Shared-Memory Optimizations for Inter-Virtual-Machine Communication

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Virtual machines (VMs) and virtualization are one of the core computing technologies today. Inter-VM communication is not only prevalent but also one of the leading costs for data-intensive systems and applications in most data centers and cloud computing environments. One way to improve inter-VM communication efficiency is to support coresident VM communication using shared-memory-based methods and resort to the traditional TCP/IP for communications between VMs that are located on different physical machines. In recent years, several independent kernel development efforts have been dedicated to improving communication efficiency between coresident VMs using shared-memory channels, and the development efforts differ from one another in terms of where and how the shared-memory channel is established. In this article, we provide a comprehensive overview of the design choices and techniques for performance optimization of coresident inter-VM communication. We examine the key issues for improving inter-VM communication using shared-memory-based mechanisms, such as implementation choices in the software stack, seamless agility for dynamic addition or removal of coresident VMs, and multilevel transparency, as well as advanced requirements in reliability, security, and stability. An in-depth comparison of state-of-the-art research efforts, implementation techniques, evaluation methods, and performance is conducted. We conjecture that this comprehensive survey will not only provide the foundation for developing the next generation of inter-VM communication optimization mechanisms but also offers opportunities to both cloud infrastructure providers and cloud service providers and consumers for improving communication efficiency between coresident VMs in virtualized computing platforms.

CCS Concepts: • **Software and its engineering → Communications management**; • *Software and its engineering → Virtual machines*; • *Networks → Network protocol design*; • Networks → Cloud computing

Additional Key Words and Phrases: Residency aware, inter-virtual-machine communication, shared memory, seamless agility, multilevel transparency

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1. INTRODUCTION

Virtual machines (VMs) are the creations of hardware virtualization. Unlike physical machines, software running on virtual machines is separated from the underlying hardware resources. Virtual machine monitor (VMM or hypervisor) technology enables a physical machine to host multiple guest VMs on the same hardware platform. As a software entity, VMM runs at the highest system privilege level and coordinates with a trusted VM, called the host domain (Dom0) or host OS, to enforce isolation across VMs residing on a physical machine. Each of the VMs is running on a guest domain (DomU) with its own operating system (guest OS). To date, VMM-based solutions have been widely adopted in many data centers and cloud computing environments [Armbrust et al. 2010; Gurav and Shaikh 2010; Younge et al. 2011; Anderson et al. 2013].

1.1. Problems of Coresident VM Communication and Related Work

It is well known that the VMM technology benefits from two orthogonal and yet complementary design choices. First, VMM technology enables VMs residing on the same physical machine to share resources through time slicing and space slicing. Second, VMM technology introduces host-neutral abstraction, which treats all VMs as independent computing nodes regardless of whether these VMs are located on the same host machine or different hosts.

Although VMM technology offers significant benefits in terms of functional isolation and performance isolation, live-migration-enabled load balance, fault tolerance, portability of applications, and higher resource utilization, both design choices carry some performance penalties. First, VMM offers significant advantages over native machines when VMs coresident on the same physical machine are not competing for computing and communication resources. However, when coresident VMs are competing for resources under high workload demands, the performance of those coresident VMs is degraded significantly compared to the performance of the native machine, due to the high overheads of switches and events in host/guest domain and VMM [Pu et al. 2012; Mei et al. 2013]. Furthermore, different patterns of high workload demands may have different impacts on the performance of VM executions [Wang et al. 2011; Imai et al. 2013]. Second, several research projects [Huang et al. 2007; Huang 2008; Kim et al. 2008; Wang et al. 2008b; Radhakrishnan and Srinivasan 2008; Ren et al. 2012] have demonstrated that even when the sender VM and receiver VM reside on the same physical machine, the overhead of shipping data between coresident VMs can be as high as the communication cost between VMs located on separate physical machines. This is because the abstraction of VMs supported by VMM technology does not differentiate between whether the data request is coming from the VMs residing on the same physical machine or from the VMs located on a different physical machine. Concretely, the Linux guest domain shows lower network performance than native Linux [Menon et al. 2006; Liu et al. 2006; SANTOS et al. 2008; YEHUDA et al. 2006; RUSSELL 2008; Li et al. 2010] when an application running on a VM communicates with another VM. Kim et al. [2008] should that with copying mode in Xen 3.1, the inter-VM communication performance is enhanced but still significantly lagging behind compared to the performance on native Linux, especially for VMs residing on the same physical machine.

The two main reasons for the performance degradation of coresident VM communication are [Wang 2009] (1) long communication data path through the TCP/IP network stack [Kim et al. 2008; Wang et al. 2008b; Ren et al. 2012] and (2) lack of communication

awareness in CPU scheduler and absence of real-time inter-VM interactions [Govindan et al. 2007; Kim et al. 2009; Ongaro et al. 2008]. The first category of solutions to improve the performance of inter-VM communication is to use a shared-memory channel mechanism for communication between coresident VMs to improve both communication throughput and latency [Huang et al. 2007; Huang 2008; Zhang et al. 2007; Kim et al. 2008; Wang et al. 2008b; Radhakrishnan and Srinivasan 2008; Ren et al. 2012; Zhang et al. 2015; Diakhaté et al. 2008; Eirakuet al. 2009; Koh 2010; Gordon 2011a; Gordon et al. 2011b; Ke 2011; Macdonell 2011]. An alternative category of solutions is to reduce inter-VM communication latency by optimizing CPU scheduling policies [Govindan et al. 2007; Kim et al. 2009; Ongaro et al. 2008; Lee et al. 2010]. Research efforts in this category show that by optimizing CPU scheduling algorithms at the hypervisor level, both inter-VM communication and I/O latency can be improved. For instance, Govindan et al. [2007] introduce an enhancement to the SEDF scheduler that gives higher priority to I/O domains over the CPU-intensive domains. Ongaro et al. [2008] provide specific optimizations to improve the I/O fairness of the credit scheduler. Task-aware scheduling [Kim et al. 2009] focuses on improving the performance of I/O-intensive tasks within different types of workloads by a lightweight partial boosting mechanism. Incorporating the knowledge of soft real-time applications, Lee et al. [2010] propose a new scheduler based on the credit scheduler to reduce the latency. However, none of the work in this category actually deals with the inter-VM communication workloads or takes colocated VM communications into consideration.

In this article, we focus on reviewing and comparing the solutions in the first category, namely, improving inter-VM communication efficiency using shared-memory-based mechanisms. To date, most of the kernel research and development efforts reported in the literature are based on shared memory for improving communication efficiency among coresident VMs. Furthermore, most of the documented efforts are centered on open-source hypervisors, such as the Xen platform and KVM platform.[1] Thus, in this article, we present a comprehensive survey on shared-memory-based techniques that are implemented on either the Xen or KVM platform for inter-VM communication optimization.

Relatively speaking, there are more shared-memory efforts on the Xen platform than on the KVM platform in the literature, such as IVC [Huang et al. 2007; Huang 2008], XenSocket [Zhang et al. 2007], XWAY [Kim et al. 2008], XenLoop [Wang et al. 2008b], MMNet [Radhakrishnan and Srinivasan 2008] on top of Fido [Burtsevet al. 2009], and XenVMC [Ren et al. 2012], while all KVM-based efforts, such as VMPI [Diakhaté et al. 2008], Socket-outsourcing [Eiraku et al. 2009; Koh 2010], and Nahanni [Gordon 2011a; Gordon et al. 2011b; Ke 2011; Macdonell 2011], are recent developments since 2009. One reason could be that Xen open source was made available since 2003 and KVM is built on hardware containing virtualization extensions (e.g., Intel VT or AMD-V) that were not available until 2005. Interestingly, even the development efforts on the same platform (Xen or KVM) differ from one another in terms of where in the software stack the shared-memory channel is established and how the inter-VM communication optimization is carried out.

We see growing demand for a comprehensive survey of the collection of concrete techniques and implementation choices on inter-VM communication optimization. Such comprehensive study not only can help researchers and developers to design and

[1]VMCI Socket of VMware [VMware Inc. 2007] was a commercial implementation to improve the efficiency of inter-VM communication using a shared memory approach. From the publically available documentations on VMCI, such as the description of its API, its programming guide, etc., we found that VMCI introduces AF_VMCI, a new socket interface, which is not compatible to the current standard interface, and VMCI socket is implemented below system calls layer and above transport layer. Unfortunately, we could not find more detail about VMCI and thus we did not include VMCI in this article.

implement the next-generation inter-VM communication optimization technology but also offers cloud service providers and cloud service consumers an opportunity to further improve the efficiency of inter-VM communication in virtualized computing platforms.

1.2. Scope and Contributions of the Article

This article provides a comprehensive survey of the literature on coresident inter-VM communication methods, focusing on the design choices and implementation techniques for optimizing the performance of the coresident inter-VM communication. We make two original contributions:

—First, we present the core design guidelines and identify a set of key issues for improving inter-VM communication using shared-memory-based mechanisms, including choice of implementation layer in the software stack, seamless agility for dynamic addition or removal of coresident VMs, and multilevel transparency, as well as advanced requirements in reliability, security, and stability. By seamless agility, we mean that residency-aware inter-VM communication mechanisms support dynamic addition or removal of coresident VMs including VM creation, VM shutdown, and VM live migration in an automatic and transparent way. We conjecture that through this in-depth study and evaluation, we provide a better understanding of the set of criteria for designing the next-generation shared-memory channel for coresident VMs.
—Second, we conduct a comprehensive survey of representative state-of-the-art research efforts on both Xen and KVM platforms using a structured approach. Concretely, we provide an in-depth analysis and comparison of existing implementation techniques with respect to the architectural layout, the fundamental functionalities, how they achieve the design goals, additional implementation choices, the software environment and source code availability, and inter-VM communication efficiency. To the best of our knowledge, this is the first effort that provides a comprehensive survey of the inter-VM communication methods from three different perspectives: implementation layer in software stack, seamless agility, and multilevel transparency.

The rest of this article is organized as follows. Section 2 provides an overview of the basic concepts and terminology of network I/O and shared-memory structures in VMMs, which are fundamental for understanding the design choices and functional requirements of shared-memory-based inter-VM communication optimization. Section 3 presents design guidelines and key issues about shared-memory-based communication mechanisms for coresident VMs, including high performance, seamless agility, and multilevel transparency. Based on the functional requirements and design choices outlined in Section 3, we provide a comprehensive comparison of existing work in five subsequent sections: architectural layout comparison in Section 4; common fundamental functionalities in Section 5; the support for seamless agility, including race condition handling, in Section 6; the multilevel transparency in Section 7; and other implementation considerations and optimizations, including buffer size, software environment, source code availability, and performance comparison, in Section 8. We conclude the article in Section 9.

2. BACKGROUND AND PRELIMINARY

VMM technology to date is broadly classified into two categories [Pearce et al. 2013]: Type I VMMs, which are hypervisor-based VMMs running directly on hardware, such as Xen and VMware ESX Server, and Type II VMMs, which are also known as hosted VMMs and represented by Linux KVM and VMware Workstation. Since the technical details of related work in industry is not publically available, in this article, we focus primarily on representative open-source VMMs, such as Xen and KVM. In this section,

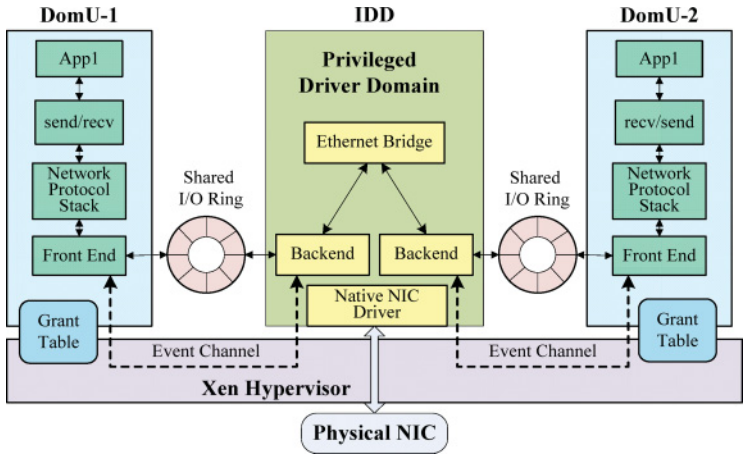


Fig. 1. Xen network I/O architecture and interfaces.

we give a brief description of network I/O and communication mechanisms among domains for Xen and KVM, respectively.

2.1. Xen Network Architecture and Interfaces

2.1.1. Network I/O Architecture. Xen is a popular open-source x86/x64 hypervisor, which coordinates the low-level interaction between VMs and physical hardware [Barham et al. 2003]. It supports both full virtualization and para-virtualization. With full virtualization, in virtue of hardware-assisted virtualization technology, the hypervisor lets VMs run unmodified operating systems. For each guest domain, it provides full abstraction of the underlying physical system. In contrast, with para-virtualization, it requires the guest OS to be modified and no hardware-assisted virtualization technology is needed. The para-virtualization mode provides a more efficient and lower-overhead mode of virtualizations.

In para-virtualization mode, Dom0, a privileged domain, performs the tasks to create, terminate, and migrate guest VMs. It can also access the control interfaces of the hypervisor. The hypervisor utilizes asynchronous hypercalls to deliver virtual interrupts and other notifications among domains via Event Channel.

Xen exports virtualized network devices instead of real physical network cards to each DomU. The native network driver is expected to run in the Isolated Device Domain (IDD), which is typically either Dom0 or a driver-specific VM. The IDD hosts a back-end network driver. An unprivileged VM uses its front-end driver to access interfaces of the back-end daemon. Figure 1 illustrates the network I/O architecture and interfaces. The front end and the corresponding back end exchange data by sharing memory pages, either in copying mode or in page flipping mode. The sharing is enabled by the Xen Grant Table mechanism that we will introduce later in this section. The bridge in IDD handles the packets from the network interface card (NIC) and performs the software-based routine in the receiver VM.

When the NIC receives a network packet, it will throw an interrupt to the upper layer. Before the interrupt reaches IDD, the Xen hypervisor handles the interrupt. First, it removes the packet from NIC and forwards the packet to the bridge. Then the bridge demultiplexes the packet and delivers it to the back-end interface corresponding to the receiver VM. The back end raises a hypercall to the hypervisor for page remapping so as to keep the overall memory allocation balanced. After that, data is copied and the

receiver VM gets the packet as if it comes from NIC. The process of packet sending is similar but performed in a reverse order.

Each I/O operation in the split I/O model requires involvement of the hypervisor or a privileged VM, which may become a performance bottleneck for systems with I/O-intensive workloads. The VMM-bypass I/O model allows time-critical I/O operations to be processed directly by guest OSs without involvement of the hypervisor or a privileged VM. High-speed interconnects, such as InfiniBand [Infiniband Trade Association. 2015], can be supported by Xen through VMM-bypass I/O [Liu et al. 2006].

2.1.2. Communication Mechanisms Among Domains. Xen provides the shared I/O Ring buffers between the front end and the back end, as shown in Figure 1. These I/O ring buffers are built upon the Grant Table and Event Channel mechanisms, two main communication channels for domains provided by Xen. Grant Table is a generic mechanism to share pages of data between domains in both page mapping mode and page transfer mode. The Grant Table contains the references of granters. By using the references, a grantee can access the granter's memory. The Grant Table mechanism offers a fast and secure way for DomUs to receive indirect access to the network hardware through Dom0. Event Channel is an asynchronous signal mechanism for domains on Xen. It supports inter-/intra-VM notification and can be bound to physical/virtual interrupt requests (IRQs).

In addition, Xen provides XenStore as a configuration and status information storage space shared between domains. The information is organized hierarchically. Each domain gets its own path in the store. Dom0 can access the entire path, while each DomU can access only its owned directories. XenStore has been utilized by some existing projects as a basic mechanism to facilitate the tracing of the dynamic membership update of coresident VMs.

2.2. QEMU/KVM

KVM is an open-source full-virtualization solution for Linux on x86 hardware that supports virtualization extension. It consists of two components: one is QEMU, which is a hardware emulator running on the host Linux as a user-level process and provides an I/O device model for VM; the other is a loadable KVM kernel device driver module, which provides core virtualization infrastructure including virtual CPU services for QEMU and supports functionalities such as VM creation and VM memory allocation. QEMU communicates with the KVM module through a device file, */dev/kvm*, which is created when the KVM module is loaded into the kernel. The KVM module is capable of supporting multiple VMs. QEMU/KVM virtualizes network devices of the host OS to allow multiple guest OSs running in different VMs to access the devices concurrently.

KVM also supports two modes of I/O virtualization: full virtualization through device emulation and the para-virtualization I/O model by Virtio [Russell 2008].

2.2.1. Network I/O Through Device Emulation. Emulated devices are software implementations of the hardware, such as E1000 and RTL8139. Device emulation is provided by the user space QEMU. It makes the guest OS using the device interact with the device as if it were actual hardware rather than software. There is no need to modify a corresponding device driver in the guest OS.

Figure 2 illustrates the architecture of the KVM full-virtualized network I/O. When the guest OS tries to access the emulated hardware device, the I/O instruction traps into the KVM kernel module. Then the module forwards the requests to QEMU. Then QEMU asks the guest OS to write data into the buffer of the virtualized NIC (VNIC) and copies the data into the TAP device, and the data is forwarded to the TAP device of the destination guest OS by the software bridge. When the TAP device receives the data, it wakes up the QEMU process. The QEMU process first copies the data into its

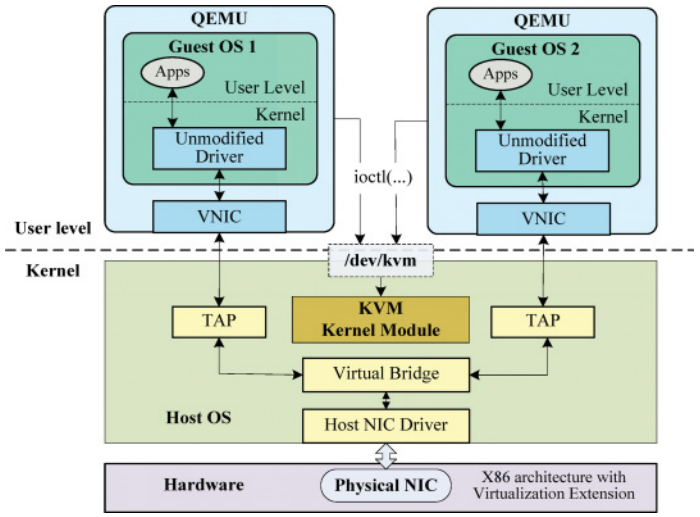


Fig. 2. The architecture of KVM full-virtualized network I/O.

VNIC buffer, from where the data is copied to the virtual device in the destination guest OS. Then, QEMU notifies the KVM kernel module to receive the data. The KVM kernel module sends interrupts to notify the guest OS about the data arrival. Finally, through the virtual driver and network protocol stack, the data is passed to the corresponding applications.

2.2.2. Virtio-Based Network I/O. Although emulated devices offer broader compatibility than para-virtualized devices, the performance is lower due to the overhead of context switches across the barrier between user-level guest OS and Linux kernel (host OS), as well as the barrier between Linux kernel and user space QEMU. Therefore, Virtio, a para-virtualized I/O framework, was introduced. The Virtio device driver consists of two parts: the front end is in the guest OS, while the back end is in the user space QEMU. The front end and the back end communicate with a circular buffer, through which the data can be copied directly from the kernel of the host OS to the kernel of the guest OS. Virtio avoids some unnecessary I/O operations. It reduces the number of data copies and context switches between the kernel and user space. It provides better performance than device emulation approaches.

3. OVERVIEW OF DESIGN CHOICES

In this section, we first discuss the motivation by comparing TCP/IP and shared-memory-based approaches to better understand the design guidelines we promote in this article. Then we present the design objectives for optimizing coresident inter-VM. We elaborate on the design choices and identify the key issues in designing and implementing a high-performance and lightweight inter-VM communication protocol based on shared-memory mechanisms.

3.1. TCP/IP Versus Shared-Memory-Based Approaches

Modern operating systems, such as Linux, provide symmetrical shared-memory facilities between processes. Typical interprocess communication mechanisms in Linux are System V IPC and POSIX IPC. With the IPC mechanisms, the processes communicate in a fast and efficient manner through shared memory or message channels since data shared between processes can be immediately visible to each other [Renesse 2012].

TCP/IP is pervasively used for inter-VM communication in many virtualized data centers, regardless of whether the VMs are coresident on the same physical machine or separate physical machines. However, TCP/IP, originally designed for communication among different computer hosts interconnected through a communication network, is not optimized for communication between VMs residing on the same physical machine.

Compared with IPC, communication via a TCP/IP-based network protocol takes a longer time because the data transfer from a sender to a receiver has to go through the TCP/IP protocol stack. Concretely, with the native TCP/IP network, if a sender process wants to transmit data to a receiver process, first the data is copied from the user space to the kernel space of the sender VM. Then it is mapped to the memory of the network device, and the data is forwarded from the sender VM to the network device of the receiver VM via the TCP/IP network. After that, the data is mapped from the network device to the kernel space of the receiver VM and copied to the user space of the receiver process. Inter-VM communication adds another layer of kernel software stack that the data has to travel along the path from the sender VM to the receiver VM via VMM. On the Xen platform, with the Xen virtualized front end/back end network, after the data reaches the buffer of NIC in the sender VM, the data is then transferred to the bridge in the IDD of the sender VM. Via TCP/IP, the data is routed to the corresponding back end of the IDD on the host of the receiver VM. Finally, the data is copied to the receiver VM. In summary, the data transferred from the sender VM to the receiver VM typically goes through a long communication path via VMM on the sender VM's host, TCP/IP stack, and VMM on receiver VM's host. Similarly, on KVM platforms, data transferred between the sender VM and the receiver VM also incurs multiple switches between VM and VMM in addition to going through the TCP/IP stack.

By introducing shared-memory-based approaches to bypass a traditional TCP/IP protocol stack for coresident VM communication, we may obtain a number of performance optimization opportunities: (1) the number of data copies is reduced by shortening the data transmission path, (2) unnecessary switches between VM and VMM are avoided by reducing dependency on VMM, and (3) using shared memory also makes data writes visible immediately. In short, shared-memory-based approaches have the potential to achieve higher communication efficiency for coresident VMs.

3.2. Design Objectives

The ultimate goal of introducing a fast coresident VM communication mechanism to coexist with the TCP/IP-based inter-VM communication protocol is to improve the performance by shortening the data transfer path and minimizing the communication overhead between coresident VMs. Concretely, when the sender VM and the receiver VM are coresident on the same host, the data will be transmitted via the local shared-memory channel (local mode) and bypass the long path of the TCP/IP + network stack. When the sender VM and the receiver VM reside on different hosts, the data will be transferred from sender to receiver through traditional TCP/IP network channel (remote mode). To establish such a shared-memory-based inter-VM communication channel, the following three core capabilities should be provided: (1) intercept every outgoing data request, examine it, and detect whether the receiver VM is coresident with the sender VM on the same host; (2) support both local and remote inter-VM communication protocols and, upon detection of local inter-VM communication, automatically switch and redirect the outgoing data request to the shared-memory-based channel instead; and (iii) incorporate the shared-memory-based inter-VM communication into the existing virtualized platform in an efficient and fully transparent manner over existing software layers [Burtsev et al. 2009; Eiraku et al. 2009; Kim et al. 2008; Radhakrishnan and Srinivasan 2008; Ren et al. 2012; Wang et al. 2008b; Wang 2009]. More importantly, the implementation of a shared-memory-based approach to

inter-VM communication should be highly efficient, highly transparent, and seamlessly agile in the presence of VM live migration and live deployment.

The objective of high efficiency aims at significant performance enhancement of different types of network I/O workloads, including both transactional and streaming TCP or UDP workloads.

The objective of seamless agility calls for the support of on-demand detection and automatic switching between the local mode and remote mode to ensure that the VM live migration and the VM deployment agility are retained.

Finally, the objective of multilevel transparency of the shared-memory-based mechanism refers to the transparency over programming languages, OS kernel, and VMM. Such transparency ensures that there is no need for code modifications, recompilation, or relinking to support legacy applications.

We argue that high performance, seamless agility, and transparency should be fully respected when coresident VM communication optimization is incorporated in an existing virtualization platform, be it Xen or KVM or any other VMM technology. We also would like to point out that a concrete implementation choice should make a careful tradeoff among conflicting goals. We will elaborate on each of these three objectives in the subsequent sections respectively. In addition, we conjecture that the next generation of shared-memory-based inter-VM communication facilities should support other desirable features, such as reliability, security, and stability, which will be elaborated on in Section 3.6.

3.3. Design Choices on High Performance and High Efficiency

The performance of a shared-memory inter-VM communication mechanism depends on a number of factors, such as the choice of implementation layer in the software stack, the optimization for streaming network I/O workloads, and the support for necessary network I/O optimization.

The implementation layer in the software stack brings potential impacts on programming transparency, kernel-hypervisor-level transparency, seamless agility, and performance efficiency. Based on the choice of in which layer the data transfer request interception mechanism is implemented, existing approaches can be classified into following three categories.

3.3.1. User Libraries and System Calls Layer (Layer 1). This is the simplest and most straightforward way to implement a shared-memory-based inter-VM communication protocol. Concretely, we can simply modify the standard user and programming interfaces in layer 1. This approach introduces less switching overhead and fewer data copies for crossing two protection barriers: from guest user level to guest kernel level and from guest OS to host OS. However, it exposes the shared memory to the user-level applications running on guest OSs and sacrifices user-level programming transparency. Most of the existing projects that choose the layer 1 approach fall into the following two categories: (1) in the HPC environment where specific interfaces based on communication dominates, such as MPI (Message Passing Interface), and (2) the earlier efforts of developing colocated VM communication mechanisms on the KVM platform.

3.3.2. Below System Calls Layer, Above Transport Layer (Layer 2). An alternative approach to implement shared-memory-based inter-VM communication is below the system calls layer, above the transport layer. There are several reasons that the layer 2 solutions may be more attractive. Due to the hierarchical structure of the TCP/IP network protocol stack, when data is sent through the stack, it has to be encapsulated with additional headers layer by layer in the sender node. Furthermore, when the encapsulated data reaches the receiver node, the headers will be removed layer by layer accordingly. However, if the data is intercepted and redirected in a higher layer in the software

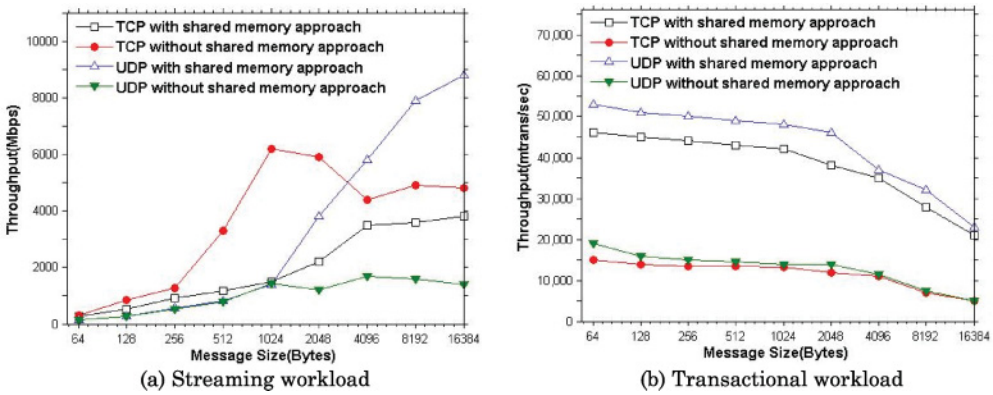


Fig. 3. XenLoop performance measured by NetPerf.

stack, it will lead to two desirable results: smaller data size and shorter processing path (less processing time on data encapsulation and the reverse process) [Wang et al. 2008b]. Based on this observation, we argue that implementation in a higher layer can potentially lead to lower latency and higher throughput of network I/O workloads. In contrast, establishing the shared-memory channel in layer 1 makes it very hard to maintain programming language transparency. Hence, layer 2 solutions are more attractive compared to layer 1 solutions [Ren et al. 2012].

3.3.3. Below IP Layer (Layer 3). The third alternative method is to implement the shared-memory-based inter-VM communication optimization below the IP layer. The advantages of this approach over those implemented at layer 1 or layer 2 include the following: (1) TCP/IP features, such as reliability, are left intact and remain to be effective, and (2) an existing third-party tool, such as netfilter [Ayuso 2006], remains available for hooking into the TCP/IP network path to facilitate the implementation of packets' interceptions. However, layer 3 is the lowest in the software stack. Thus, it potentially leads to higher latency due to higher network protocol processing overheads and more data copy operations and context switches across barriers.

3.3.4. Problems with Existing Solutions. Implementing shared-memory-based inter-VM communication for coresident VMs at layer 1 has some obvious shortcomings due to the need to modify applications. Thus, most of the existing shared-memory inter-VM communication mechanisms are implemented at either layer 2 or layer 3. However, implementation at layer 2 will result in missing some important TCP/IP features, such as reliability, and some existing third-party tools, such as netfilter [Ayuso 2006]. Layer 3 solutions offer high transparency and high reliability but may incur high overhead. Among the collection of shared-memory-based inter-VM protocols, XenLoop is the most representative in terms of performance, seamless agility, programming transparency, and availability of open-source release. To better understand the performance of shared-memory-based inter-VM approaches, we conduct extensive experimental evaluation of XenLoop [Zhang et al. 2013a]. Figure 3 shows the results of running XenLoop for both TCP and UDP workloads by Netperf [Netperf 2015].

It compares the performance of TCP STREAM, UDP STREAM, TCP TRANSACTION, and UDP TRANSACTION workloads that are running on VMs with and without shared-memory approaches, respectively. We make three interesting observations. First, for the UDP STREAM workload, shared-memory-based colocated inter-VM communication performance is up to 6 times higher than native colocated inter-VM communication. Also, the performance of UDP STREAM workloads increases dramatically

Table I. Three Most Frequently Invoked Kernel Functions

Samples	Image	Function
4,684 (7.16%)	vmlinux	__do_softirq
229 (0.35%)	vmlinux	csum_partial_copy_generic
222 (0.34%)	vmlinux	tcp_ack

when the message size grows above 1KB. Second, the performance of transactional workloads is always beneficial using the shared-memory approach. Third, the performance of TCP STREAM workloads running with the shared-memory approach is always worse than that in native inter-VM communication, irrespective of message size.

In order to understand the reasons for poor performance of shared-memory mechanisms under streaming TCP workloads, we conduct further investigation by using Oprofile [Levon 2014], a low-overhead system-wide profiler for Linux. We found that the frequent software interrupts incurred in shared-memory-based inter-VM communications can severely degrade the performance of TCP STREAM workloads between two colocated VMs. We analyze the types and the amount of events occurring in the VM kernel while TCP streaming workloads are running between colocated VMs optimized with MemPipe [Zhang et al. 2015]. Table I shows the three most frequent kernel functions that are invoked during the TCP STREAM workloads. We noticed that the function *do softirq* is executed in a very high frequency compared with others. In the Linux network subsystem, *do softirq* is an interrupt handler responsible for extracting packets from the socket buffer and delivering them to the applications. The CPU stack switching cost brought by executing a software interrupt handler is nonnegligible, especially in the case where the frequency of software interruption is high.

These results indicate that reducing the frequency of software interrupts can be a potential opportunity to further improve the performance of shared-memory-based inter-VM communication systems, especially for TCP streaming workloads. Interesting to note is that our observation is aligned with the active-tx/rx technologies that are adopted by the NIC drivers to constantly monitor the workload and adaptively tune the hardware interrupt coalescing scheme. This helps to reduce the OS overhead encountered when servicing one interrupt per received frame or per transmitted frame. However, when a shared-memory mechanism and its packet interception are implemented at layer 2 (below the system's call layer and above the transport layer), the inter-VM network frames are transmitted via shared memory and never go through the hardware or virtual NICs. Thus, the adaptive-tx/rx technologies supported in NIC can no longer help to better manage the overhead of software interrupts in the shared-memory-based inter-VM communication protocols.

In our MemPipe [Zhang et al. 2015] system, we overcome this problem by introducing an *anticipatory time window (ATW)*-based notification grouping algorithm to substitute the simple and intuitive *per packet notification issuing (PNI)* algorithm. The idea is that, for the sender VM, instead of issuing a notification to the receiver VM for each single network packet, it is always anticipating that more packets will arrive in the near future. Thus, we set the anticipation time window t such that the sender can partition notifications into multiple ATW-based notification partitions of the same size N, such that each partition batches N packets in a single notification. The reduced number of notifications between the sender VM and the receiver VM can significantly cut down on the amount of software interrupts to be handled in both sender and receiver VMs. Proper setting of the parameter N and the ATW interval t is critical for achieving optimal performance. In MemPipe, each streaming partition is formed when N packets have arrived or when the ATW interval t expires. This ensures that the ATW-based

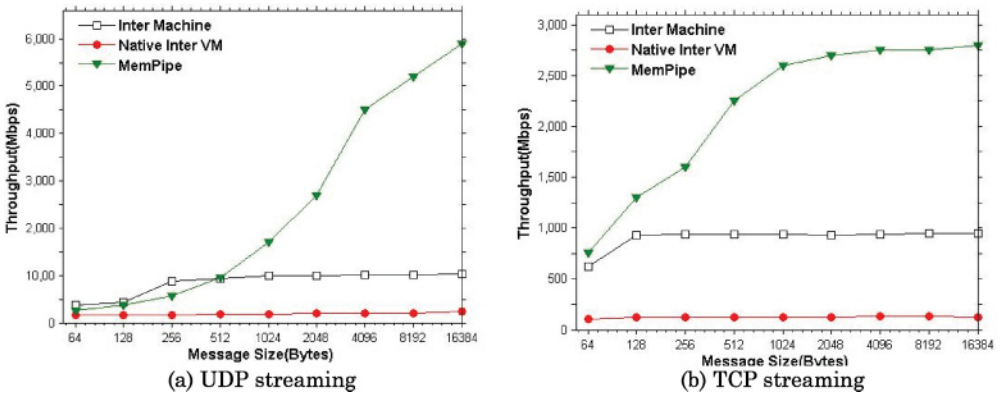


Fig. 4. MemPipe throughput performance by running NetPerf.

notification incurs only a bounded delay by t and a notification will be issued by the sender at most every t time, even when there are less than N new packets in the shared memory. Figure 4 shows the experimental evaluation of MemPipe, which is a XenLoop-like implementation of the shared-memory inter-VM communication protocol on the KVM platform [Zhang et al. 2015].

Figure 4 measures the UDP and the TCP streaming throughput by varying the message size from 64B to 16KB using Netperf. Figure 4(a) shows that, for UDP workloads, throughput increases as the message size increases for all three scenarios. When the message size is larger than 256B, throughput in intermachine and native inter-VM scenarios becomes relatively stable, which indicates that the network communication channel is saturated. In contrast, MemPipe consistently outperforms the native inter-VM scenario in all message sizes, and MemPipe outperforms the intermachine scenario when the message size is larger than 512B and the performance gap increases as the message size increases from 0.5KB to 16KB with up to 32 times higher throughput compared with that in the native inter-VM case. This is because for small message sizes, the performance is dominated by the per-message system call overhead. However, as the message size increases, the performance becomes dominated by the data transmission. The advantages of using shared-memory outweigh the overhead caused by per-message system call overhead. Similarly, for TCP streaming workloads, as shown in Figure 4(b), MemPipe reliably outperforms the other two scenarios for all message sizes thanks to the *ATW*-based notification grouping algorithm.

In summary, the MemPipe experience shows that the design of a shared-memory inter-VM communication protocol needs to take into account the layer in which the shared memory channel will be established and the necessary optimizations due to bypassing the higher layer in the software stack.

3.4. Design Choices for Seamless Agility

VM live migration is one of the most attractive features provided by virtualization technologies. It provides the ability to transport a VM from one host to another in a short period of time as if the VM's execution has not been interrupted. VM live migration allows VMs to be relocated to different hosts to respond to the load balancing due to varying load or performance, save power, recover from failures, and improve manageability. It is considered by many as a "default" feature of VM technologies.

However, VMs are by design not aware of the existence of one another directly due to the abstraction and isolation support by virtualization. Therefore, seamless agility calls for the support of on-demand coresident VM detection and automatic switch between

the local mode and remote mode to retain the benefits of VM live migration and the flexibility for VM deployment.

3.4.1. Automatic Detection of Coresident VMs. Two different methods can be used to detect coresident VMs and maintain VM coresidency information. The simplest one is static, which collects the membership of coresident VMs during the system configuration time prior to runtime. Such collection is primarily done manually by the administrator and is assumed unchanged during runtime. Thus, user applications are aware of coresidency information of communicating VMs by the static VM detection method. The most commonly used coresident VM detection method is dynamic, which provides automatic detection mechanisms. In contrast to the static method, which fails to detect the arrival of new VMs or the departure of existing VMs without an administrator's intervention, dynamic coresident VM detection can be done either periodically and asynchronously or as a tightly integrated synchronous process with the live migration and VM dynamic deployment subsystem:

—The privileged domain or corresponding self-defined software entity periodically gathers coresidency information and transmits it to the VMs on the same host.
—VM peers advertise their presence/absence to all other VMs on the same host upon significant events, such as VM creation, VM shutdown, VM live migration in/out, and so forth.

The first approach is asynchronous and needs centralized management by the host domain. It is relatively easier to implement since coresidency information is scattered in a top-down fashion and the information is supposed to be sent to VMs residing on the same host consistently. However, the frequency or time period between two periodical probing operations needs to be configured properly. If the period is set longer than needed, the delay may bring inaccuracy to the coresidency information, leading to possible race conditions. For instance, if VM_1 that migrated from host A to another host B is still communicating with VM_2 on host A via the shared-memory channel, then it may lead to system errors. However, if the time period is set to be too short, it might lead to unnecessary probing and CPU cost.

The second approach is event driven and synchronous. When a VM migrates out/in, related VMs are notified and the coresidency information is updated as an integral part of the live migration transaction. Thus, the coresidency information is kept fresh and updated immediately upon the occurrence of the corresponding events. Unless the list of coresident VMs on a physical machine is updated, it is protected from read. Thus, the consistency of the VM coresidency information is maintained.

3.4.2. Transparent Switch Between Local Mode and Remote Mode. Two tasks are involved in performing the transparent switch between the local and remote mode:

—To identify if the communicating VMs are residing on the same physical machine
—To automatically determine the right spot of where and when to perform the transparent switch

For the first task, the unique identity of every VM and the coresident information are needed. *<Dom ID, IP/Mac address>* pairs can be used to uniquely identify domains. Whether it is the IP address or Mac address, it depends on in which layer the automatic switch feature is implemented. Maintaining coresident VMs within one list makes the identification easier. The coresident membership information is dynamically updated by the automatic detection mechanism for coresident VMs. For the second task, one of the good spots for determining the local or remote switching is to intercept the requests before setting up or tearing down connections or before the sender VM transfers the data. For example, we can make the checking of whether the coresident VM list is

updated and the setting up of a connection or the transferring of data between two VMs as one single atomic transaction to ensure correctness.

3.5. Multilevel Transparency

The next design objective is the maintenance of multilevel transparency for developing efficient and scalable inter-VM communication mechanisms. We argue that three levels of transparency are desirable for effective inter-VM communication optimization using shared-memory approaches.

3.5.1. User-Level Transparency. User-level transparency refers to a key design choice regarding whether applications can take advantages of the coresident inter-VM communication mechanism without any modifications to the existing applications and user libraries. With user-level transparency, legacy network applications using standard TCP/IP interfaces do not need to be modified in order to use the shared-memory-based communication channel. To achieve this level of transparency, shared-memory-based inter-VM communication is supposed to be implemented in a layer lower than the system calls and user libraries such that there is no modification to layer 1 and thus applications.

3.5.2. OS Kernel Transparency. By OS kernel transparency, we mean that incorporating the shared-memory channel requires no modification to either the host OS kernel or guest OS kernel, and thus no kernel recompilation and relinking are needed. No customized OS kernel and kernel patches need to be introduced, which indicates a more general and ready-to-deploy solution. To obtain the feature of OS kernel transparency, one feasible approach is to use nonintrusive and self-contained kernel modules. Kernel modules are compiled separately from the OS kernel, so recompiling and relinking the kernel can be avoided. Moreover, they can be loaded at runtime without system reboot. A typical kernel-module-based approach is to utilize a standard virtual device development framework to implement the guest kernel optimization as standard and a clean kernel driver module, which is flexible to be loaded/unloaded. In fact, most state-of-the-art hypervisors support emulated devices (network, block, etc.) to provide functionalities to guest OSs.

3.5.3. VMM Transparency. With VMM transparency, no modification to VMM is required to incorporate shared-memory communication mechanisms, maintaining the independence between VMM and guest OS instances. It is well known that modifying VMM is hard and can be error prone; thus, it is highly desirable to use and preserve the existing interfaces exported by the VMM instead of modifying them.

The design choice of multilevel transparency closely interacts with other design choices, such as implementation layers, seamless agility, degree of development difficulty, and performance improvement. For example, the benefits of layer 1 implementation, such as less kernel work, fewer data copies, and lower overhead of context switches across the boundaries, are obtained at the cost of sacrificing user-level transparency. We will detail some of these interactions in Section 4 when we compare the architectural design of existing representative systems.

3.6. Other Desired Features

In addition to high performance, implementation layer in software stack, seamless agility, and multilevel transparency, we argue that full consideration of how to provide reliability, security, and stability is also important for the next-generation co-residency-aware inter-VM communication mechanisms. However, most of the related work to date pays little attention to these advanced features.

3.6.1. Reliability. By reliability, we mean that a shared-memory-based implementation of residency-aware inter-VM communication should be error free and fault tolerant. Concretely, the incorporation of a shared-memory channel into the existing virtualization platform should not introduce additional errors and should be able to handle exceptions introduced smoothly and automatically. We discuss next two example exception handlings: connection failures and race conditions upon VM migration or dynamic VM deployment.

Connection failures. Connection failures may occur in a virtualization system for both local connections (connection between VMs on the same host) and remote connections (connection between VMs on separate hosts). For local connection failures, the shared-memory buffer mapped by the communicating VMs should be deallocated by explicitly unmapping those pages. For remote connections, we will resort to the traditional methods for network failure recovery.

Race conditions. Race conditions may occur when the coresident VM detection is performed dynamically but periodically. For example, when a VM_1 on host A is migrated to host B right after the coresident VM detection has updated the list of coresident VMs and before the list of coresident VMs will be updated in the next time interval, it is possible that VM_1 communicates with VM_2 still via the previously established shared-memory channel on host A, which can lead to race conditions due to connection failure since VM_1 is no longer present on host A.

One approach to address this type of race condition is to use the *synchronous update method* instead of an asynchronous update method, such as a periodic update based on a predefined time interval, or static update method. The synchronous update method enables the update to the list of coresident VMs to be triggered synchronously with a live migration transaction, offering strong consistency support. More importantly, the synchronous update method also avoids race conditions. However, the support of the synchronous update method requires one to modify the live migration module and the dynamic VM deployment module to add the support of synchronization.

Alternatively to the synchronous update, if the automatic coresident VM detection mechanism is accompanied by an *asynchronous update method*, which periodically updates the list of coresident VMs, then the period update method will periodically check the membership tracing mechanism, such as XenStore, to see if any existing VMs in the coresident VM list have been added to or removed from the current host. If yes, it will trigger an update to the list of coresident VMs on the host. The problem with the periodic update method is the possibility of race conditions during the time interval between two consecutive updates, as illustrated by the aforementioned example. Thus, any shared-memory-based inter-VM communication protocol that adopts the periodic update method for refreshing the coresident VM list will need to provide an exception handling method to address the possible occurrence of race conditions. There are two possible approaches to this problem: race condition prevention and race condition resolution.

Race condition prevention. To prevent the occurrence of a race condition under the periodic update method, we need to add a VM-status checking module as an integral part of operations, such as connection establishment. Prior to the communication from one VM to another coresident VM, this consistency checking module will double-check if they remain to be colocated and their shared memory channel is established. This consistency checking is performed by examining the membership tracing mechanism from the most recent time point of the periodic update. Upon detecting the addition of new VMs or the removal of existing VMs on the current host machine, for instance, if it detects the occurrence of VM_1's migration from host A to host B, then it will trigger three tasks: (1) the switching of the communication channel between VM_1 (on host B) and VM_2 (on host A) to the remote mode using the conventional TCP/IP protocol,

with pending data properly handled; (2) the shared-memory tear-down procedure; and (3) the update to the coresident VM list. The advantage of this solution compared to the synchronous update method is that it is independent of the live migration module, the dynamic VM deployment module, and possibly other relevant modules at the cost of an additional delay for every connection establishment.

Race condition resolution. One way to avoid the additional delay introduced in connection establishments to deal with possible race conditions is to handle connection errors using timeout until the next round of the periodic update is performed. We have two cases to consider:

Case 1: adding new VMs. The communication between the new VM and the other coresident VMs will be using the remote mode instead of the shared-memory mode because the coresident VM list is not yet updated.

Case 2: removal of existing VMs. The communication between the removed VM and the other coresident VMs will still be using the shared-memory mode. Thus, when VM_1 is migrated from host A to host B, its resource allocations on host A have been deallocated. Thus, the attempt to use the shared-memory communication between VM_1 (on host B) and VM_2 (on host A) will result in a failure and eventually timeout. If VM_1 (on host B) is the sender, it will fail until its coresident VM list on host B is updated by the next update interval. Similarly, if VM_1 (on host B) is the receiver, it will not be able to access the data placed by VM_2 on their previously established shared-memory channel on host A, leading to a communication failure for the sender until the coresident VM list of VM_2 on host A is updated by the next update interval.

In either case, some inter-VM communications are delayed until the periodic update to the coresident list is performed. And possible pending data problems during the switch of the local and remote mode need to be considered. This solution is lightweight compared to the other alternatives and allows us to avoid the additional overhead introduced to every connection (local and remote). One can further study the adaptive setting of the time interval for the periodic update method, for example, with a smaller interval for frequent live migration and a larger interval for infrequent live migration.

3.6.2. Security. By security, we mean that the shared-memory-based implementation should provide a proper protection level for memory sharing between coresident VMs based on the degree of mutual trust between coresident VMs. For example, by implementing the shared-memory-based inter-VM communication mechanism as a kernel module, it manages the access to the globally allocated shared memory by keeping track of the mapping between shared-memory regions for each pair of communicating VMs, and performs an address boundary check for each access attempt before it grants the access to the shared memory. By utilizing the protection models of host/guest OSs, it assumes that a sender VM has implicit trust in its receiver VM. One way to introduce a higher level of security protection is to add an additional level of explicit trust among VMs to allow a VM to choose which other VMs it wants to communicate with. One way to establish such explicit trust is based on past transaction history and feedback ratings [Su et al. 2015]. Other possible solutions can be found from the excellent survey by Pearce et al. [2013]. Also, Gebhardt and Tomlinson [2010] present some suggestions on creating a proper security model and offer protection strategies for virtual machine communications.

3.6.3. Performance Stability. We have shown in Section 3.3.4 (Figure 3) that some existing shared-memory approaches deliver a good performance improvement on UDP workloads for coresident inter-VM communications compared to using conventional approaches but a small or no performance improvement for larger message sizes and streaming TCP workloads [Zhang et al. 2013a]. We argue that to enable the wide deployment of a shared-memory approach to inter-VM communication, we need to

ensure the performance stability for shared-memory-based inter-VM communication mechanisms, no matter whether the network protocol is TCP or UDP, the workload is transactional or streaming, the size of messages is small or large, the incoming rate of the messages is normal or very high, or the number of coresident VMs is small or large. Furthermore, when the VM live migration and VM dynamic deployment are present, the throughput performance should be stable regardless of whether it is before or after the migration.

3.7. Concluding Remarks

We would like to state that a careful tradeoff should be made regarding different design choices and requirements. For example, the choice of implementation layer is directly related to user-level transparency, and it also has an impact on the performance of shared-memory approaches. In addition, achieving higher reliability and security often leads to certain losses of performance. Thus, reliability and security facilities should be carefully designed and incorporated to minimize the unnecessary performance overhead. Finally, customizability and configurability are highly desirable and highly recommended features for designing and implementing a scalable and reliable shared-memory-based coresident VM communication protocol.

4. ARCHITECTURAL LAYOUT: A COMPARISON

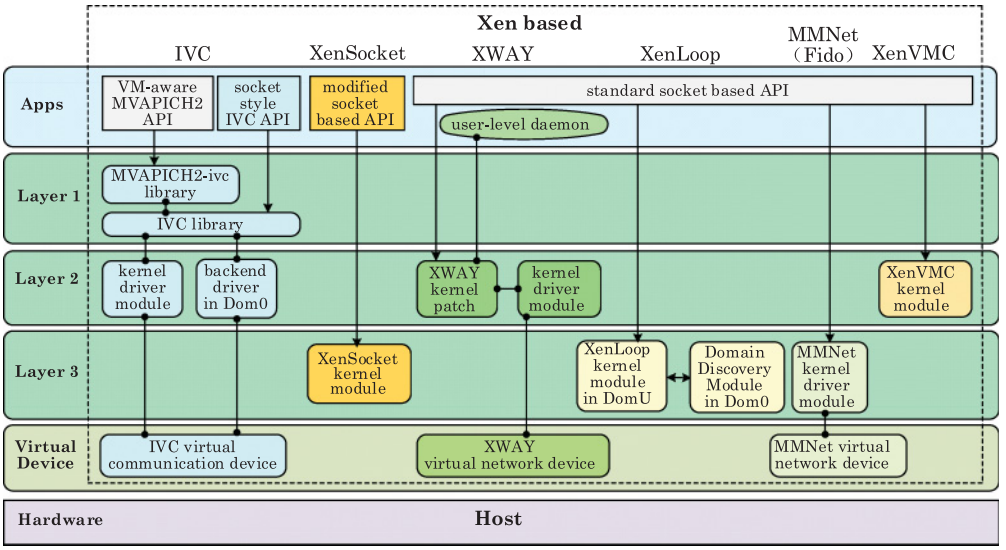
In this section, we classify existing representative shared-memory inter-VM communication mechanisms based on their architecture layout in the software stack and provide a comprehensive analysis and comparison on their design choices, including the implementation techniques for fundamental functionalities, seamless agility support, multilevel transparency, and additional features. In addition, we will compare Xen-based implementations with KVM-based implementations and identify similarities and differences in their design and implementation choices.

Figure 5 shows our classification of existing representative shared-memory approaches by their implementation layers in the software stack: layer 1 is the user libraries and system calls layer, layer 2 is the below system calls layer and above transport layer, and layer 3 is the below IP layer. To facilitate the comparative analysis, we show the Xen-based systems and KVM-based systems in Figure 5(a) and Figure 5(b), respectively. We illustrate each system with one or several components and show that different components may be designed and implemented at different layers within a single system. For presentation clarity, we defer the discussion on the modifications to VMMs to Section 7.3. We say that an existing shared-memory system belongs to the category of layer X (X = 1, 2, or 3) when its data transfer request interception mechanism is implemented in this layer.

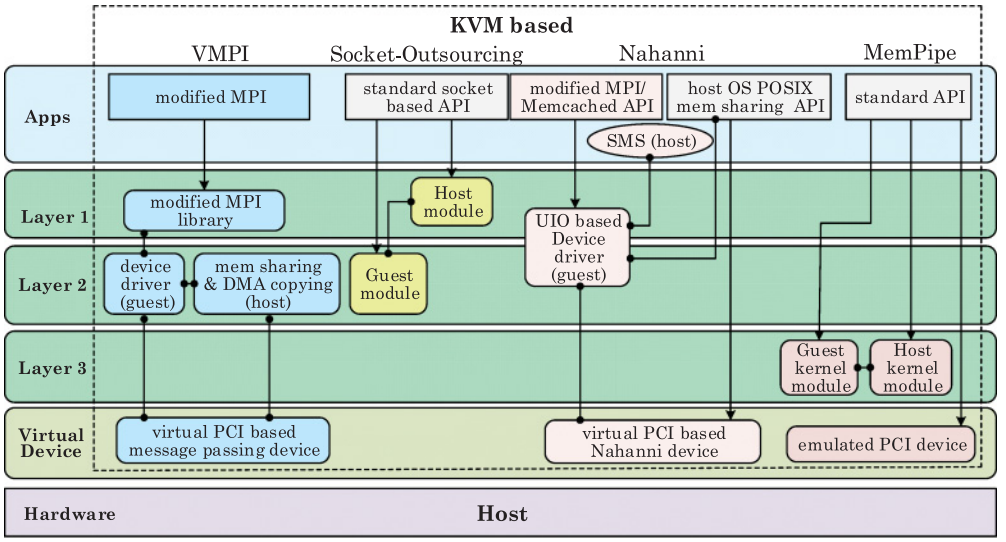
For Xen-based systems, we include IVC [Huang et al. 2007], XenSocket [Zhang et al. 2007], XWay [Kim et al. 2008], XenLoop [Wang et al. 2008b], MMNet [Radhakrishnan and Srinivasan 2008], and XenVMC [Ren et al. 2012] in our comparative analysis study. For KVM-based systems, we include VMPI [Diakhaté et al. 2008], Socket-outsourcing [Eiraku et al. 2009], Nahanni [MacDonell 2011], and MemPipe [Zhang et al. 2015] in our comparative analysis study. There have been some recent developments in the KVM category [Hwang et al. 2014, Zhang et al. 2014b, Zhang et al. 2015]. We have added some discussions on the new developments to date when appropriate.

4.1. User Libraries and System Calls Layer

Implementing the shared-memory-based inter-VM communication in the user libraries and system calls layer has a number of advantages as we have discussed in Section 3. IVC on the Xen platform and VMPI and Nahanni on the KVM platform are the representative efforts in this layer.



(a) Xen based coresident VM communication mechanisms



(b) KVM based coresident VM communication mechanisms

Fig. 5. Architectural layout of coresident VM communication mechanisms.

4.1.1. IVC. IVC is one of the earliest shared-memory efforts based on the Xen hypervisor [Huang et al. 2007]. It is designed for a cluster-based HPC environment and is a representative Xen-based approach whose user libraries are implemented in layer 1. Different from other related work on the Xen platform, IVC is developed based on the VMM-bypass I/O model instead of the split I/O model.

IVC consists of three parts: a user space VM-aware communication IVC library, a user space MVAPICH2-ivc library, and a kernel driver. The IVC library supports shared-memory-based fast communication between coresident VMs, which provides

socket-style interfaces. Supported by IVC, the MVAPICH2-ivc library is developed, which is derived from MVAPICH2, an MPI library over Infiniband. The kernel driver is called by the user space libraries to grant the receiver VM the right to access the sharing buffer allocated by the IVC library and gets the reference handles from the Xen hypervisor.

To verify the performance of IVC, Huang et al. [2007] and Huang [2008] conducted evaluations of MVAPICH2-ivc on a cluster environment with multicore systems and PCI-Express InfiniBand Host Channel Adapters (HCAs). InfiniBand is a kind of interconnect offering high bandwidth and low latency through user-level communication and OS bypass. It can be supported with a Xen platform via VMM-bypass I/O [Liu et al. 2006]. High performance and additional features make Infiniband popular in HPC cluster computing environments. Evaluation results demonstrate that in the multicore systems with Infiniband interconnections, IVC achieves comparable performance with native platforms [Huang et al. 2007; Huang 2008].

4.1.2. VMPI. VMPI [Diakhaté et al. 2008] is an Inter-VM MPI communication mechanism for coresident VMs targeted to the HPC cluster environment on the KVM platform. In VMPI, only local channels are supported. Different from other related work, VMPI supports two types of local channels: one to allow fast MPI data transfers between coresident VMs based on shared buffers accessible directly from guest OSs' user spaces, and the other to enable direct data copies through the hypervisor. VMPI provides a virtual device that supports these two types of local channels.

To implement VMPI, both guest and host OSs and the hypervisor are extended and modified. In guest implementation, the device is developed as a PCI (Peripheral Component Interface) device for each guest OS based on the Virtio framework. It offers a shared-memory message passing API similar to but not compatible with MPI via the device driver to guest OSs. The modified user libraries and the device enable applications in guest OSs to use shared memory instead of the TCP/IP network to communicate with each other. *mmap()* is used to map the shared memory of the device to user space. *ioctl* is used to issue DMA requests. In host implementation, basic functionalities, such as memory allocation, memory sharing and DMA copies, are provided. Slight modifications are made to QEMU instances to allow them to allocate memory from a shared-memory pool.

Experimental results show that VMPI achieves near-native performance in terms of MPI latency and bandwidth [Diakhaté et al. 2008]. Currently, VMPI only supports a small subset of MPI API. And its scalability is limited since it does not support a varying number of coresident VMs to communicate by using *fork()* to create the QEMU instances.

4.1.3. Nahanni. Nahanni [Macdonell 2011] provides coresident inter-VM shared-memory API and commands for both host-to-guest and guest-to-guest communication on the KVM platform. In order to avoid the overhead of crossing protection barriers from the guest user level to guest kernel and from guest OS to host, it is designed and implemented mainly in layer 1. Nahanni's interfaces are visible to user space applications. The MPI-Nahanni user-level library is implemented for computational science applications. The Memcached client and server are modified and extended to benefit from Nahanni [Gordon 2011a; Gordon et al. 2011b]. Nahanni supports only local channels. Both stream data and structured data are supported to aim at a broader range of applications.

Nahanni consists of three components: a POSIX shared-memory region on the host OS, a modified QEMU that supports a new Nahanni PCI device named *ivshmem*, and a Nahanni guest kernel driver developed based on the UIO (Userspace I/O) device driver model. The shared-memory region is allocated by host POSIX operations. It is

mapped to the QEMU process address space via *mmap()* and is added to the *RAMblocks* structure in QEMU, which makes it possible to manage virtual device memory through available interfaces. After the driver of device *ivshmem* is loaded, the mapped memory can be used by guest applications through mapping it to guest user space via the *mmap()* operation. The Shared-Memory Server (SMS), a standalone host process running outside of QEMU, is designed and implemented to enable inter-VM notification.

Evaluation results show that applications or benchmarks powered by Nahanni achieve better performance [Macdonell 2011; Gordon 2011a; Gordon et al. 2011b; Ke 2011]. However, to take advantage of Nahanni, it is required to rewrite applications and libraries, or to modify and extend existing applications and libraries. In addition, Nahanni by design does not consider VM live migration. Thus, it is supposed to be used by applications that do not expect to migrate or to make switches between the local and remote mode.

4.2. Below System Calls Layer, Above Transport Layer

Implementing shared-memory-based inter-VM communication below the system calls layer and above the transport layer represents the layer 2 solution. As we discussed in Section 3, although the implementation of the shared-memory channel in layer 1 can potentially lead to lower latency and higher throughput of network I/O workloads, it requires modification of user-level applications and libraries and thus has the worst user-level transparency. This motivates the research efforts to explore the implementation of shared-memory mechanisms at the lower layer. XWAY, XenVMC and Socket-outsourcing are the representative developments to date in layer 2.

4.2.1. XWAY. XWAY is another inter-VM communication optimization for coresident VMs [Kim et al. 2008]. XWAY is designed based on the belief that it is not practical to rewrite legacy applications with new APIs even if implementation at a lower layer of the software stack indicates some performance loss. The design of XWAY makes efforts to abstract all socket options and keeps user-level transparency. XWAY modifies the OS kernel by patching it. It intercepts TCP socket calls below the system calls layer and above the transport layer.

Hierarchically, XWAY consists of three components: switch, protocol, and device driver. They are implemented as a few lines of kernel patch and a loadable kernel module. Upon the very first packet delivery attempt, the switch component is used to intercept socket-related calls between the INET and TCP layer. It determines if the receiver is a coresident VM or not. Then it transparently chooses between the TCP socket and the local XWAY protocol, which should be called whenever a message is transmitted. The protocol component conducts the task of data transmission via the device driver. The device driver plays a basic role to support the XWAY socket and XWAY protocol. It writes data into the sharing buffer or reads data from it. It also transfers events between the sender and the receiver and makes a callback to upper components when necessary. In the implementation of XWAY, the virtual device is represented as XWAY channels.

Evaluation results show that under various workloads, XWAY achieves better performance than the native TCP socket by bypassing the long TCP/IP network stack and providing a direct shared-memory-based channel for coresident VMs [Kim et al. 2008].

4.2.2. XenVMC. XenVMC is another residency-aware inter-VM communication protocol implemented at layer 2, with transparent VM live migration and dynamic VM deployment support [Ren et al. 2012]. It satisfies the three design criteria: high performance, seamless agility, and multilevel transparency. For XenVMC, each guest OS

hosts a nonintrusive self-contained XenVMC kernel module, which is inserted as a thin layer below the system calls layer and above the transport layer.

The XenVMC kernel module contains six submodules: Connection Manager, Data Transfer Manager, Event Manager, System Call Analyzer, VM State Publisher, and Live Migration Assistant. The Connection Manager is responsible for establishing or tearing down shared-memory-based connections between two VM peers. The Data Transfer Manager is responsible for data sending and receiving. The Event Manager handles data-transmission-related notifications between the sender and the receiver. The System Call Analyzer enables transparent system call interception. It intercepts related system calls and analyzes them. If coresident VMs are identified, it bypasses traditional TCP/IP paths. The VM State Publisher is responsible for announcement of VM coresidency membership modification to related guest OSs. The Live Migration Assistant supports the transparent switch between the local and remote mode together with other submodules.

Experimental evaluation shows that compared with the virtualized TCP/IP method, XenVMC improves coresident VM communication throughput by up to a factor of 9 and reduces the corresponding latency by up to a factor of 6 [Ren et al. 2012].

4.2.3. Socket-Outsourcing. Socket-outsourcing [Eiraku et al. 2009] enables the shared-memory inter-VM communication between coresident VMs by bypassing the network protocol stack in guest OSs. Socket-outsourcing is implemented in layer 2. It supports two representative operating systems (Linux and NetBSD), with two separate versions for two VMMs (Linux KVM and PansyVM). We focus our discussion on its Linux KVM version.

Socket-outsourcing consists of three parts: a socket layer guest module, the VMM extension, and a user-level host module. In guest OSs, a high-level functionality module in the socket layer is replaced to implement the guest module. Concretely, the socket function in structure *proto_ops* for TCP and UDP is replaced with self-defined ones so that it can bypass the protocol stack in guest OSs by calling the high-level host module implemented in the host OS and improve the performance of coresident inter-VM communication. The outsourcing of the socket layer is called Socket-outsourcing. Socket-outsourcing supports standard socket API. It is user transparent. However, the VMM is extended to provide (1) a shared-memory region between coresident VMs, (2) event queues for asynchronous notification between the host module and guest module, and (3) a VM Remote Procedure Call (VRPC). The user-level host module acts as a VRPC server for the guest module. It provides socket-like interfaces between the guest module and the host module.

Experimental results show that by using Socket-outsourcing, a guest OS achieves similar network throughput as a native OS using up to 4 Gigabit Ethernet links [Koh 2010]. From the results of an N-tier web benchmark with a significant amount of inter-VM communication, the performance is improved by up to 45% over the conventional KVM-hosted VM approach [Eiraku et al. 2009]. VM live migration is not a part of the design choices and thus not supported by Socket-outsourcing.

4.3. Below IP Layer

Implementing the shared-memory-based inter-VM communication below the IP layer has several advantages, such as higher transparency, as outlined in Section 3. However, layer 3 is lower in the software stack, and implementation at layer 3 may potentially lead to higher latency due to higher protocol processing overheads and a higher number of data copies and context switches across barriers. XenSocket, XenLoop, and MMNet are the representative efforts developed in layer 3 on the Xen platform. MemPipe

[Zhang et al. 2015] is a recent implementation on the KVM platform in layer 3. All these efforts are focused on optimization techniques for high performance.

4.3.1. XenSocket. XenSocket [Zhang et al. 2007] provides a shared-memory-based one-way coresident channel between two VMs and bypasses the TCP/IP network protocol stack when the communication is local. It is designed for applications in large-scale distributed stream processing systems. Most of its code is in layer 3 and is compiled into a kernel module. It is not binary compatible with existing applications. And it makes no modification to either the OS kernel or VMM.

In XenSocket, there are two types of memory pages shared by the communicating VM peers: a descriptor page and buffer pages. The descriptor page is used for control information storage, while the buffer pages are used for data transmission. They work together to form a circular buffer. To establish a connection, the shared memory for the circular buffer is allocated by the receiver VM and later mapped by the sender VM. Then the sender writes data into the FIFO buffer and the receiver reads data from it in a blocking mode. The connection is torn down from the sender's side after data transfer to ensure that the shared resources are released properly. To enhance the security, application components with different trust levels are placed on separate VMs or physical machines.

Performance evaluation shows that XenSocket achieves better bandwidth than the TCP/IP network [Zhang et al. 2007]. Without the support of automatic coresident VM detection, XenSocket is primarily used by applications that are aware of the coresidency information and do not expect to migrate or make switches between local and remote mode during runtime. Once XenSocket is used, the remote path will be bypassed.

4.3.2. XenLoop. XenLoop [Wang et al. 2008] provides fast inter-VM shared-memory channels for coresident VMs based on Xen memory sharing facilities to conduct direct network traffic with less intervention of the privileged domain, compared with that of traditional TCP/IP network communication. It provides multilevel transparency and needs no modification, recompilation, or relinking to existing applications, guest OS kernelm and Xen hypervisor. To utilize netfilter [Ayuso 2006], a third-party hook mechanism, XenLoop is implemented below the IP layer, the same layer in which netfilter resides.

XenLoop consists of two parts: (1) a kernel module named the XenLoop module, which is loaded between the network layer and link layer into each guest OS that wants to benefit from the fast local channel, and (2) a domain discovery module in Dom0. Implemented on top of netfilter, the module in the guest OS intercepts outgoing network packets below the IP layer and automatically switches between the standard network path and a high-speed inter-VM shared memory channel. *<guest-ID, MAC address>* pairs are used to identify every VM. One of the kernel parts of the XenLoop module is its fast bidirectional inter-VM channel. The channel structure is similar to that of XWAY. The channel consists of two FIFO data channels (one for data sending, the other for data receiving) and a bidirectional event channel that is used to enable notifications of data presence for the communicating VM peers. The module in Dom0 is responsible for discovering coresident VMs dynamically and maintaining the coresidency information, with the help of XenStore. XenLoop supports transparent VM live migration via the aforementioned modules.

Evaluations demonstrate that XenLoop increases the bandwidth by up to a factor of 6 and reduces the inter-VM round-trip latency by up to a factor of 5, compared with the front-end/back-end mode [Wang et al. 2008b]. Although XenLoop satisfies the three design criteria we outlined in Section 3, we have shown in Figure 3 (Section 3) some problems inherent in the XenLoop implementation, due to the choice of layer 3, such as bypassing some important optimizations provided at the NIC layer.

4.3.3. MMNet. Different from other related work, MMNet [Radhakrishnan and Srinivasan 2008] works together with the Fido framework [Burtsev et al. 2009] to provide shared-memory-based inter-VM communication optimization for coresident VMs on the Xen platform. Fido was designed for enterprise-class appliances, such as storage systems and network-router systems. It offers three fundamental facilities: a shared-memory mapping mechanism, a signaling mechanism for inter-VM synchronization, and a connection handling mechanism. Built on top of Fido, MMNet emulates a link layer network device that provides shared-memory-based mechanisms to improve the performance of coresident inter-VM communication. Its driver is implemented in the lowest layer of the protocol stack. It easily achieves user-level transparency by providing a standard Ethernet interface. Fido and MMNet together give the user a view of standard network device interfaces, while the optimization of shared-memory-based inter-VM communication is hidden beneath the IP layer. MMNet enables switching between the local and remote communication mode by updating the IP routing tables.

Different from other Xen-based related work, Fido leverages the relaxed trust model to enable zero copy and to reduce data transfer overhead. It maps the entire kernel space of the sender VM to that of the receiver VM in a read-only manner to avoid unnecessary data copies and to ensure security. Actually, it is designed for communication between VMs that are trustable to each other, where the mapping of guest OSs' memory is acceptable since the possibility of malicious memory access is low in a private, well-controlled environment. As for reliability, Fido provides heartbeat-check-based connection monitoring and failure handling mechanisms to be capable of detecting VM failures and conducting proper operations accordingly.

MMNet obtains lower performance overhead by incorporating the relax trust model [Burtsev et al. 2009; Radhakrishnan and Srinivasan 2008]. Evaluation [Burtsev et al. 2009] shows that for the TCP STREAM and UDP STREAM workload, MMNet provides near-native performance. For the TCP STREAM workload, it achieves twice the throughput compared with XenLoop. And for the UDP STREAM workload, MMNet increased the throughput by up to a factor of 4 compared with that of Netfront, and its latencies are comparable to XenLoop for smaller message sizes. As the message sizes increase ($\geqslant$8KB), MMNet outperforms XenLoop by up to a factor of 2.

4.3.4. MemPipe. MemPipe is the most recent shared-memory inter-VM communication method implemented in layer 3 on the KVM platform [Zhang et al. 2015]. To optimize the performance of layer 3 implementation, MemPipe introduced a dynamic shared-memory pipe framework for efficient data transfer between colocated VMs with three interesting features: (1) MemPipe promotes a dynamic proportional memory allocation mechanism to enhance the utility of shared-memory channels while improving the colocated inter-VM network communication performance. Instead of statically and equally allocating a shared-memory pipe to each pair of colocated communicating VMs, MemPipe slices the shared memory into small chunks and allocates the chunks proportionally to each pair of VMs based on their runtime demands. (2) MemPipe introduces two optimization techniques: time-window-based streaming partitions and socket buffer redirection. The former enhances the performance of inter-VM communication for streaming networking workloads, and the latter eliminates the network packet data copy from the sender VM's user space to its VM kernel. (3) MemPipe is implemented as kernel modules to achieve high transparency. Its functionalities are split between a kernel module running in the guest kernel and a kernel module in the host kernel. The MemPipe kernel module in the host is responsible for allocating the shared-memory region from the host kernel memory and initializing the allocated shared-memory region so that guest VMs are able to build their own memory pipes.

The MemPipe kernel module in a guest VM manages the shared-memory pipes for its communication with other colocated VMs. It consists of a Peer VM Organizer, Packet Analyzer, Memory Pipe Manager, Emulated PCI Device, and Error Handler.

The Peer VM Organizer enables each VM to distinguish its colocated VMs from remote VMs (VMs running on a different host machine). It is implemented using a hashmap, with the Mac address of a VM as the hash key and the corresponding data structure used for establishing the memory pipe as the hash value. The Packet Analyzer helps VMs to determine whether a network packet is heading to its colocated VMs or remote VMs. The Memory Pipe Manager consists of four parts: Pipe Initiator, Pipe Reader/Writer, Pipe Analyzer, and Pipe Inflator/Deflator. Since KVM does not allow sharing memory between the host and the guest VM, MemPipe creates an emulated PCI device in each VM to overcome this limitation. The PCI device takes the memory, which is allocated and initialized by the Shared Memory Initiator in the host, as its own I/O region. Then it maps its I/O region into the VM's kernel address and transfers the base virtual address to the Memory Pipe Manager. Thus, the Memory Pipe Manager is able to access the shared memory from this virtual address. Although the based virtual addresses may not be the same in different VMs, they are pointing to the same physical address: the beginning of the memory allocated by the Shared Memory Initiator. After putting a packet into a shared-memory pipe, the sender VM notifies the receiver VM through the Events Handler to fetch the packets.

Experimental evaluations show that MemPipe outperforms existing layer 3 systems such as XenLoop (recall Figure 4 in Section 3) for both transactional workloads and streaming workloads under TCP and UDP. The most recent release of MemPipe is built on KVM [Kivity et al. 2007] 3.6, QEMU (http://wiki.gemu.org) 1.2.0, and Linux kernel 3.2.68.

4.4. Comparing Xen-Based Implementation Versus KVM-Based Implementation

Shared-memory-based inter-VM communication optimization for coresident VMs is desirable for both the Xen-based virtualization environment and the KVM-based virtualization environment. Early research is primarily targeted for HPC MPI applications. Recent trends are toward more generic computing areas such as large-scale distributed computing, web transaction processing, and cloud computing and big data analytics services. Understanding the similarity and subtle differences between Xen-based implementations and KVM-based implementations is critical and beneficial for the development and deployment of next-generation shared-memory-based inter-VM communication systems.

In general, Xen-based shared-memory implementations and KVM-based efforts share all the design objectives and functional and nonfunctional requirements for shared-memory-based inter-VM communication optimization. For example, they share common fundamental functionalities, such as memory sharing, connection setup and tear-down, local connection handling, and data sending and receiving, to name a few. In addition, they also share the nonfunctional requirements such as high performance, multilevel transparency, seamless agility, reliability, and security.

However, Xen and KVM are different virtualization platforms with different network architectures and interfaces, as outlined in Section 2. These architectural and network interface differences contribute to the differences in the design and implementation of their respective shared-memory communication mechanisms. For Xen-based shared-memory communication development efforts, there are more fundamental mechanisms available, such as Xen Grant Table, Xen Event Channel, and XenStore, which provide a good foundation to simplify the design and implementation of shared-memory channels between coresident VMs. In comparison, KVM does not offer as many fundamental

Table II. Architectural Layout and General Features

	Xen Based						KVM Based			
	IVC	*Xen Socket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
Scope of application	HPC	Distributed processing	Network intensive	Network intensive	Enterprise-class services	Network intensive	HPC	Not specified	HPC, MemCached	Network intensive
Type of API	IVC-specific API, VM-aware MVAPICH 2 API	Modified socket-based API	Standard API	Standard API	Standard API	Standard API	Modified MPI	Standard socket-based API	Modified MPI & Memcached API	Standard API
I/O virtualization model supported	VMM-bypass I/O	Split I/O	Split I/O	Split I/O	Split I/O	Split I/O	Virtio based	Software-emulated I/O	Software-emulated I/O	Software-emulated I/O
Location of local shared-memory channel	Layer 1	Layer 3	Layer 2	Layer 3	Layer 3	Layer 2	Layer 1	Layer 2	Layer 1	Layer 3
Form of main components	Libraries, kernel driver	Kernel module	Kernel patch, kernel driver	Kernel modules	Kernel driver	Kernel module	Library, kernel driver, patch for QEMU	Host module, guest module, patch for KVM & PansyVM	UIO-based device driver, patch for QEMU/KVM	Host module, guest module Patch for KVM

programmable capabilities as Xen. Thus, KVM-based research and development efforts need to focus more on mechanisms to provide a local memory sharing method for guest-guest VM communication and host-guest VM communication.

The architectural design and general features of existing representative shared-memory inter-VM communication systems are summarized in Table II.

Although *virtqueues* in the Virtio framework can be used like I/O ring buffers, Virtio is based on DMA semantics, which is not suitable for every design. Regardless of whether one is using the Virtio framework or not, the QEMU/KVM needs to be extended to provide similar facilities like the Xen Grant Table, Xen Event Channel, and XenStore. For example, to extend the current hypervisor for providing underlying support of shared memory, Nahanni and VMPI modify QEMU, and Socket-outsourcing modifies the KVM module and QEMU. As layer 1 implementation, VMPI and Nahanni choose to sacrifice their user-level transparency to simplify the implementation of the shared-memory channel and reduce potential context switch overhead. Thus, the shared-memory channel in both systems is visible to applications. The legacy applications need to be rewritten or modified to know about the coresidency information of the respective VMs in order to benefit from the shared-memory-based inter-VM communication mechanisms. As layer 2 implementation, Socket-outsourcing provides the shared memory region between coresident VMs, event queues for asynchronous notification between host and guest, and VM remote procedure call (VRPC) using the user-level host module as a VRPC server for the guest with socket-like interfaces between the guest and the host. Moreover, all three existing KVM-based developments provide no support for seamless agility, namely, no support for automated switching between local and remote communication channels. MemPipe is the only full-fledged shared-memory system on the KVM platform, which satisfies the three design criteria discussed in Section 3: high performance, seamless agility, and multilevel transparency.

4.5. Recent Advances in Network I/O Virtualization

Recent research on network I/O virtualization has centered on improving the inter-VM network I/O performance by software-defined network (SDN) and network function virtualization (NFV). Representative technology includes the single-root I/O virtualization (SR-IOV) [MSDN 2014] for making PCI devices interoperable, and the Intel Data Plane Development Kit (DPDK) [Sanger 2013; Intel 2013] for fast packet processing using multicore systems.

SR-IOV-capable devices allow multiple VMs to independently share a single I/O device and can move data from/to the device by bypassing the VMM. SR-IOV offers an attractive alternative for the virtualization of high-performance interconnects such as InfiniBand. Jose et al. [2013] show that by combining SR-IOV with InfiniBand, instead of TCP/IP networks, based on the VMM-bypass I/O model, one can obtain near-native performance for internode MPI point-to-point communication. Zhang et al. [2014a, 2014b] show that by introducing VM residency-aware communication, the performance of MPI communication on SR-IOV-based InfiniBand clusters can be further improved.

Although SR-IOV improves the communication between VM and its physical device, it cannot remove the overhead of colocated inter-VM communication. This is because with SR-IOV, packets still need to travel through the network stack of the sender VM, to be sent from the VM to the SR-IOV device, and then sent to the receiver VM. This long path can still lead to an unnecessarily high cost for colocated inter-VM communication, especially for larger-size messages.

Alternatively, Intel DPDK [Intel 2013] is a software framework that allows high-throughput and low-latency packet processing. It allows the applications to receive data directly from NIC without going through the Linux kernel and eliminates the overhead of interrupt-driven packet processing in traditional OSs. As a set of libraries and drivers, Intel DPDK utilizes huge pages in guest VMs and multicore processing to provide applications direct access to the packets on NIC. The huge pages in DPDK are statically allocated to each VM. However, DPDK is restricted and on its own cannot yet support flexible and fast network functions [Sanger 2013].

NetVM [Hwang et al. 2014] is the most recent development by utilizing the shared-memory mechanism on top of DPDK. NetVM shows that the virtualized edge servers can provide fast packet delivery to VMs, bypassing the hypervisor and the physical network interface. However, NetVM is limited to run on a DPDK-enabled multicore platform, and no open source is made available to date.

In summary, shared-memory-based inter-VM communication mechanisms are important value-added methods for further improving the performance of network I/O virtualization.

5. FUNDAMENTAL FUNCTIONAL COMPONENTS: DESIGN COMPARISON

All shared-memory-based residency-aware inter-VM communication mechanisms must provide three fundamental functionalities: (1) memory sharing structures and corresponding facilities, (2) shared-memory channel (local connection) setup/tear down, and (3) sending and receiving data. Figure 6 illustrates the interactions of these three common functional components for enabling inter-VM communication.

5.1. Memory Sharing

For VMs to communicate via their shared-memory channel, it is necessary to build a buffer of shared physical pages for both VMs such that the two VMs can communicate directly by accessing the specific slot in the buffer.

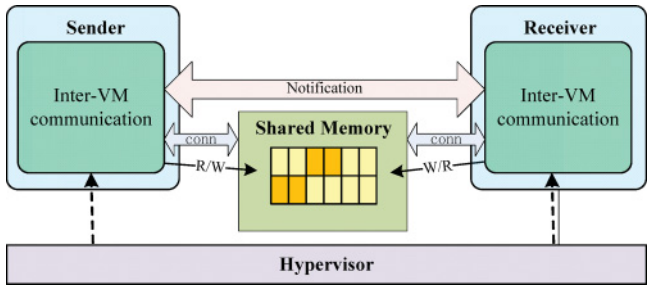


Fig. 6. Fundamental common functionalities of inter-VM communication between coresident VMs.

For existing shared-memory systems implemented on Xen platform, the Xen Grant Table is usually used as a fundamental memory sharing facility to offer mapping/transfer pages between the sender VM and receiver VM. The Grant Table provides an efficient and secure way for memory sharing. The Grant Table API is accessible from the OS kernel, which explains to some extent why most of the Xen-based shared-memory mechanisms are implemented in the kernel. Implementation at the kernel level makes it easier to support both the shared-memory-based local channel and the traditional network-based remote channel since functionalities, such as packet interception and redirection, can be supported in the kernel between user applications and inter-VM communication enabling components.

However, different shared-memory methods implemented on the KVM platform may differ from one another in terms of their support for memory sharing: *virtqueues* in the Virtio framework provides the interfaces to manage a list of buffer descriptors, which are used by VMPI as ring buffers to implement its message passing MPI. However, *virtqueues* itself does not provide the semantics of guest-guest or host-guest memory sharing. Nahanni shows that instead of using the Virtio framework, it is preferable to expose *ivshmem*, the virtual device, as a PCI device to the guest OSs. Nahanni's shared memory is created by the host OS with POSIX API and is mapped to the shared-memory region of the virtual PCI device, which is exposed by the device driver to the guest OS and is mapped again to the user level. For KVM, user-level QEMU is capable of accessing guest physical memory. By taking advantage of this feature, Socket-outsourcing implements its self-defined memory sharing algorithms.

5.2. Local Connection Handling

When the sender VM or the receiver VM detects the first network traffic to its coresident communicating VM, it initiates the procedures to establish shared-memory-based local connection. The local connections are set up usually as a client-server model between the sender and the receiver. The simplified procedures are, first, memory for shared buffer is allocated by the client who sponsors the connection establishment procedure, and then the client passes the handles of the buffer to the server, which maps the communication buffer to its own address space through inter-VM shared-memory facilities. The event channel or similar structures are initialized for control flow between communicating VMs.

After the data transfer is finished, the sender or the receiver is shut down, or, when the connection is to be switched from local to remote, the local connection needs to be torn down. Different from a traditional network connection, where the sender and the receiver can be shut down independently, specific care should be given to correctly tear down the shared-memory-based local channel to make sure that the shared memory is unmapped properly and, consequently, the memory is deallocated.

5.3. Data Transmission

Once the shared-memory channel is established, the local connection is initialized, and the send VM can send the network traffic to the receiver VM via the local channels. There are two popular ways to organize the shared buffer for data transferring: circular-buffer-based method and non-circular-buffer-based method.

5.3.1. Circular-Buffer-Based Approaches. The circular-buffer-based approaches organize the shared buffer into two producer-consumer circular buffers (one for sending and one for receiving) with one event channel for every pair of communicating VMs. The producer writes data into the buffer and the consumer reads data from it in an asynchronous manner. The event channel is used to notify the communicating VMs of the presence of data in the circular buffer. The offset in the buffer should be well maintained. Circular-buffer-based mechanisms offer the advantage that data in the buffer is kept in order and thus no explicit cross-domain synchronization is needed.

XenSocket, XWAY, XenLoop, and XenVMC are representative shared-memory-based methods on the Xen platform, which incorporate the circular buffer mechanism. IVC and VMPI are layer 1 shared-memory implementations on KVM. They share the idea with the previously mentioned related work but with small differences. For the IVC channel, the shared buffer consists of two circular buffers containing multiple data segments and a pair of producer/consumer pointers. Instead of using the Xen Event-Channel-based notification mechanism, both the sender and the receiver check the pointers to determine if the buffer is full or if data has arrived. VMPI provides two types of local channels: a producer/consumer circular buffer for small messages ($\leqslant$32KB) and a rendezvous-protocol-based DMA channel for larger messages. Different from other existing works, the XenSocket channel is one way and does not support bidirectional data transmission.

5.3.2. Non-Circular-Buffer-Based Approaches. There are a number of existing shared-memory mechanisms, such as MMNet on the Xen platform, and Nahanni and Socket-outsourcing on the KVM platform, which organize their buffer for data sharing differently from the circular-buffer-based approaches. MMNet is built on top of Fido, which adopts a relaxed trust model and maps the entire address space of the sender VM into the receiver VM's space before any data transmission is initiated, so that the data is transferred with zero copy. For Socket-outsourcing, the guest module allows the host module to access its memory regions, which makes memory sharing between the host and guest possible. Event queues are allocated in the shared memory and can be accessed via self-defined API to enable asynchronous communication between the host module and the guest module. The socket-like VRPC protocol is implemented between the sender and the receiver to set up or tear down connections, to transfer data, and so forth. For Nahanni, it modifies QEMU to support a virtual PCI device named *ivshmem*. The shared-memory object allocated by host POSIX operations is mapped to the shared buffer of this device. The UIO device driver in the guest OS makes the shared buffer available to the guest user-level applications. Its SMS coordinates with Linux *eventfds* and *ivshmem's* register memory mechanisms to provide an inter-VM notification mechanism for Nahanni. Different from other related works, Nahanni supports not only stream data but also structured data.

Table III summarizes the features of fundamental functionalities for both Xen-based and KVM-based shared-memory systems.

6. SEAMLESS AGILITY: COMPARATIVE ANALYSIS

Recall from Section 3.4 that seamless agility refers to the support for (1) automatic detection of coresident VMs, (2) automatic switch between local shared-memory mode

Table III. Features of Fundamental Functionalities

	Xen Based						KVM Based			
	IVC	*XenSocket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
Approach to bypassing traditional network path	Via VM-aware MVAPICH 2-ivc library	Via modified API and user libraries	Socket-related calls inter-ception	Netfilter hooks	IP routing tables updating	Transparent system call interception	Via modified MPI and user libraries	Replacing related kernel functions with self-defined ones	Via modified API and device ivshmem	Replace/ extend kernel functions with self-defined ones
Auxiliary facilities for local connection and data exchange	Grant Table Event Channel	Grant Table Event Channel	Grant Table Event Channel	Grant Table XenStore Event Channel	Grant Table XenStore Event Channel	Grant Table XenStore Event Channel	Virtio	Shared memory, event queues, VRPC of extended KVM	PCI, mmap, UIO, eventfds	Shared memory, PCI, event queues
Complete memory isolation	Yes	Yes	Yes	Yes	No Relaxed	Yes	Yes	Yes	Yes	Yes
Bidirectional connection	Yes	No One way	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Data buffer type	Circular buffer	Circular buffer	Circular buffer	Circular buffer	Address space mapping	Circular buffer	Circular buffer for message (≤32KB)	N/A	Host: POSIX memory object Guest: device memory region	Circular buffer

of communication and remote TCP/IP communication, and (3) dynamic addition or removal of coresident VMs. These functionalities are critical for shared-memory-based inter-VM communication to work effectively and correctly in the presence of VM live migration and VM dynamic deployment. We dedicate this section to provide a comparative analysis on whether and how seamless agility is supported in existing representative shared-memory-based coresident VM communication mechanisms.

6.1. Automatic Detection of Coresident VMs

As mentioned in Section 3.4, there are two approaches to maintain VM coresidency information: static method and dynamic method.

For Xen-based shared-memory systems, XenSocket does not provide any support for dynamic addition or removal of coresident VMs, and thus cannot work in conjunction with the VM live migration. XWAY [Kim et al. 2008] utilizes a static method to generate and maintain its coresident VM list. When a sender VM sends a request to a receiver VM, XWAY refers to the static file that lists all coresident VMs to determine whether the receiver VM resides on the same physical machine or not. If yes, XWAY performs an automatic switch between the shared-memory-based local channel and the traditional network path. However, XWAY does not support dynamic addition or removal of coresident VMs. Thus, XWAY only works when VM live migration and VM dynamic deployment are performed manually.

IVC [Huang et al. 2007] initially registers the VM coresidency information in the back-end driver of Dom0 in a static manner. During runtime, IVC provides API for communicating the client (sender) and server (receiver) to be registered to form a local communication group and to obtain the group membership information such as *magic id*. All registered domains with the same *magic id* will communicate through local IVC channels. Although IVC's original coresident VM information is collected in

a static manner, it supports automatic detection of coresident VMs by dynamically maintaining an IVC-active list, a list of active virtual connections between coresident VMs.

XenLoop [Wang et al. 2008] provides a soft-state domain detection mechanism to monitor the addition/removal of coresident VMs and to dynamically gather and update VM coresidency information. A Domain Discovery module in Dom0 periodically scans all guest entries in XenStore, where each entry represents its state. Then the module advertises the updated information to all the VMs covered by the existing entries and the VMs update their local *<guest-ID, Mac address>* lists. MMNet [Radhakrishnan and Srinivasan 2008] claims that it provides an automatic VM detection mechanism and supports VM live migration, but related technical details are not made available.

XenVMC differs from XenLoop in that there is no centralized management. Coresident VMs and their related local channels' information are organized in a structure defined as *vms[]*, which is an array of coresident VMs maintained by every VM. Each item in *vms[]* represents one of the coresident VMs on the physical host machine (excluding the Dom0 VM itself). It stores not only coresidency information but also the data of local channels. When one VM is created or migrated into a new host, *vms[]* of this VM will be initialized. When an event such as creation, migration in/out, or shutdown of a coresident VM occurs, all the other VMs on the same physical machine will be notified so that their *vms[]* will be correctly updated. The *vms[]* entry of a VM will be deleted, upon receiving the request to migrate out, from its current physical host machine.

For KVM-based shared-memory systems, VMPI [Diakhate et al. 2008], Nahanni [Macdonell 2011], and Socket-outsoucing [Eiraku et al. 2009] all provide no support for transparent detection of coresident VMs. Nahanni's shared-memory server (SMS) was originally designed and implemented to enable inter-VM notification. The guest OS is required to be registered with SMS when it is first connected to SMS. However, automatic coresident VM detection and auto-switch between the local channel and remote network path are not supported in Nahanni. In order to support dynamic coresident VM membership maintenance, Nahanni needs to be extended. For example, to facilitate the Memcached client and server to use Nahanni, Adam Wolfe Gordon implemented Locality Discovery, a user-level mechanism, to judge if the client and the server application are in two coresident VMs [Gordon 2011a; Gordon et al. 2011b]. MemPipe [Zhang et al. 2015] extends QEMU/KVM to provide full-fledged support for seamless agility for shared-memory communication on the KVM platform. Similarly, for the Xen-based platform, XenLoop and XenVMC support fully transparent VM migration, transparent switch between local and remote mode, and automatic coresident VM detection.

6.2. Auto-Switch Between Local Mode and Remote Mode of Inter-VM Communication

To support transparent switch between the local mode and remote mode, the two tasks as mentioned in Section 3.4.2 are involved.

For Xen-based shared-memory solutions, IVC has two kinds of communication channels available in MVAPICH2-ivc: a shared-memory-based local IVC channel over user space shared memory for coresident communicating VMs, and a network-based remote channel over InfiniBand for communicating VMs on separate hosts. As VMs migrates in/out, the MVAPICH2-ivc library supports an intelligent switch between the local IVC channel and remote network channel via its communication coordinator implemented in user space libraries, which are responsible for dynamically setting up or tearing down the connections when VM migration occurs. It also keeps an IVC-active list and updates it when necessary. IVC offers the flexibility of supporting VM live migration.

However, since information such as *magic id* must be preconfigured, live migration is not supported with full transparency.

XWAY determines whether the receiver VM is coresident or not by referring to a preconfigured static file through its switch component at the first packet delivery. Then it decides to choose between the TCP socket and local XWAY protocol to transmit the data.

XenVMC transparently intercepts every network-related system call and executes its user-defined system call handler. The handler analyzes from the context whether the communicating VMs are coresident or not. If yes, it bypasses the TCP/IP path by executing the codes for shared-memory-based communication. Otherwise, it recovers the entry address of the original handler and executes it. The entries in the system call table are modified in a way that is transparent to the OS kernel.

MMNet supports automatic coresident VM membership maintenance, which enables communicating VMs to establish connections dynamically. MMNet also allows running applications within a VM to seamlessly switch from/to the local shared-memory path by updating the IP routing tables accordingly.

Instead of implementing the interception mechanism from scratch, XenLoop uses netfilter [Ayuso 2006], a third-party hook mechanism provided inside the Linux kernel for kernel modules to register callback functions within the network stack, to intercept every outgoing network packet below the IP layer, and to determine the next hop node by the information in its header. Since netfilter resides below the IP layer, its interception mechanism indicates a longer data transmission path compared with alternative approaches in layer 2.

For KVM-based shared-memory communication methods, such as Nahanni and VMPI, the user applications need to explicitly specify whether the local optimized channel or original network channel is to be used via different APIs: specific shared-memory API or standard network API. Nahanni does not support the transparent switch between the local and remote mode. Socket-outsourcing replaces traditional socket communication functions with shared-memory-oriented ones at the socket layer, without modifying standard socket API. However, no technical details are provided to indicate that it supports the transparent switch between the local and remote mode. MemPipe [Zhang et al. 2015] supports the auto-switch between local shared-memory communication and remote inter-VM communication through a conventional network channel as part of its kernel module implementation.

6.3. Discussion on Race Condition

Seamless agility not only refers to auto-detection of coresident VMs and auto-switch between local and remote communication channels but also requires the guarantee that residency-aware inter-VM communication is reliable and robust in the presence of dynamic addition or removal of coresident VMs. Ideally, dynamic addition or removal of a VM should be made visible to other VMs on the same physical host machine immediately after the event occurs. However, when VMs on the same host cannot be notified of the membership changes immediately and synchronously upon the update to the VM coresidency information, race conditions may occur. Thus, not only should the detection of VM coresidency information be done on demand and whenever a VM communicates with another VM, but also we need to provide immediate update mechanisms for refreshing the list of coresident VMs on the respective physical host machine(s). For example, when a VM is migrated out to another physical host machine, it should notify all its coresident VMs on both the current host machine and the new destination host machine to update their coresident VM list. This will avoid errors concerning local/remote connection management and pending data handling because the coresident VM list is out of date.

Recall our discussion on reliability in Section 3.6.1: we described what race conditions are and how they may occur for shared-memory inter-VM communication in the presence of dynamic VM migration and dynamic VM deployment. We also briefly described some race condition prevention or resolution mechanisms. In general, the following three categories of operations need coresidency information either explicitly or implicitly and thus may become vulnerable when the coresidency information is not kept up to date: (1) *connection establishment*, (2) *pending data handling* for data remaining from former local/remote connections, and (3) *connection tearing down*. Let t_{op} denote the beginning time for an operation, t_{event} denote the time when the addition or removal of a VM occurs, and $t_{notified}$ denote the time when corresponding coresident VMs are notified of the events. If the gap between t_{event} and $t_{notified}$ is large and t_{op} happens to fall into the time interval specified by the gap, then a race condition is created due to the inconsistency between the up-to-date coresident VM information and the out-of-date coresident VM list maintained in the VMs of the respective host machines. In the rest of this section, we will provide a comparative analysis on how existing shared-memory systems handle such race conditions.

6.3.1. Race Condition Handling in Existing Shared-Memory Systems. For residency-aware inter-VM communication mechanisms that adopt static methods for detection of coresident VMs, such as IVC and XWAY, no race condition (as defined in Section 3.6.1) exists. The reason is that once the coresidency information is prefigured, no membership changing is allowed during runtime, unless the static file with membership information is modified and the coresident VM list is updated via a specific API manually.

For implementations with dynamic coresident VM detection, race conditions may occur if the update to the coresident VM list is asynchronous and deferred with respect to the on-demand addition or removal of VMs. For example, for several Xen-based shared memory systems, such as XenLoop, MMNet, and XenVMC, which support dynamic coresident VM detection via XenStore, race conditions exist. However, neither of these systems has discussed how it handles race conditions in the presence of VM live migration.

In order to support race condition prevention, the XenStore-based module needs to be extended to enable synchronous notification to be triggered before any update transaction over the XenStore to update the coresidency information of a VM is committed. Compared to the prevention methods that require modifying the XenStore-based module to maintain strong consistency, the race condition resolution methods use the optimistic approaches to handle or compensate for the possible errors after the occurrence of race condition. They maintain weak consistency in the sense that the notification of changes to the coresidency information caused by VM live migration is delayed until the respective VMs initiate or are involved in an inter-VM communication request.

For KVM-based shared-memory systems, only MemPipe provides auto-detection of coresident VMs and auto-switch between the local mode and remote mode of inter-VM communications. In addition, the first release of MemPipe is implemented as a solution in layer 3. It maintains the coresident VM membership information asynchronously using a periodic update method. Also, MemPipe checks the update to the coresidency information before determining whether to switch the inter-VM communication to the local shared-memory channel.

6.3.2. Potential Impacts on Connection Management and Pending Data Handing. To better understand how race condition management may affect the correctness and performance of residency-aware inter-VM communication mechanisms, Table IV shows the potential impact for connection management, for handling of pending data remaining from previous local/remote connections, and for connection teardown along two dimensions:

Table IV. Impacts of Race Conditions on Connection Management and Pending Data Handling

	VM Addition		VM Removal	
	VM Migration In	VM Creation	Migration Out	VM Shutdown
Connection establishment	No error Performance overhead	No error Deferred establishment	Error	Error
Pending data handling	N/A	N/A	Layer 2 approachs: Error	N/A
			Layer 3 approachs: No error	
Connection tearing down	No error	N/A	Possible error	N/A

(1) events leading to the change of coresident VM membership and (2) operations affected by race condition.

Note that not all the events are included in previous table. For example, events such as VM reboot and VM destroy are not enumerated, since they are similar to VM addition or VM removal under connection establishment or teardown. The commonality of these events is that they all need coresident VM information explicitly or implicitly to proceed.

For race conditions in the case of VM addition, no additional error will be introduced, though additional performance overhead may be experienced in some cases. Concretely, when VM_i is migrated to host A from another physical machine host B, if VMs on host A have not been notified of the addition of VM_i, then they can continue their remote communication with VM_i. Thus, no pending data needs to be handled and connection tearing down is performed as if VM_i were on host B, and no error occurs. Once the list of coresident VMs is updated, for example, through a periodic update scheme, the race condition will be naturally eliminated. Similarly, when VM_i is added to host A through dynamic VM deployment, before other VMs on the same host A become aware of the coresidency of VM_i, connections to VM_i cannot be set up until it is visible to its communicating VMs. Thus, no pending data and connection tearing down are needed.

For race conditions in the case of VM removal, the situations are somewhat more complicated. After VM_i is migrated out from current host A to host B, it needs to switch all its shared-memory-based communications with VMs on host A (if any) from its original local channel to the remote channel between host A and host B. Without such a switch, due to race conditions, VM_i may attempt to communicate with VMs on host A through the local shared-memory channels that were set up previously, which can lead to errors since without switching to the remote channel, VMs cannot communicate with each other across physical hosts. To enable such a switch, we need tear down the local channels between VM_i and VMs on host A. Upon the command of local connection tearing down, a local channel should not be released until all its pending data are processed. Regarding the pending data remaining from the original local channel, if the local channel is established below the IP layer (layer 3), then data transfer error is tolerable and is transparent to end-users since the upper-layer TCP/IP protocol has the ability to handle such error and to make amends, although the amending process may lead to additional overhead. On the other hand, if the local channel is in layer 2, the residency-aware inter-VM communication mechanism itself will need to provide functionalities to guarantee the reliability of pending data transmission, as outlined previously.

In summary, race conditions do not necessarily lead to errors. The general guideline for preventing race conditions is to ensure that the coresident VM membership is updated immediately and synchronously with the event of VM addition or VM removal and before conducting any corresponding operations listed in Table IV. If the update to

Table V. The Feature of Seamless Agility

	Xen Based						KVM Based			
	IVC	*XenSocket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
Coresident VM membership maintenance	Yes Static	No	Yes Static	Yes Dynamic	Yes Dynamic	Yes Dynamic	No	No	Yes	Yes
Automatic switch between local and remote channels	Yes	No	Yes	Yes	Yes	Yes	No	No	No	Yes
Transparent VM live migration support	Not fully transparent	No	No	Yes	Yes	Yes	No	No	No	Yes
Dynamic VM deployment support	No	No	No	Yes	Yes	Yes	No	No	No	Yes

the coresidency information is done asynchronously and periodically, then the proper tuning of the settings for the update cycle period is critical: smaller frequency leads to higher freshness quality at higher cost. With proper prevention or resolution methods, race conditions due to VM addition or removal do not happen with high frequency. Thus, lightweight solutions that can guarantee correctness while maintaining acceptable performance are desirable.

Table V shows a comparison of the seamless agility support in existing representative shared-memory inter-VM communication systems.

7. MULTILEVEL TRANSPARENCY: COMPARATIVE ANALYSIS

7.1. User-Level Transparency

Among Xen-based representative approaches, XWAY, XenLoop, XenVMC, and MMNet achieve user-level transparency by lower-layer design choices and no modification to layer 1. IVC is not user-level transparent for generic applications that use IVC library. However, for MPI applications, they can take advantage of MVAPICH2-ivc without modification. XenSocket introduces XenSocket API, a new type of socket family to allow users to communicate across shared-memory channels. The API is different from current standard sockets. The Grant Table reference is required to be passed to *connect()* explicitly as a parameter. It uses one shared variable to indicate the number of bytes for writes in the circular data channel. Thus, in order to benefit from XenSocket, applications need to be developed/modified to incorporate the proposed interfaces.

Among KVM-based representative approaches, Socket-outsourcing is implemented in layer 2. MemPipe is implemented in layer 3. Both keep the feature of user-level transparency. VMPI exposes a shared-memory message passing API that is not compatible with the standard MPI. For Nahanni, user-level transparency and the ease of usage are sacrificed to achieve simplicity of implementation and potentially better performance. For example, to allow Memcached-based applications to benefit from Nahanni, the Memcached server is modified to use Nahanni API. The Memcached client library is also extended to identify whether a Memcached server is local. Since Nahanni only provides a local shared-memory channel, it does not support inter-VM communication across physical machines.

7.2. Guest OS Kernel Transparency

Among the existing representative shared-memory systems, XWAY and Socket-outsourcing are not OS kernel transparent. XWAY offers full binary compatibility for applications communicating over TCP sockets. However, it gives up the transparency of the OS kernel by patching the kernel. Except for the patch, the other part of XWAY is implemented as a virtual network device and its kernel driver. Socket-outsourcing modifies the kernel by replacing existing socket functions with self-defined ones.

Table VI. Multilevel Transparency Features

	Xen Based						KVM Based			
	IVC	*XenSocket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
User-level transparency	No	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
OS kernel transparency	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
VMM-level transparency	No	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes

XenSocket, XenLoop, XenVMC, MMNet, IVC, MemPipe, Nahanni, and VMPI are OS kernel transparent. Among them, XenSocket, XenLoop, XenVMC, and MemPipe are designed as kernel modules. MMNet, IVC, Nahanni, and VMPI are implemented as kernel device driver modules. For instance, MMNet is in the form of a kernel driver module of a link layer device. The OS kernel part of IVC is a kernel driver module for a para-virtualized Xen network device. Nahanni's guest OS part is implemented as a UIO device driver for virtual PCI device *ivshmem*, which is created in the same way a graphics device is. VMPI is implemented as a kernel driver module of a virtual PCI character device for message passing.

7.3. VMM/Hypervisor Transparency

Xen-based existing representative developments utilize the existing Xen Grant Table, XenStore, and Xen Event Channel to facilitate the design and implementation of the shared-memory communication channel and the notification protocol. Almost all of them keep the feature of VMM transparency except that IVC modifies the VMM to enable VM live migration.

KVM-based development efforts, such as Nahanni, VMPI, and Socket-outsourcing, are not VMM transparent. Before Nahanni is merged into QEMU as a sharing memory facility at the user level, there is no mechanism provided by QEMU/KVM to support host-guest and guest-guest memory sharing as the Xen Grant Table does on the Xen platform [Macdonell 2011]. For Nahanni, QEMU is modified to provide virtual device *ivshmem* to enable the management of shared memory. For VMPI, slight modifications are made to QEMU to implement the emulation of a new virtual device. For Socket-outsourcing, VMM is extended to provide the support for implementing facilities including shared memory, event queues, and VRPC. MemPipe [Zhang et al. 2015] is the recent shared-memory inter-VM communication system on the KVM platform, which provides VMM transparency in addition to user-level and guest OS kernel-level transparency.

Table VI summarizes a comparison of the multilevel transparency feature in existing representative shared-memory communication systems.

We observe from Table VI that four existing shared-memory developments meet the requirement of multilevel transparency. They are XenLoop, MMNet, and XenVMC on the Xen platform and MemPipe on the KVM platform. These four systems also meet the seamless agility requirement according to Table V by supporting dynamic coresident VM detection and automatic switch between local and remote channels. However, they employ different approaches in the memory sharing and implementation layer: (1) MMNet maps the entire address space of the sender VM into the receiver VM's space before data transmission, while XenLoop, XenVMC, and MemPipe map requested pages on demand; (2) XenVMC builds shared-memory-based local channels in layer 2, and XenLoop, MMNet, and MemPipe establish local channels in layer 3; and (3) XenLoop, XenVMC, and MMNet manage the shared memory by static allocation of shared-memory

regions to the communicating VMs on the same host, whereas MemPipe uses a dynamic proportional resource allocation mechanism to manage shared-memory regions for communicating VMs on a physical host.

8. PERFORMANCE COMPARISONS AND IMPACT OF IMPLEMENTATION CHOICES

8.1. Functional Choices

TCP and UDP support. TCP and UDP are two of the most commonly used network protocols. TCP is connection oriented, while UDP is connectionless. They provide different levels of reliability and their performance differs due to different features they offer. Typically, TCP and UDP protocols are used in different application areas. Among existing shared-memory inter-VM communication systems, XenLoop, MMNet, XenVMC, and Socket-outsourcing currently support both TCP and UDP workloads, while XenSocket and XWAY to date support only inter-VM communication for TCP-oriented applications. For VMPI and Nahanni, only local channels are provided, and neither TCP nor UDP is supported. For IVC, the technical detail for TCP/UDP support is not available.

Blocking I/O and nonblocking I/O. Shared-memory buffer access algorithms can be implemented to support either blocking or nonblocking I/O. With blocking I/O, a thread is blocked until the I/O operations are finished. With nonblocking I/O, the functions return immediately after activating the read/write operations. Generally speaking, the blocking I/O mode is easy to implement but less efficient than the nonblocking I/O mode. XWAY and XenVMC support both modes, which is desirable for shared-memory-based inter-VM communication mechanisms. IVC offers *ivc_write* and *ivc_read* functions that are implemented as nonblocking I/O mode. The socket operations in the host module of Socket-outsourcing indicate its nonblocking I/O feature. XenSocket does not support nonblocking I/O mode.

Host-guest and guest-guest communication. For shared-memory approaches on the Xen platform, they all leverage on the Xen Grant Table and offer optimized inter-VM communication across domains. In contrast, for the KVM platform, the communicating VMs are either host OS or guest OS; thus, host-guest and guest-guest are the two typical modes of inter-VM communication. Based on different design objectives and different implementation techniques adopted, KVM-based shared-memory systems support different communication types: Nahanni supports both host-guest and guest-guest communication. In Socket-outsourcing, its guest module allows the host module to access its memory region through VRPC and Event interfaces between the host module and the guest module. VMPI explicitly supports guest-guest communication. MemPipe provides direct support for host-guest communication and indirect support for guest-guest communication.

Buffer size. A majority of existing shared-memory developments choose to design and implement the buffer for data sharing as FIFO circular structure. Experimental observation shows that the FIFO buffer size may impact on achievable bandwidth [Wang et al. 2008b]. IVC, XenLoop, and XenVMC support tunable buffer size to offer tunable bandwidth. Also in XenLoop, if the packet size is larger than the FIFO buffer size, then the packet is transmitted by traditional network path. XenSocket utilizes a fixed-size buffer that is composed of 32 buffer pages and each page size is 4KB.

Table VII provides a comparison on different implementation choices by existing shared-memory implementations.

8.2. Software Environment and Source Code Availability

All existing representative shared-memory channels are implemented and evaluated exclusively with different versions of Linux kernel and VMM as shown in Table VIII.

Table VII. Additional Implementation Choices

	Xen Based						KVM Based			
	IVC	*XenSocket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
TCP/UDP support	N/A	TCP	TCP	Both	Both	Both	N/A	Both	N/A	Both
Blocking/ nonblocking	Non-blocking	Blocking	Both	N/A	N/A	Both	N/A	N/A	N/A	Both
Host-guest/ guest-guest	Interdomain	Interdomain	Interdomain	Interdomain	Interdomain	Interdomain	Guest-guest	Host-guest	Both	Both
Data buffer size	Tunable	4KB*32	N/A	Tunable	N/A	Tunable	N/A	N/A	N/A	Tunable

Table VIII. Software Environment and Source Code Availability

	Xen Based						KVM Based			
	IVC	*XenSocket*	*XWAY*	*XenLoop*	*MMNet (Fido)*	*XenVMC*	*VMPI*	*Socket-outsourcing*	*Nahanni*	*MemPipe*
Linux kernel version	2.6.6.38	2.6.6.18	2.6.16.29	2.6.18.8	2.6.18.8	3.13.0	N/A	2.6.25	Since 2.6.37	3.2.68
VMM version	Xen 3.0.4	Xen 3.0.2	Xen 3.0.3 Xen3.1	Xen 3.2.0	Xen 3.2	Xen 4.5	N/A	KVM-66	Since QEMU 0.13	KVM 3.6/ QEMU 1.2.0
Source code availability	N/A	Open source	Open source	Open source	N/A	N/A	N/A	N/A	Open source	Open source

Among them, XenSocket [Zhang and Mcintosh 2013b], XWAY [Kim et al. 2013], XenLoop [Wang et al. 2008], Nahanni [Macdonell 2014], and MemPipe [Zhang et al. 2015] are open-source systems. Nahanni open-source code is included in the QEMU/KVM release since its version 0.13 from August 2010. It has become a part of QEMU/KVM, which is the default hypervisor in Ubuntu as well as Red Hat Enterprise Linux.

8.3. Performance Comparison

As indicated in Table VIII, most of the existing representative shared-memory inter-VM communication systems to date have not provided open-source release of their implementations. For Xen-based systems, only XenSocket, XWAY, and XenLoop have released their software. XenVMC was developed by the authors of NUDT. For KVM-based systems, only Nahanni and MemPipe release their systems as open-source software. However, among these systems, XenSocket and Nahanni are not user-level transparent (Table VI), which means existing applications and benchmarks cannot be easily deployed to run on XenSocket or Nahanni without modification. Therefore, they do not support Netperf, the widely used network I/O benchmark. As a result, XWAY, XenLoop, XenVMC, and MemPipe become candidates for the performance comparison. XenLoop and MemPipe are implemented in layer 3, and XWAY and XenVMC are implemented in layer 2. Also, compared with XenLoop, XenVMC, and MemPipe, which support both TCP and UDP semantics and meet all three design criteria of shared memory optimization, seamless agility, and multilevel transparency, XWAY falls short in a couple aspects: (1) XWAY does not support UDP and (2) XWAY does not support seamless agility or OS kernel transparency. Taking these different factors into consideration, we provide a comparison of performance based on the reported experimental results from related papers [Huang et al. 2007; Zhang et al. 2007; Kim et al. 2008; Wang et al. 2008b; Burtsevet al. 2009; Ren et al. 2012; Diakhaté et al. 2008; Eiraku et al. 2009; Koh 2010; Gordon 2011a; Gordon et al. 2011b; Ke 2011; Macdonell 2011, Zhang et al. 2015], including experimental setups, test cases or benchmarks, comparison dimensions, comparison systems, and the description of performance improvement. Table IX

Table IX. Performance Comparison for Existing Shared-Memory Systems

Plat.	Name	Hardware Setup	Test Case/ Benchmark	Dimensions (Netperf)	Contrast Systems	Normalized Performance Improvement
Xen	IVC	2 2.8GHz 4GB, 2 3.6GHz 2GB, 2 quad-core 2.0GHz 4GB, PCI-E IB HCAs	Intel MPI, NAS parallel, LAMMPS, NAMD, SMG2000, HPL	N/A (Migration)	IVC, inter-VM, native Linux	Near-native Linux NAS parellel: up to 11%+
	XenSocket	2 2.8GHz CPU, 4GB RAM	Netperf 2.4.2	TCP STREAM TCP RR	Native Linux, inter-VM, XenSocket	Inter-VM: up to 72×
	XWAY	3.2GHz CPU, 1GB RAM	Netperf 2.4.3, Apps(scp, ftp, wget), DBT-1	N/A (Connection overhead)	Unix Domain, TCP (Xen 3.0/3.1, Page Flip/Copy), XWAY	Better than native TCP socket Binary compatable
	XenLoop	dual-core 2.8GHz CPU, 4GB RAM	Netperf, lmbench, netpipe-mpich, OSU MPI, ICMP ECHO REQUEST/REPLY	UDP SREAM TCP RR UDP RR	Intermachine, netfront, XenLoop, loopback	Latency: reduces by up to 5× Bandwidth: increases by up to 6×
	MMNet (Fido)	2 quad-core 2.1GHz CPU, 16GB RAM, 2 1Gbps NICs	Netperf 2.4.4	TCP SREAM UDP SREAM TCP RR	Loopback, netfront, XenLoop, MMNet	TCP&UDP STREAM: about 2× (XenLoop) up to 4× (Netfront)
	XenVMC	2.67GHz CPU 4GB RAM	Netperf 2.4.5	TCP SREAM TCP RR	Netfront, XenVMC	thoughput: up tp 9× latency: improves by up tp 6×
KVM	VMPI	2 quad-core 2.33GHz CPU, 4GB RAM	Pingpong benchmark	N/A	MPICH2	near native performance
	Socket-outsourcing	3GHz CPU, 2GB RAM, 4 Gigabit NICs	Iperf, RUBiS benchmark 1.4.3	N/A	KVM-emu, KVM-virtio, KVM-out	iperf: up to 25× RUBiS: 45%+ (KVM-emu)
	Nahanni	2 quad-core 2.67GHz CPU, 48GB RAM	Modified: GAMESS, SPEC MPI2007, Memcached, MPICH2	N/A	Inter-VM	20%–80%+
	MemPipe	quad-core 2.4GHz CPU, 4GB RAM, Gigabit NIC	Netperf, network apps (scope, wget, sftp, etc.)	TCP SREAM UDP SREAM TCP RR UDP RR	Inter machine, inter-VM, MemPipe	Intermachine: 1.1×–3× Inter-VM: 2.5× –65×

shows the summary information. Given that the experimental environments and system configurations vary from one system to another, we use the normalized numbers in the performance improvement column to make comparison more straightforward.

Note that in Table IX, the normalized performance number is respective to each shared-memory system compared to intermachine, inter-VM, and loopback scenarios. Given that the experimental results are obtained with different versions of hypervisor and Linux kernel and under diverse hardware configurations, the higher/lower-performance numbers should not be interpreted as an absolutely better/worse throughput or lower/higher latency. Take Nahanni as an example; Nahanni achieves the runtime speedup by 20% to 80% for the benchmark workloads used in the experiments reported in Macdonell [2011]. For example, Nahanni is faster for transferring data compared to other mechanisms such as Netcat and SCP. Copying data across

shared memory is between 4 and 8 times faster than Netcat and is an order of magnitude faster than SCP.

9. CONCLUSION

We have presented an in-depth analysis and comparison of the state-of-the-art shared-memory-based techniques for inter-VM communication. To the best of our knowledge, this is the first effort that provides a comprehensive survey of the inter-VM communication methods. Concretely, this article makes two original contributions. First, we present the main design and implementation choices of the shared-memory-based inter-VM communication methods with respect to the implementation layer in the software stack, the support of seamless agility, and the guarantee of multilevel transparency. Second, based on the objectives and design choices, we present a comparative analysis on a selection of important issues, including how to achieve high performance, how to guarantee multilevel transparency, how to automatically detect coresident VMs, and how to support automatic switch between the local and remote mode of shared-memory-based inter-VM communication so that dynamic addition or removal of coresident VMs can be supported. We conclude that the implementation layer may have a critical impact on transparency and performance, as well as seamless agility. Third, but not the least, we provide an extensive comparison on shared-memory implementations on top of the two most popular and yet architecturally different open-source VMM platforms, Xen and KVM. The comparison covers architectural layout, fundamental functionalities, seamless agility, multilevel transparency, additional implementation considerations, software environment, and source code availability. We conjecture that this survey provides not only a comprehensive overview of important issues, design choices, and practical implementation techniques for developing the next generation of shared-memory-based inter-VM communication mechanisms but also offers both cloud infrastructure providers and cloud service consumers an opportunity to further improve inter-VM communication efficiency in virtualized data centers.

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