port of the destination information would be grouped together and sent to the FALCON. The FALCON in the replica side would parse the log and send the real data to the virtual machine in replica through the connection established previously. Finally, the FIN flag would invoke the function deleting the related file descriptor in the replica's host machine, in other words, disconnection operation.

After adding the codes into FALCON, it is of great significance producing a shared memory. With this shared memory, it becomes much easier for embedding the whole FALCON into QEMU-KVM. Declare the function which would be called in the QEMU-KVM in the header file, and add a header file statement in the source code of QEMU.

4.3.2 Add libfalcon.so into KVM

As we have produced the shared library libfalcon.so, the following task is to link the library with QEMU's executable file. In the main function of QEMU, we directly invoke the RDMA initialization function to establish connections between replicas. Only after initialization is completed would virtual machine begins to run.

In the source file of TAP device, we just added a header file and a line of code to make the FALCON work.

4.4 Summary

The steps to run a replicated virtual machine is not complicated. First, intercept the network packet in the source code of virtual network device. Then, analyze the network packet and preprocess the packet. Finally, embed FALCON into KVM and run a virtual machine with replication.

Chapter 5

Evaluation

Our evaluation was done on a set of three replica machines, with each having Linux 3.16.0, QEMU-KVM 1.2.50, 2.6 GHz Intel Xeon with 24 hyper-threading cores, 64GB memory, and 1TB SSD. Each machine is equipped with a Mellanox ConnectX-3 Pro Dual Port 40 Gbps NIC. These NICs are connected using the Infiniband architecture.

To mitigate network latency, benchmark clients were running within the replicas' LAN. The average ping latency between the client machine and a virtual machine on the server machine is 210us. Larger latency will mask FALCON's overhead.

For the virtual machine, 2GB memory and 4 CPU cores are allocated to every replica. Except the difference of IP address and Mac address of these virtual machines, they are identical in the other aspects.

We evaluated the performance of the replicated virtual machine on three widely used server programs, including MySQL, an SQL database; a key-value store Memcached [25]; and a NoSQL database MongoDB [26].

Replicated virtual machine's high availability and fault-tolerance are attractive to these server programs, because these programs provide on-line service and contain important in-memory execution states and storage.

5.1 Evaluation result of MySQL

MySQL is an open-sourced relational database management system where the data is stored on disk rather than memory. As a matter of fact, many corporations use MySQL database in large-scale websites, including famous companies Facebook, Twitter, YouTube and Google. Although the newest release version MySQL supports replication itself. The default replication method for MySQL is not very perfect in response time and consistency.

No modification is acting on MySQL server's default configuration except the listening IP address. To make the server could be access by the clients outside the virtual machine, we modify the default listening address.

We used benchmark Sysbench [4] to generate random select queries. But before we use this benchmark, we have to create a sysbench database in the MySQL first. Otherwise, MySQL would respond failure for every query.

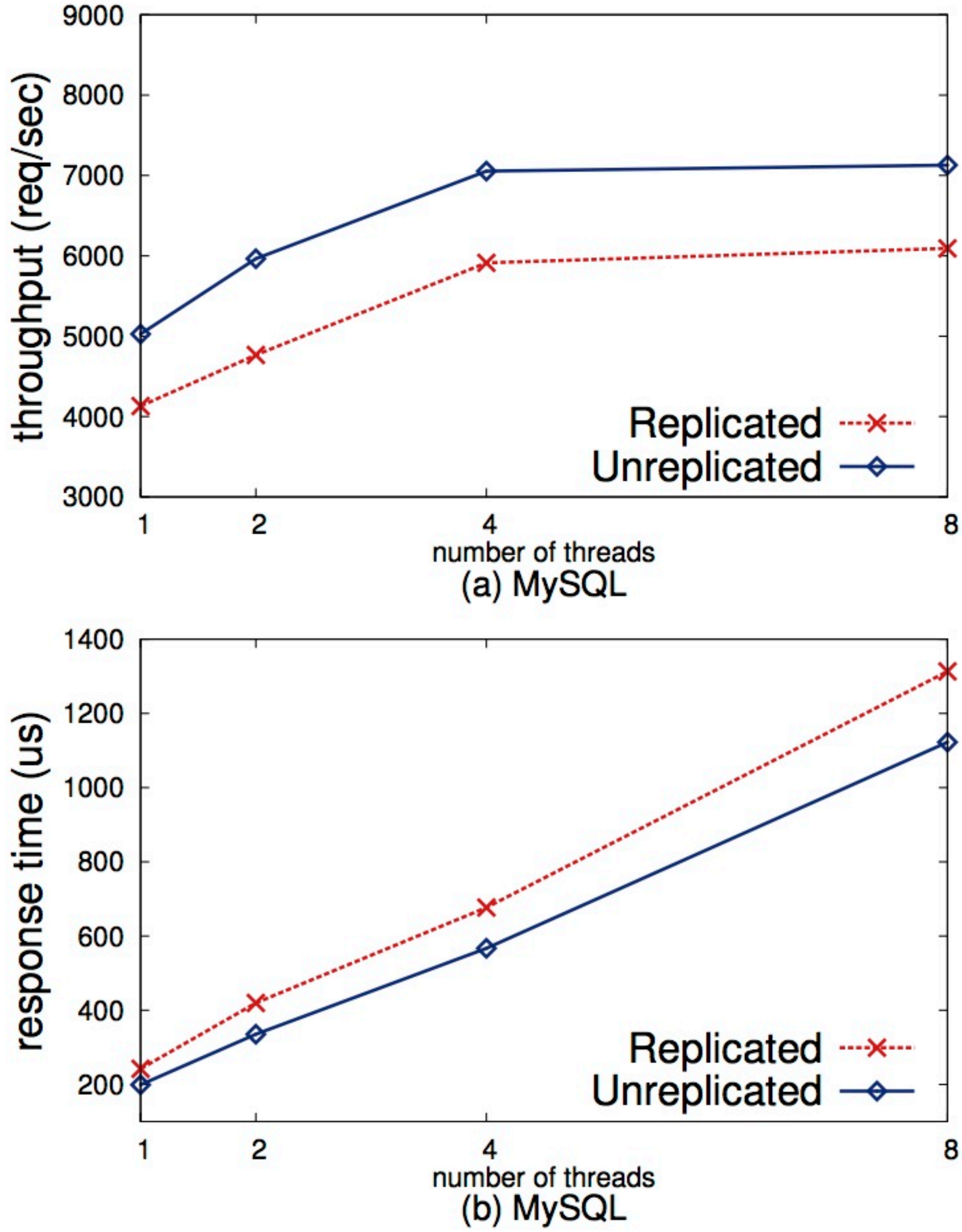

Figure 5.1: MySQL's throughput and latency of replicated and unreplicated execution

The Figure 5.1 shows the throughput and latency of MySQL. We varied the number of concurrent client connections from 1 to 8 threads.

Overall, with the increasing of the clients, the throughput is going up slowly. When there are 4 threads, the throughput reaches the peak. The main reason is that the virtual machine only has 4 cores. It cannot provide service concurrently when the number of threads expire this limit. As for the response time, the competition becomes fiercer with the growth of the number of threads. So the latency rises rapidly.

Compared the replicated virtual machine with the unreplicated one. No matter how many number of threads, the throughput is only dropping 1000 requests per second.

5.2 Evaluation result of Memcached

Memecached is a high-performance distributed memory object caching system. It provides a large hash table and uses CRC-32 to calculate the key. When the hash table is full, the following insertion will replace the data in least recently used order. Users could use Memcached as the cache of some slow backing databases. It could effectively raise efficiency of insertion. However, Memcached could also evaluated as a key-value database here.

We allocate 64MB memory for Memcached in our evaluation. And we used twemperf benchmark [3] from Twitter to issue mixed set and get operations. The size of every fixed item is 10 bytes. Every connection is created after the previous connection is closed. We sent total 10000 requests in every test.

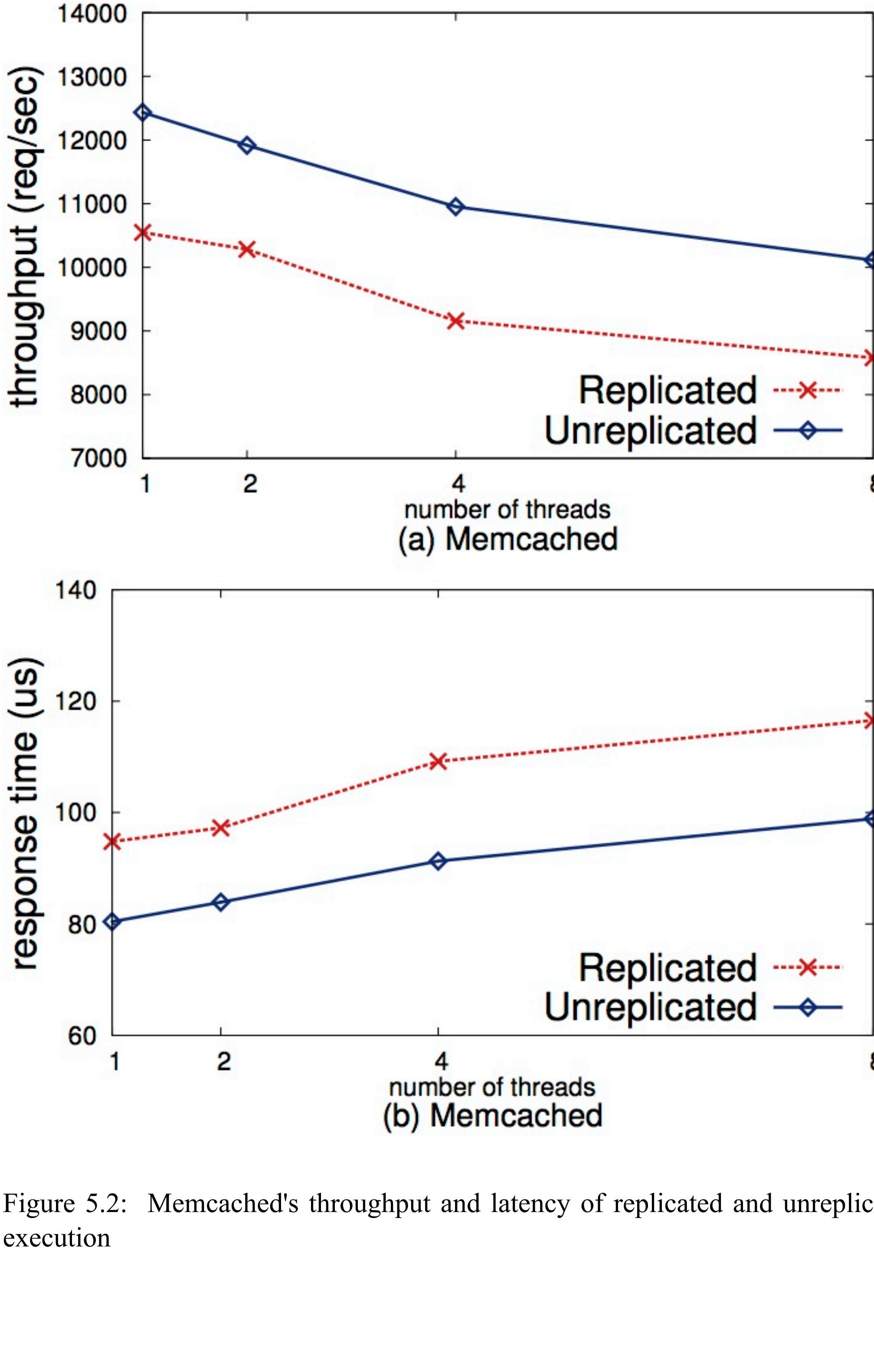

Figure 5.2: Memcached's throughput and latency of replicated and unreplicated execution

The Figure 5.2 shows the throughput and latency of Memcached [16]. Similar to MySQL, we also varied the number of concurrent client connections from 1 to 8 threads.

Memcached's tendency of throughput is quite different from the counterpart of MySQL. As the connections cannot be created concurrently, the throughput drops with the increasing of clients.

For Memcached, the response time could better reflect replicated virtual machine's performance, around 15us overhead is added to every operation.

5.3 Evaluation result of MongoDB

MongoDB is a free and open-source NoSQL database widely used in distributed system. It can run over multiple servers, balancing the load or duplicating data to keep the system up and running in case of hardware failure. Also, it achieves fault tolerant servers with replica sets. There are usually two or more copies of data stored in different physical machines. Two roles are involved in replica set: primary and secondary. Compared with simple master and slave replication, it solves the problem of single point of failure. It elects a healthy node as the primary to handle set operation when no primary exists in set. However, the inconsistency issue cannot resolve.

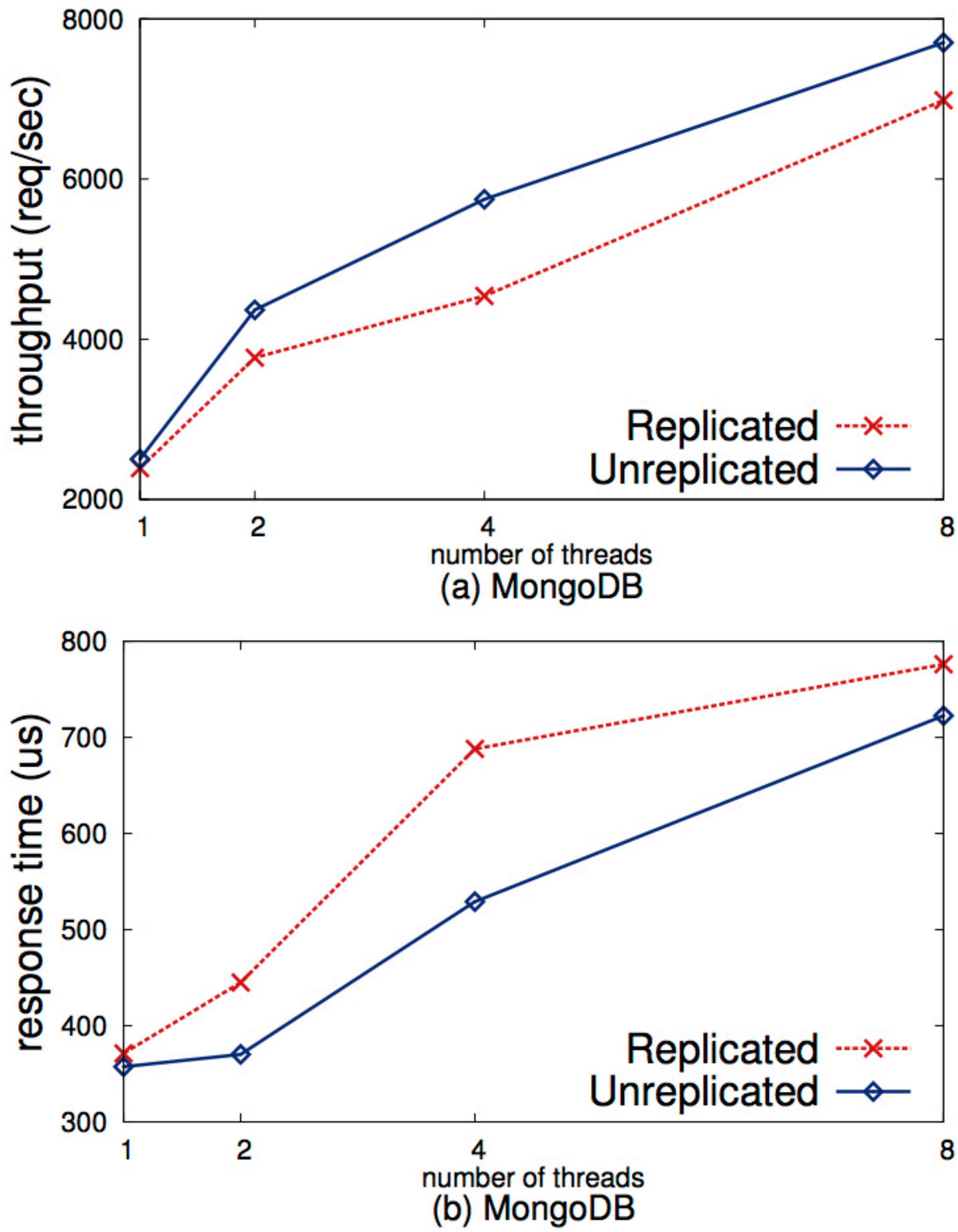

Figure 5.3: MongoDB's throughput and latency of replicated and unreplicated execution

No special configuration is applied in our MongoDB servers but the listening IP address. We just modified default configuration file's listening IP address to cater for the needs of running benchmark outside the virtual machine. We used Yahoo

Cloud Serving Benchmark (YCSB) [5] as benchmark. Every time, we sent 10000 set requests to server in virtual machine to get the average throughput and latency.

The Figure 5.3 shows the throughput and latency of MongoDB. The trend of throughput and response time is similar with the counterpart of MySQL. Although it seems there are some noisy points in the figure. The main tendency shows only a small portion overhead is added for the replicated virtual machine.

5.4 Summary

Overall, compared to these server programs' unreplicated executions, replicated virtual machine's average overhead on throughput and response time was 14.7% and 17.9% respectively. As the number of threads increase, all programs' unreplicated executions got a performance improvement except Memcached. The reason has been discussed in the previous section. Furthermore, replicated virtual machine scaled almost as well as the unreplicated executions.

Chapter 6

Conclusions and future work

In my dissertation, I aim at exploiting the replication feature of KVM for providing fault tolerant servers in virtual machines. I research on the state machine replication for KVM where incoming network packets are interposed and FALCON is invoked to agree on the inputs across replicas.

Compared with the traditional state-transfer based high availability system Remus. We can find that the amount of data transferred in our replicated virtual machine is much less. Different from the Remus requires to transport changed memory, CPU and I/O device information frequently, our replicated virtual machine method provides high availability feature by replicating a small amount of network packets.

Evaluation on three widely used programs shows that our proposed replication method achieves moderate overhead. Even in the LAN, the throughput is not dropping fiercely, and there is just a little increase in response time.

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