An Efficient End-host Architecture for Cluster Communication Services

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Introduction

- General-purpose systems provide a general set of abstractions that allow for a good combination of
  - Fairness between processes
  - Simple abstraction of the base hardware to all application processes
- With generality, fine grained control is sacrificed
  - Copying of data via kernel for network stack
  - Networking core cannot be easily extended with new protocols
- High performance applications may demand more than these generic abstractions can provide

Contributions

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- High performance networking using "user-level sandboxing"
  - Zero copy
  - Eliminates scheduling overheads
- Safe abstraction
  - Kernel controls access rights to user-level sandbox services
  - Regulated access to I/O devices is guaranteed
- Example usages:
  - Efficient middleware routing of high bandwidth/low latency data streams
  - A proxy server handing remote procedure calls

User-level Sandboxing

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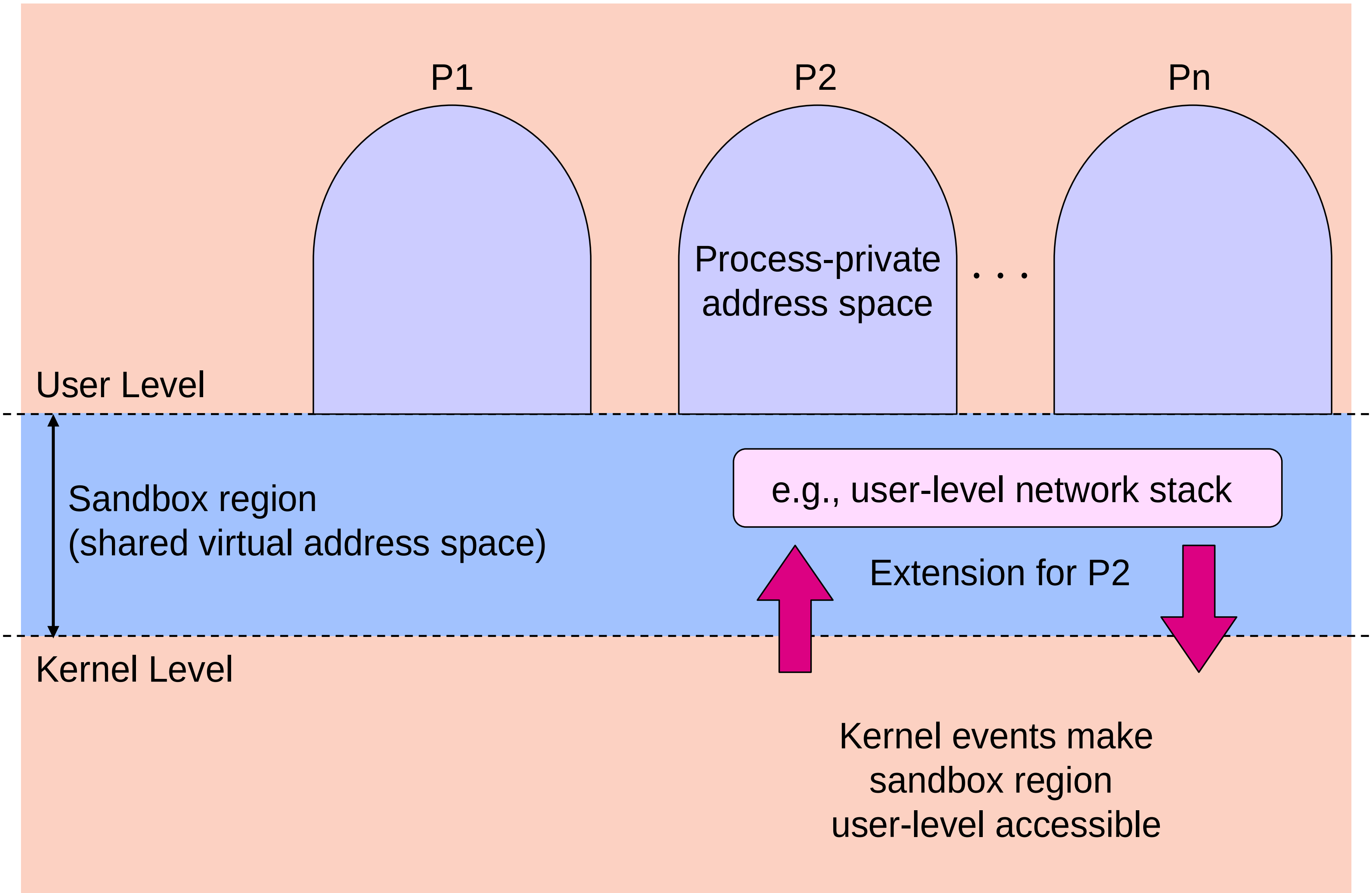
- Provides user-level environment for the execution of service extensions
- Separate kernel from app-specific code
- Use only page-level hardware protection
  - Approach does not require specific hardware protection features, such as *segmentation* and *tagged TLBs*
- Extension code only activated by the kernel via upcalls
- Sandbox extensions can be executed in the context of **any** process to avoid scheduling overheads

Hardware Support for Memory-safe Extensions

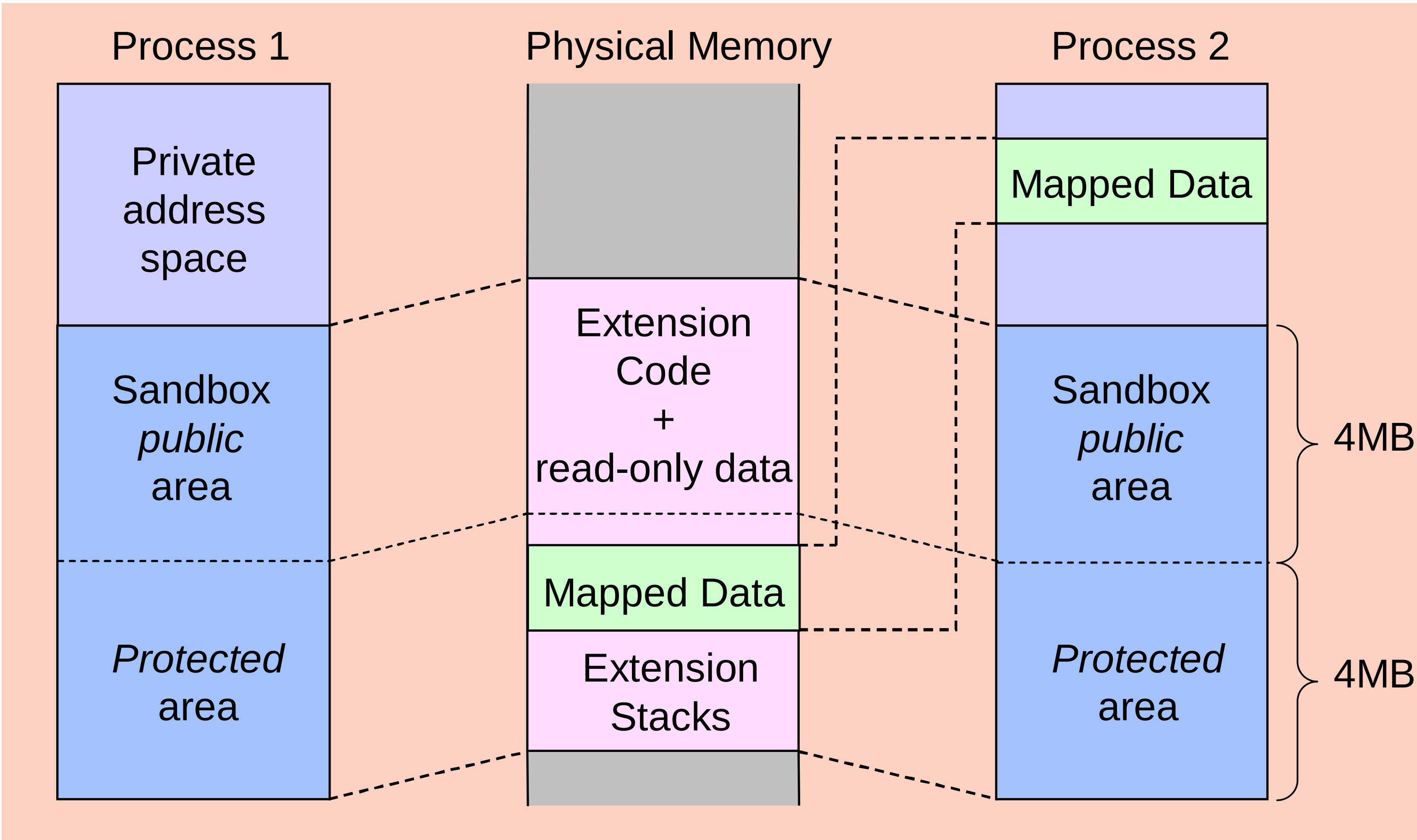


User-level Sandboxing Implementation

- Modify address spaces of all processes to contain one or more shared pages of virtual addresses
  - Shared pages used for sandbox
    - Normally inaccessible at user-level
    - Kernel upcalls toggle sandbox page protection bits & perform TLB invalidation on corresponding page(s)

- Current x86 approach
  - 2x4MB superpages
  - Modified dietlibc supports most normal functionality
  - ELF loader to map code into sandbox
  - Support sandboxed threads that can block on syscalls

Hardware Support for Memory-safe Extensions



Invoking Sandbox Extensions

- Fast Upcalls
  - Leverage SYSEXIT/SYSENTER on x86
    - Support Traditional IRET approach also

- Kernel Events
  - Generic interface supports delivery of events to specific extensions
  - Each extension has its own stack & thread structure
  - Events can be queued -- like POSIX.4 (real time) signals

User-level Networking

- Issues involved in building a high performance customizable user-level networking stack:
  - Memory Management
    - A slab allocator that has a-priori knowledge of objects such as packet descriptors
  - Kernel Bypassing
    - An abstraction for passing control to an extension for interrupt time (asynchronous) processing
  - NIC interaction
    - Support DMA transfers of packet data to / from sandboxed extension code

User-level Networking

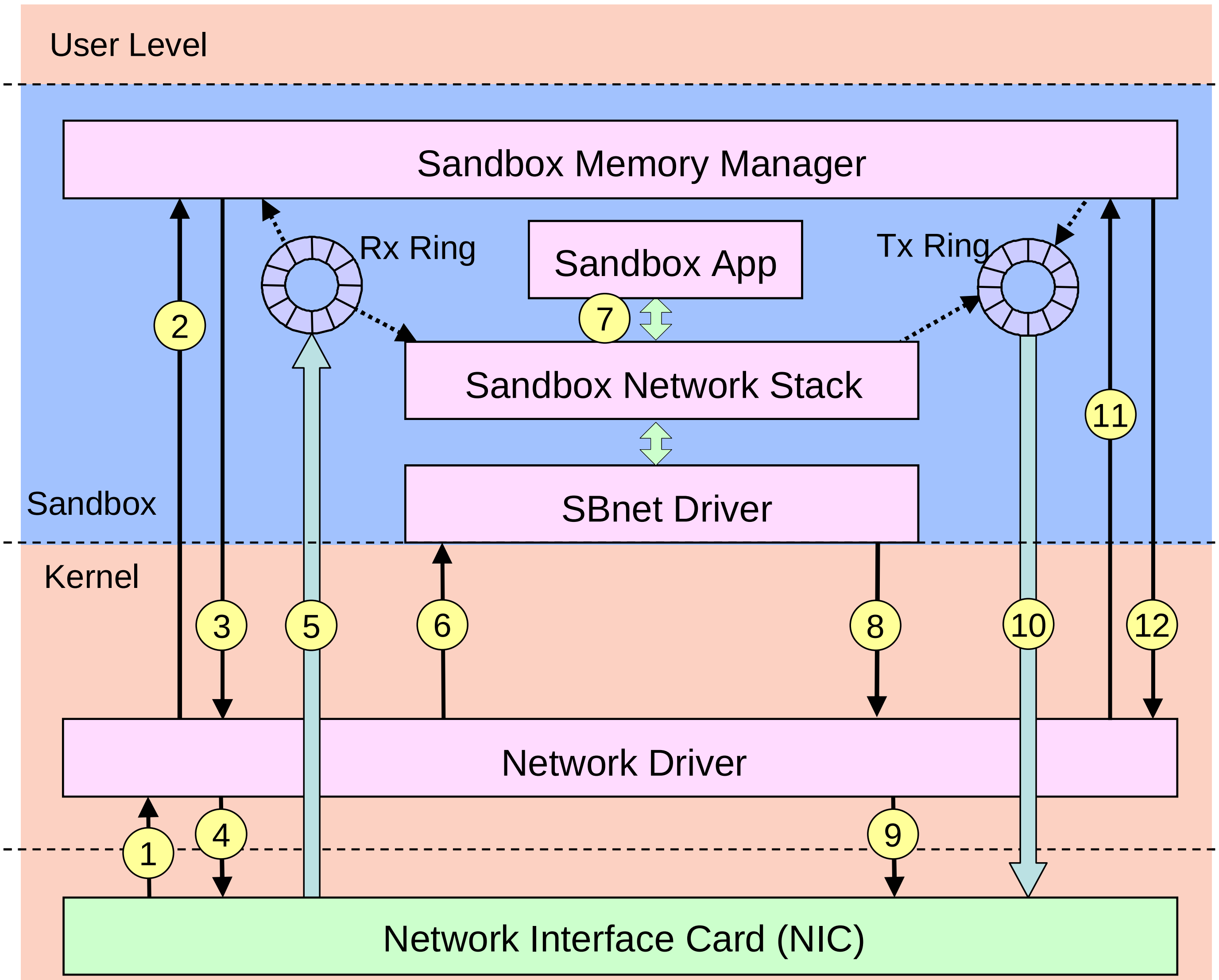
- UML (User Mode Linux) used as the basis for network service extensions, by providing:
  - memory allocation
  - a modular device interface
  - a fully functional, modular networking stack

- A well defined set of communication channels between kernel and sandbox to pass memory location for packet arrival and transmission
  - High speed DMA to user level is only possible because sandbox exists in every process virtual address space

User-level Networking

- Demultiplexing packets
  - Some technologies rely on programmable NICs which have a-priori knowledge of the destination of incoming packets
  - *All* incoming packets must still be allocated and transferred to sandbox area
  - A light-weight classifier can be written either in the kernel or sandbox
  - Sandbox networking scheme is not intended for efficient processing of *all* packets
    - We focus on efficient communication for sandbox extensions

User-level Networking --(Asynchronous Mode)



User-level Networking --(Synchronous Mode)

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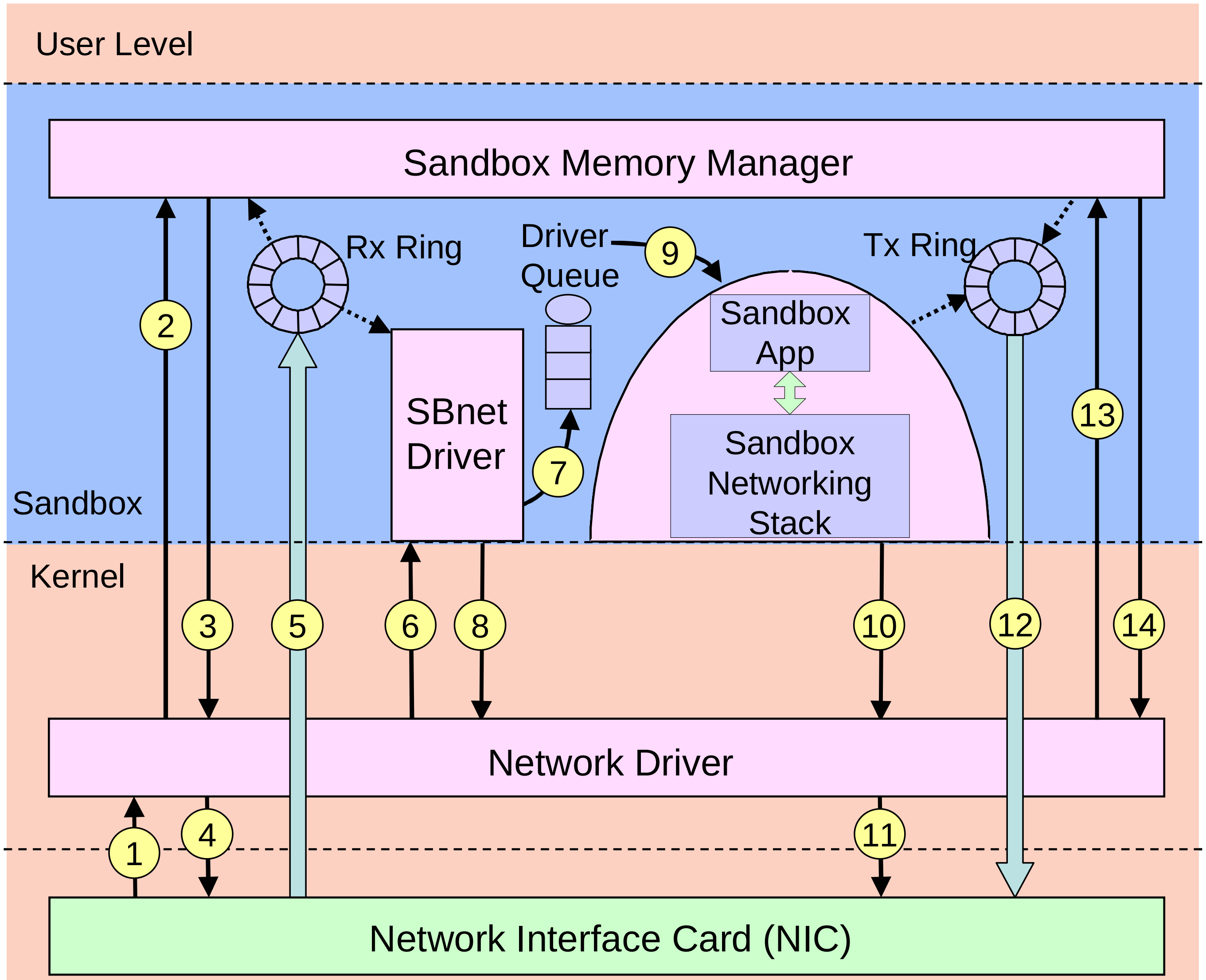
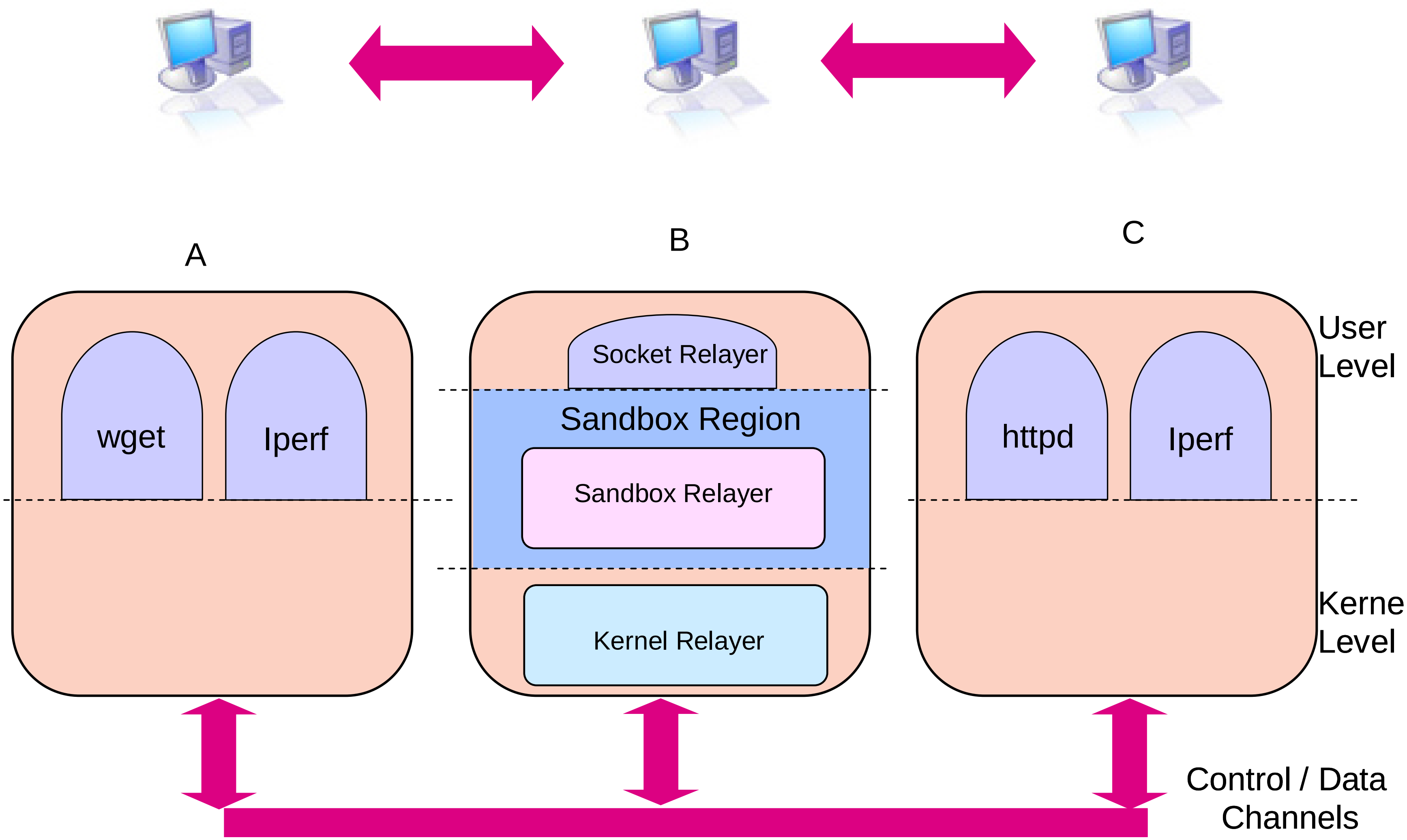


Experimental Results

- Example customized service extension: Relay Socket
  - To bind a pair of sockets together
  - For efficient forwarding of packets at transport layer
- UDP Forwarding
  - Comparison of networking implementations
  - Transfer time jitter
- TCP Forwarding

Experiment Environment



UDP forwarding (1/2)

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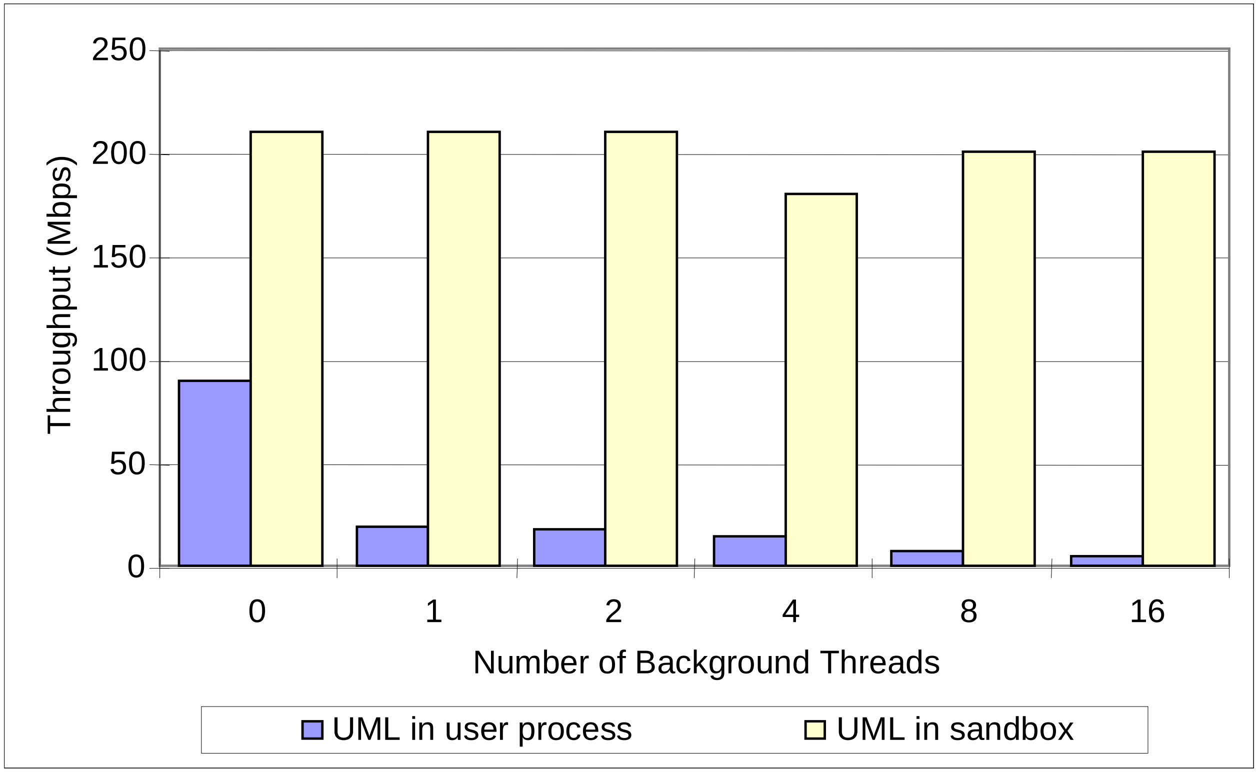
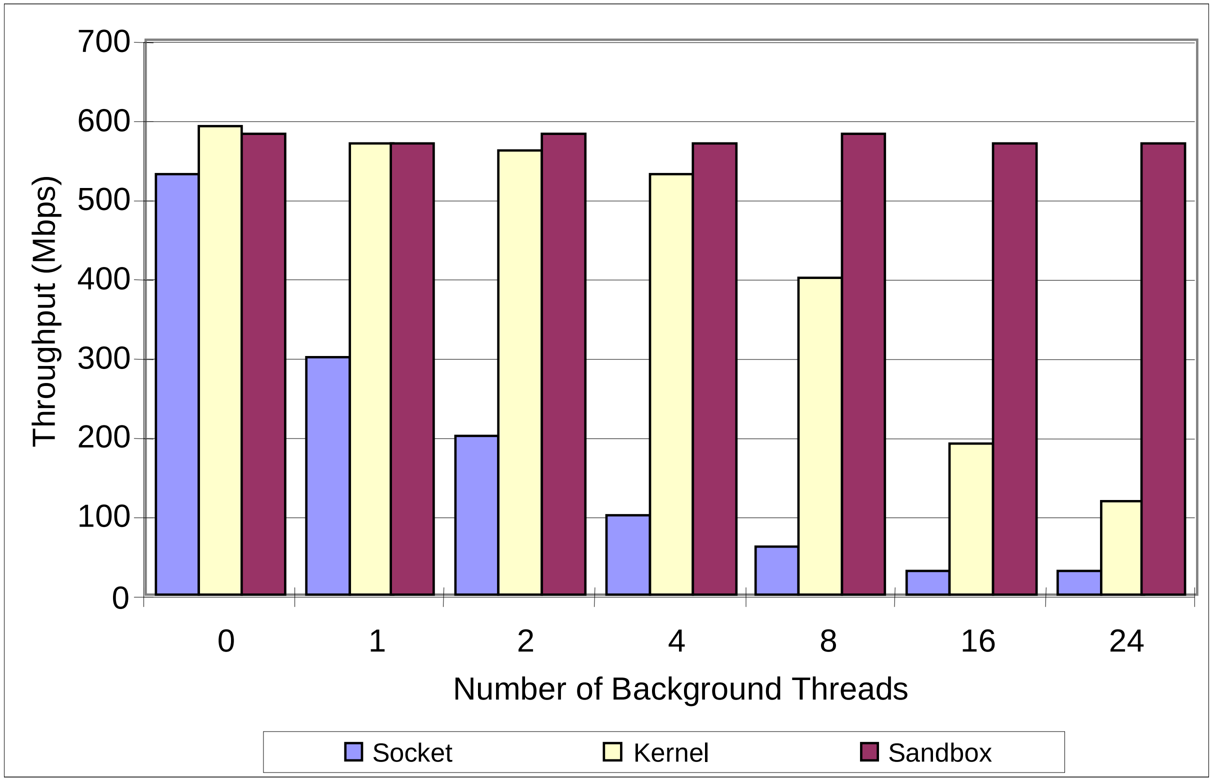


- UML in user process vs. UML in sandbox
  - An improvement of 130% with no background threads
  - With more background threads, sandbox agent does not suffer scheduling delays and therefore maintains high throughput

UDP forwarding (2/2)



- User-level vs. Kernel-level vs. Sandbox Networking
  - Sandbox networking is comparable to kernel approach with no background threads
  - Throughput remains constant irrespective of background threads

Transfer Time Jitter

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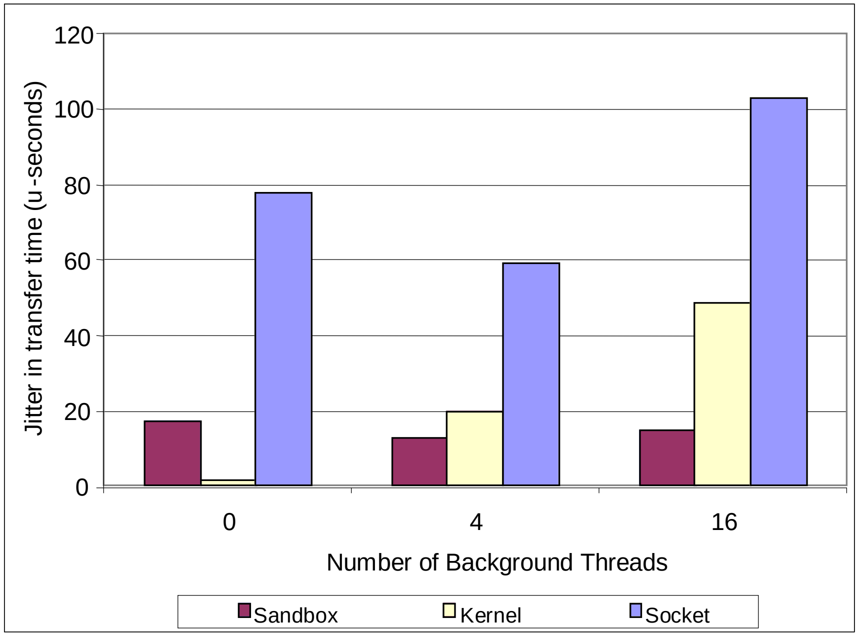
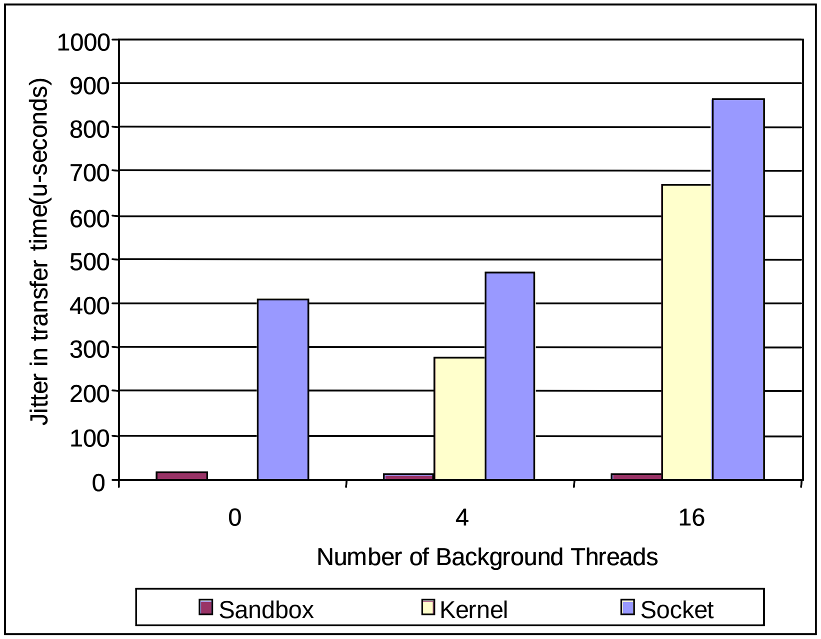


Average Jitter



Maximum Jitter

- Low jitter is important for QoS-constrained (e.g. multimedia) applications
- Near constant jitter is demonstrated by the sandboxed networking scheme
  - other two approaches show larger and more variable jitter as the number of background threads increases

TCP Forwarding

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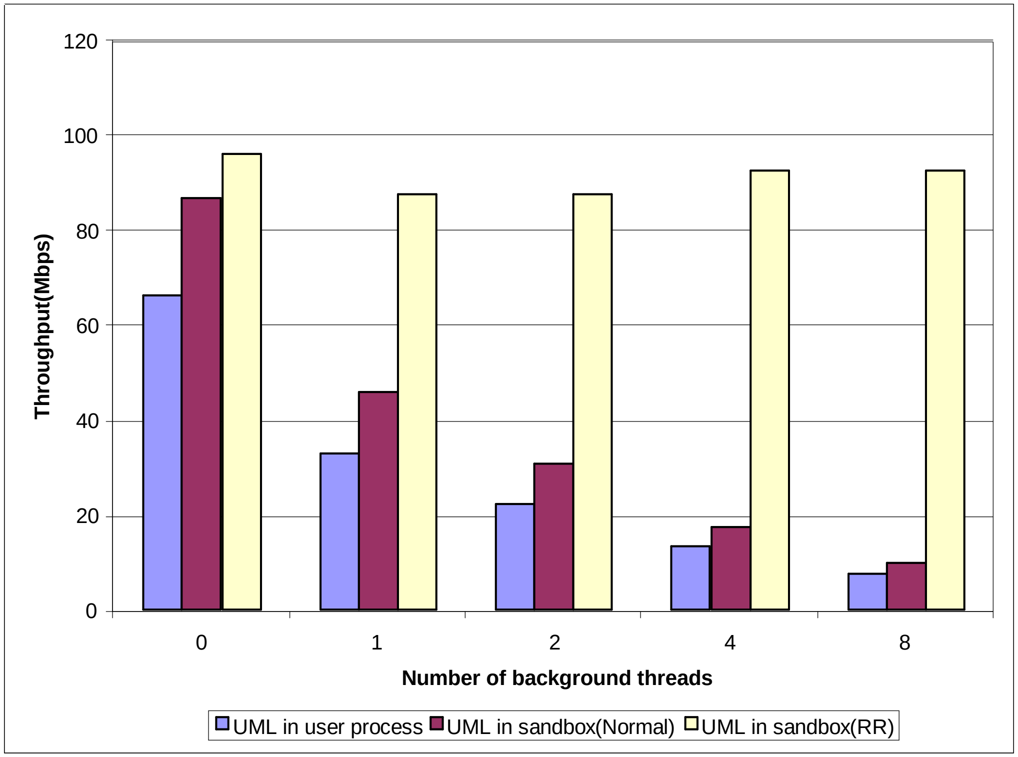

- UML in user space vs. sandbox
  - Using *wget* to get 1GB file from Apache server via intermediate node
  - 30% improvements in throughput using SCHED_OTHER
  - Prioritizing the sandbox thread using SCHED_RR yields more than 50% higher throughput irrespective of background threads

Microbenchmarks

Operation	Cost in CPU Cycles
Null Fast Upcall	1370
Sandbox Packet Processing time	6360
Kernel Packet Processing time	4800

Conclusions

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- Efficient networking stack in a "user-level sandbox"
  - Higher throughput and lower jitter than traditional middleware services implemented in process-private address spaces
  - In many cases, our architecture enables user-level services to outperform equivalent kernel-based services that require scheduling
- User-level sandboxing scheme allows extension code to:
  - Safely and efficiently access lower-level abstractions (e.g., interrupt time execution, network hardware)
  - Execute without scheduling process-private address spaces
  - Easy to debug and implement new services.

Future Work

- Type safe language support / software-based fault isolation
- Binary rewriting techniques to avoid patching host kernel for sandbox support