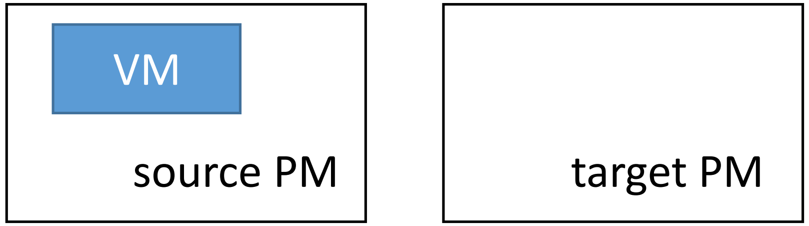
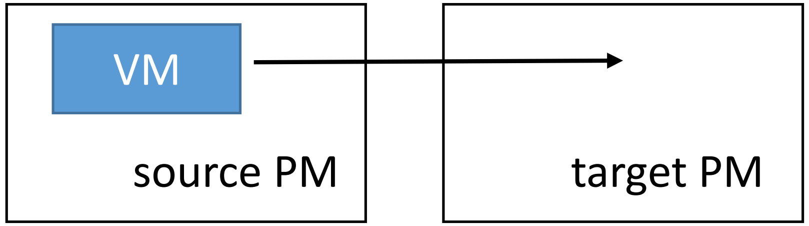
VM Live Migration



- Migrate an entire VM from one physical host to another
  - All user processes and kernel state
  - Without having to shut down the machine
- Why migrate VMs?
  - Distribute VM load efficiently across servers in a cloud
  - System maintenance
- Easier than migrating processes
  - VM has a much narrower interface than a process
- Two main techniques: pre-copy and post-copy

"Live Migration of Virtual Machines", Christopher Clark, Keir Fraser, Steven Hand, Jacob Gorm Hansen, Eric Jul, Christian Limpach, Ian Pratt, Andrew Warfield
"Post-Copy Based Live Virtual Machine Migration Using Adaptive Pre-Paging and Dynamic Self-Ballooning", Michael R. Hines and Kartik Gopalan

What is migrated?



- CPU context of VM, contents of main memory
  - Narrow interface, easier than process migration
- Disk: assume NAS (network attached storage) that is accessible from both hosts, or local disk is mirrored
  - We do not consider migrating disk data
- Network: assume both hosts on same LAN
  - Migrate IP address, advertise new MAC address to IP mapping via ARP reply
  - Migrate MAC address, let switches learn new MAC location
  - Network packets redirected to new location (with transient losses)
- I/O devices are provisioned at target
  - Virtual I/O devices easier to migrate, direct device assignment of physical devices to VMs (device passthrough) makes migration harder

Steps to migrate a VM

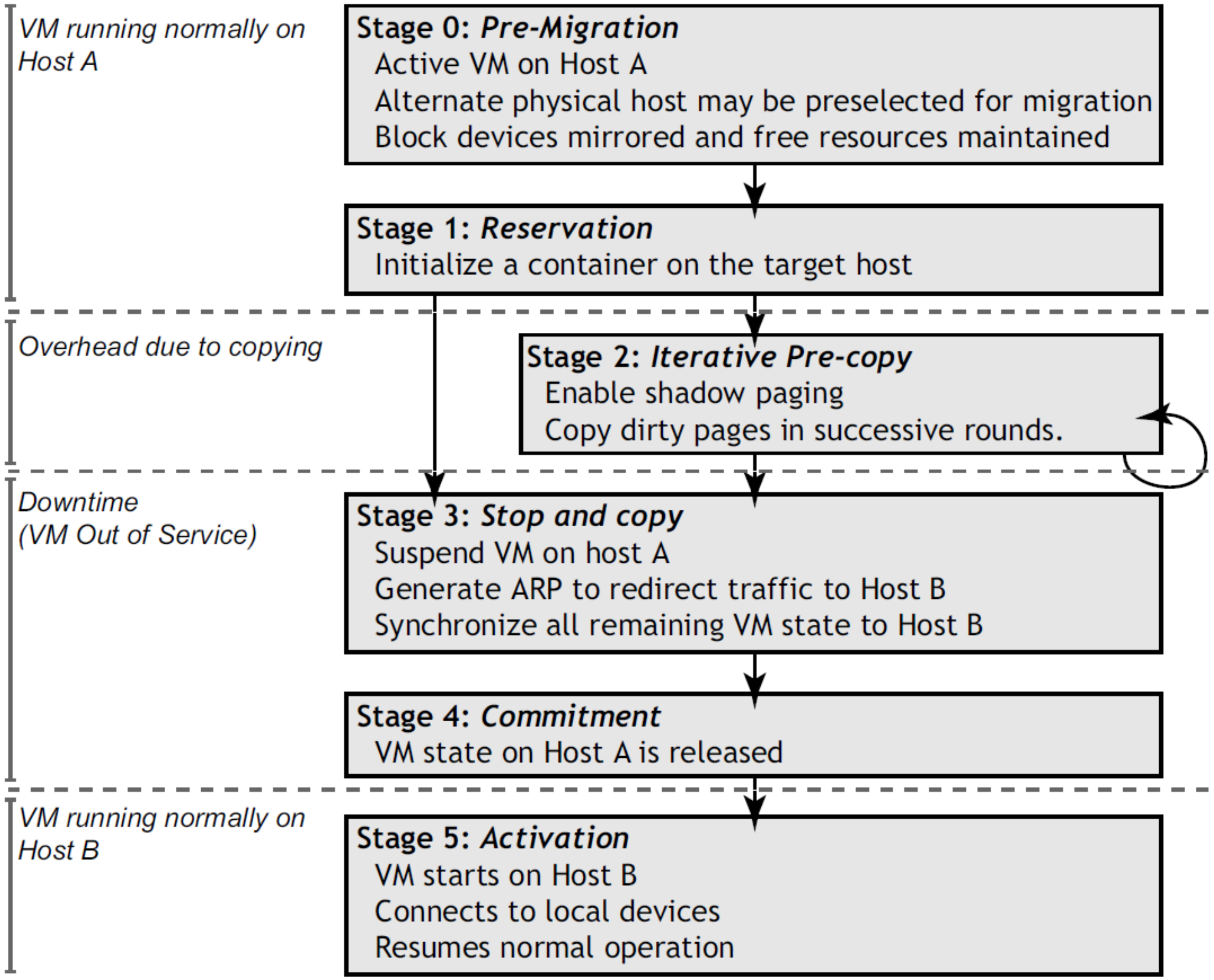
- Broad steps in any migration technique: Suppose we are migrating a VM from host A to host B
  1. Setup target host B, reserve resources for the VM
  2. Push phase: push some memory of VM from A to B
  3. Stop-and-copy: stop the VM at A, copy CPU context, and some memory
  4. Pull phase: Start VM at host B, pull any further memory required from A
  5. Clean up state from host A, migration complete
- Total migration time: time for steps 2,3,4
- Service downtime: time for step 3
- Other metrics: impact on application performance, network bandwidth consumed, total pages transferred

Flavors of migration techniques

- Pure stop-and-copy: VM stopped, all state transferred to target, VM restarts
  - Too much downtime to be classified as "live" migration
- Pre-copy: most state is transferred in the push phase, followed by a brief stop-and-copy phase
- Post-copy: VM stopped, bare minimum state required to run the VM is transferred to the target host. Remaining state is pulled on demand while the VM is running at the new location.
- Hybrid: a mix of pre-copy and post-copy. Some pushing of state followed by stop-and-copy, followed by pulling of state on demand.

Pre-copy based live migration

- Iterative pre-copy + stop-and-copy for remaining memory
- First push round copies all pages
- Every round copies pages dirtied in previous round
  - A page maybe copied multiple times
- Writable Working Set (WWS): pages commonly written to
  - WWS will be copied multiple times
  - Finally transferred in stop-and-copy
- How many rounds? Stop when rate of dirtying > rate of transfer
  - Diminishing returns with more than few rounds


VM running normally on Host A
Overhead due to copying
Downtime (VM Out of Service)
VM running normally on Host B

Stage 0: ***Pre-Migration***
Active VM on Host A
Alternate physical host may be preselected for migration
Block devices mirrored and free resources maintained

Stage 1: ***Reservation***
Initialize a container on the target host

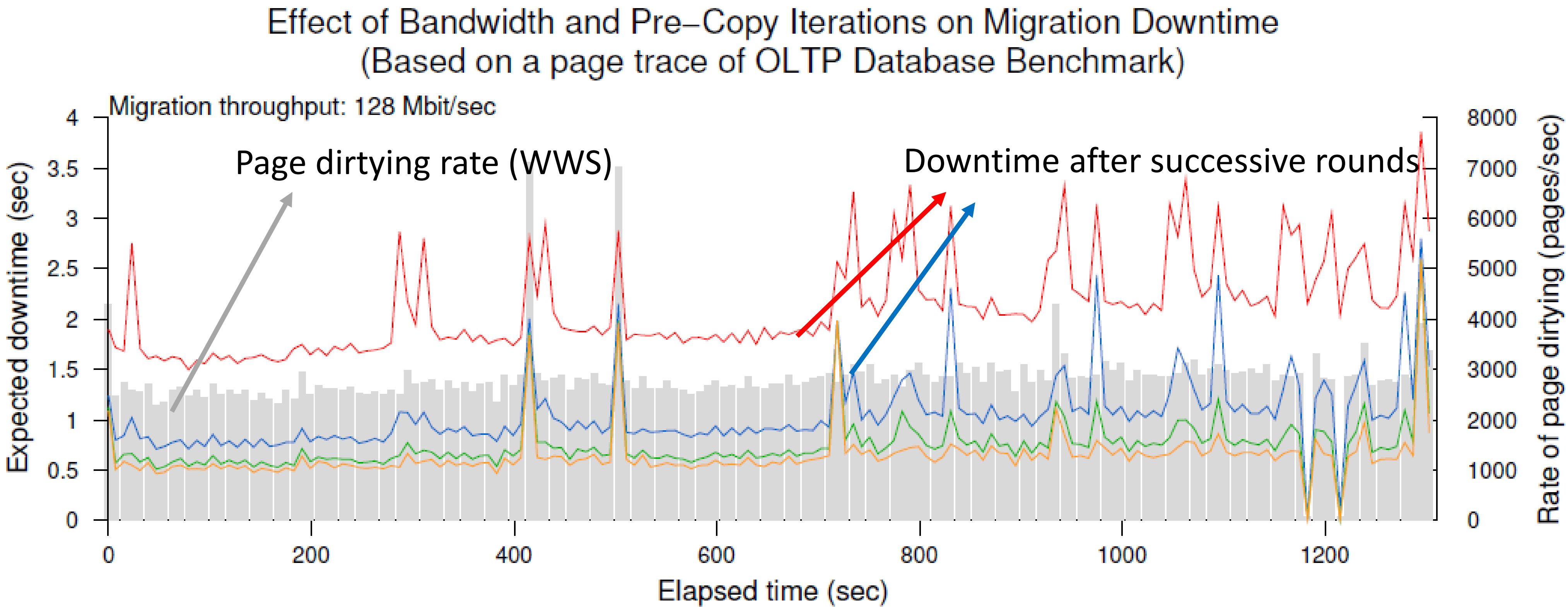
Stage 2: ***Iterative Pre-copy***
Enable shadow paging
Copy dirty pages in successive rounds.

Stage 3: ***Stop and copy***
Suspend VM on host A
Generate ARP to redirect traffic to Host B
Synchronize all remaining VM state to Host B

Stage 4: ***Commitment***
VM state on Host A is released

Stage 5: ***Activation***
VM starts on Host B
Connects to local devices
Resumes normal operation

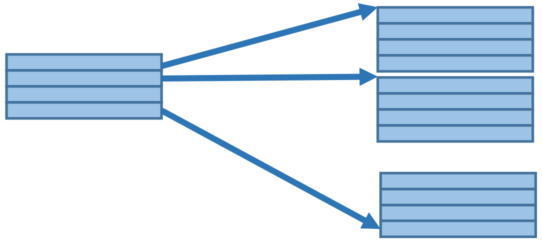
Impact of iterative pre-copy



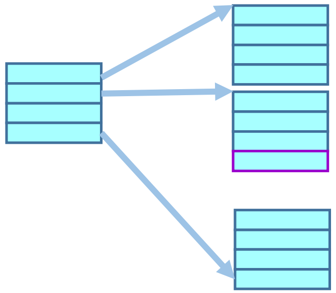
- If stop-and-copy, 512MB VM, 128 Mbps network, downtime = 32 sec
- With one pre-copy round, downtime goes to 2-3 sec
    - ~1 second for 2 or more rounds

Tracking dirty pages

Guest page table



Shadow page table in Xen



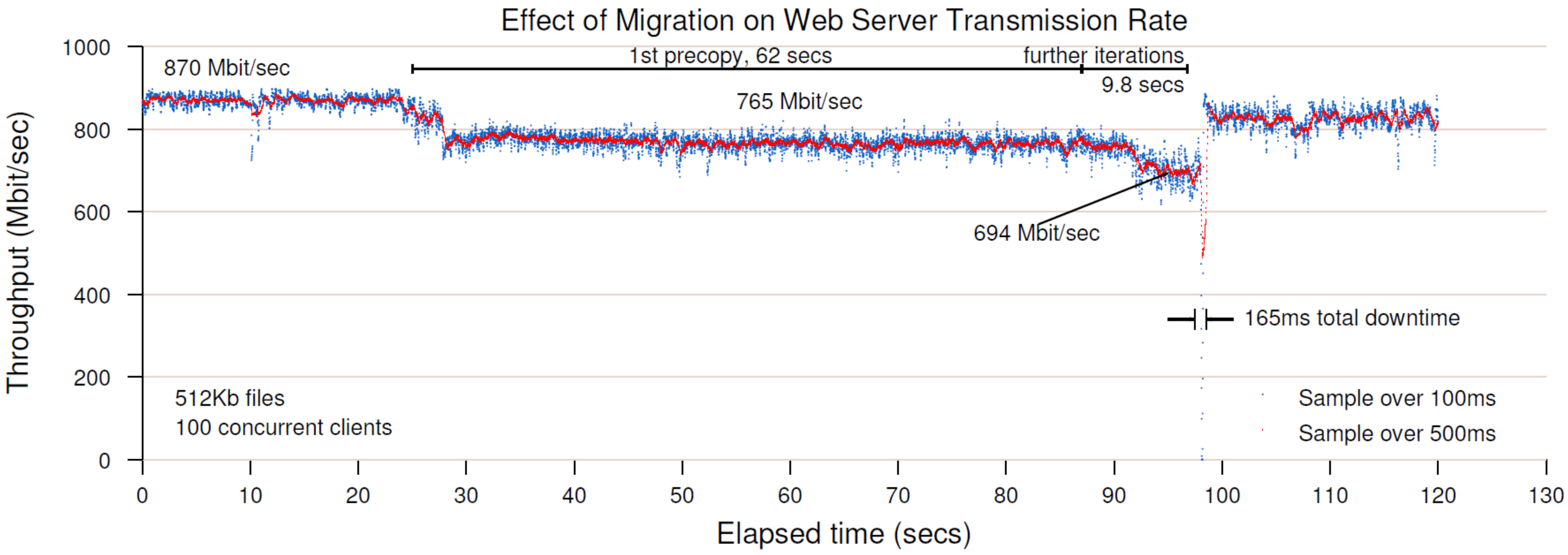
- Xen-based implementation
  - Page tables in Xen maintained by guest
  - Move to shadow page tables for migration
  - Migration managed by control software in domain0
- Shadow page table constructed on demand for every round
  - Dirty bitmap maintained for every round
  - Any page access by guest → page fault to Xen, shadow page table updated
  - PTE marked as read-only by default in shadow
  - If valid write access, shadow PTE marked writeable, page marked dirty in bitmap
  - At end of round, dirty pages are marked for transfer in control software
  - Shadow page table and dirty bitmap reinitialized after every round
  - Last set of dirty pages copied in stop-and-copy
- Guest page table in target host changed based on new physical addresses

Some optimizations

- Avoid transferring page multiple times
  - Before transmitting page, peek into the current round's dirty bitmap
  - Skip transmission if page is already dirtied in ongoing round
- Move non-interactive processes generating dirty pages to wait queue
  - Execution paused until migration completes
- Free up page cache and other unnecessary pages
  - Reduce memory footprint
  - Much like ballooning

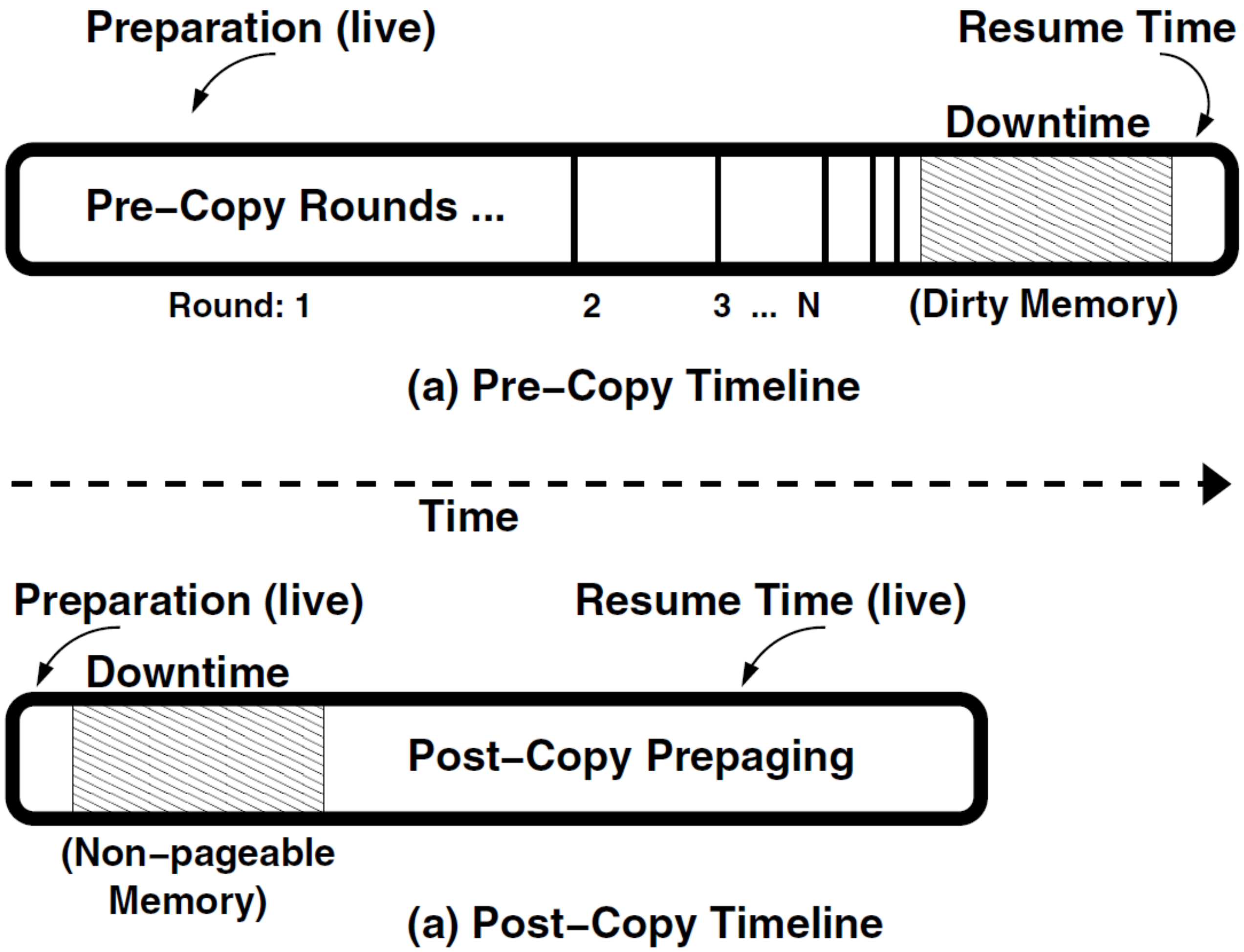
Pre-copy performance

- Downtime: ~100 millisec, total migration time of few tens of seconds
- Worse for memory-intensive applications, better for interactive apps



Post-copy based live migration

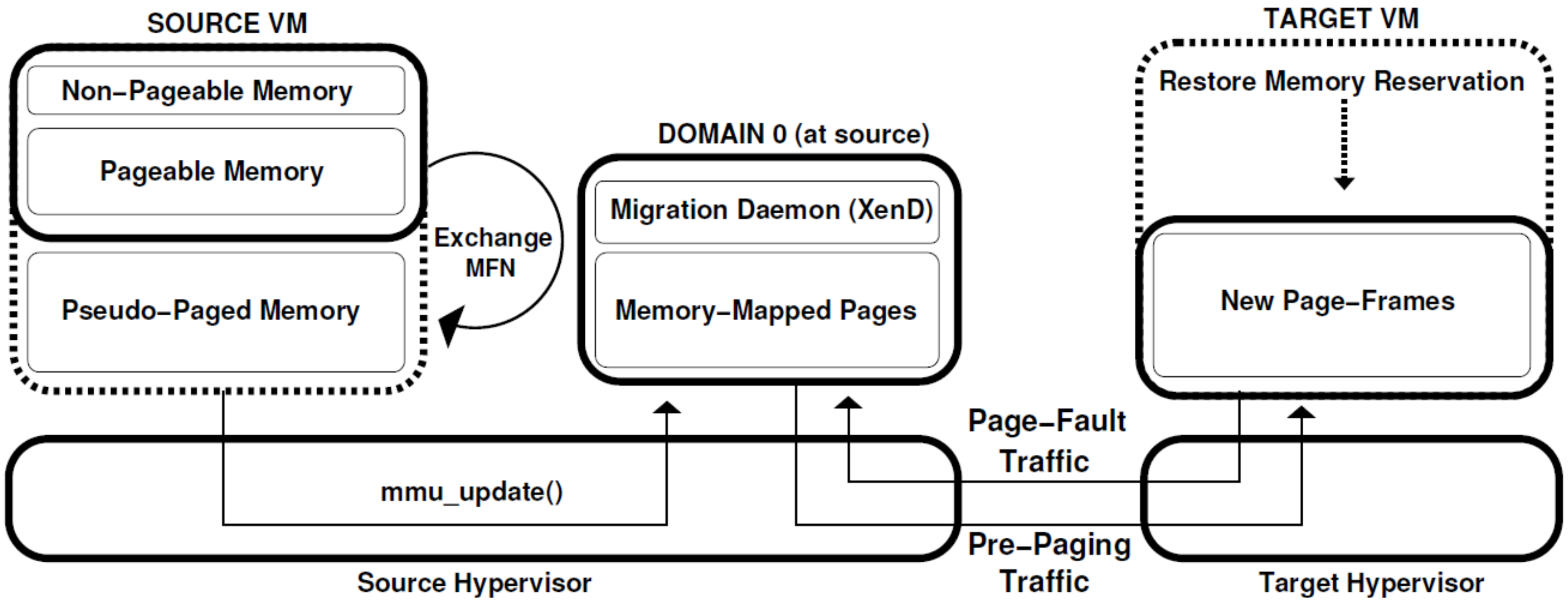
- Avoid multiple transfers of same page as happens in pre-copy
- Prepare target, stop VM, copy CPU context and minimum memory to target
- Start VM at target, pull memory from source via demand paging
    - Memory access at target causes page fault, page fetched from source



Optimizations

- Active pushing: source proactively pushes important pages, in addition to pulling pages via page faults
- Pre-paging: a “bubble” of pages around faulted page and proactively pushed, in anticipation of future accesses
- Dynamic self-ballooning: VM periodically frees up unnecessary memory and gives it back to hypervisor
    - Reduces memory footprint, speeds up page transfer
    - Performed carefully without hurting application performance
    - Can be used to optimize pre-copy migration as well
- Hybrid: one pre-copy round, followed by post copy

Implementation details (Xen)



- How are pages pulled at target? “Pseudo-paging”
  - Page to a pseudo, in-memory, swap device (part of domain0). No memory copy, just transfer pages across domains. Guest page table updated suitably.
  - Only non-pageable memory transferred during stop-and-copy
  - When guest resumes at target, fetch memory from pseudo-paging device via page fault mechanism
  - Special swap device driver fetches from source over the network
- Alternative: use shadow page tables
  - If page fault to non-existent page at target, trap to hypervisor, fetch from source and update

What about failures?

- What if target machine fails during migration?
- Pre-copy can simply abort the migration, restart with another target
  - With pre-copy, latest state is on source only, so can recover
- With post copy, source has stale memory, target has updated memory
  - If target crashes during post copy, cannot recover application data (unless some replication is performed)

Post copy performance

- Longer downtime as compared to pre-copy, but lower total migration time, fewer page transfers, lesser disruption to application

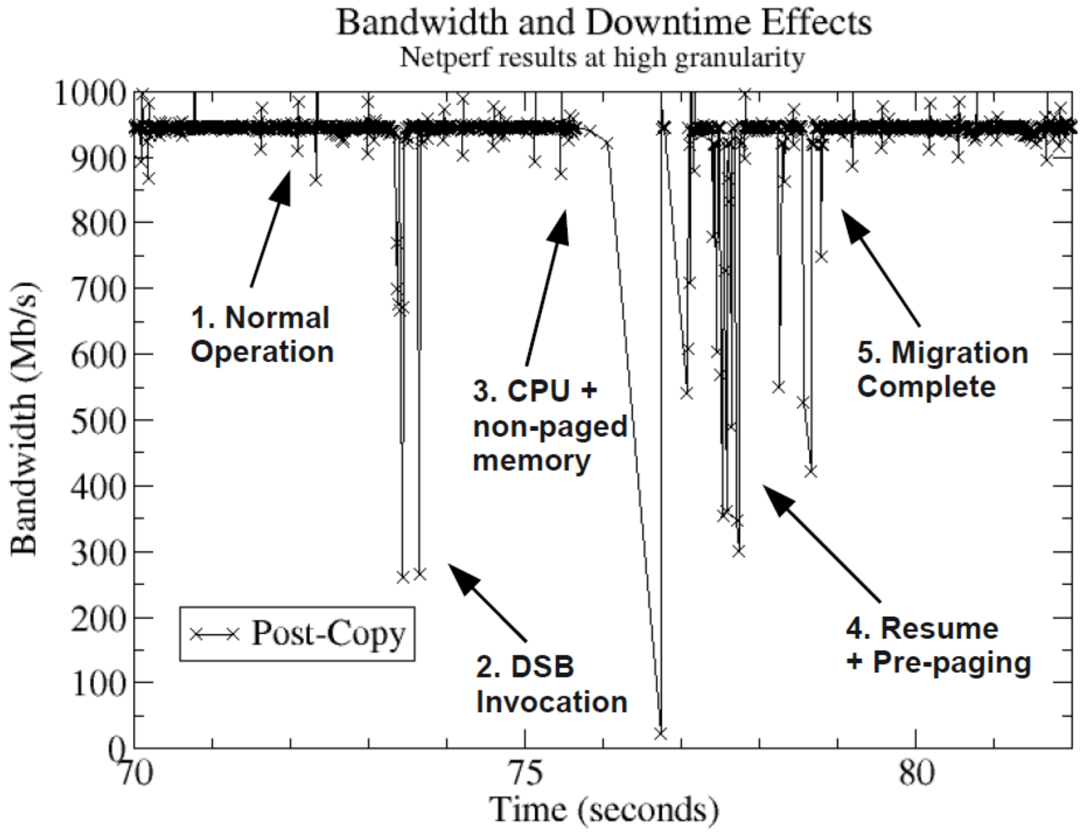


Figure 9. Impact of post-copy on NetPerf bandwidth.

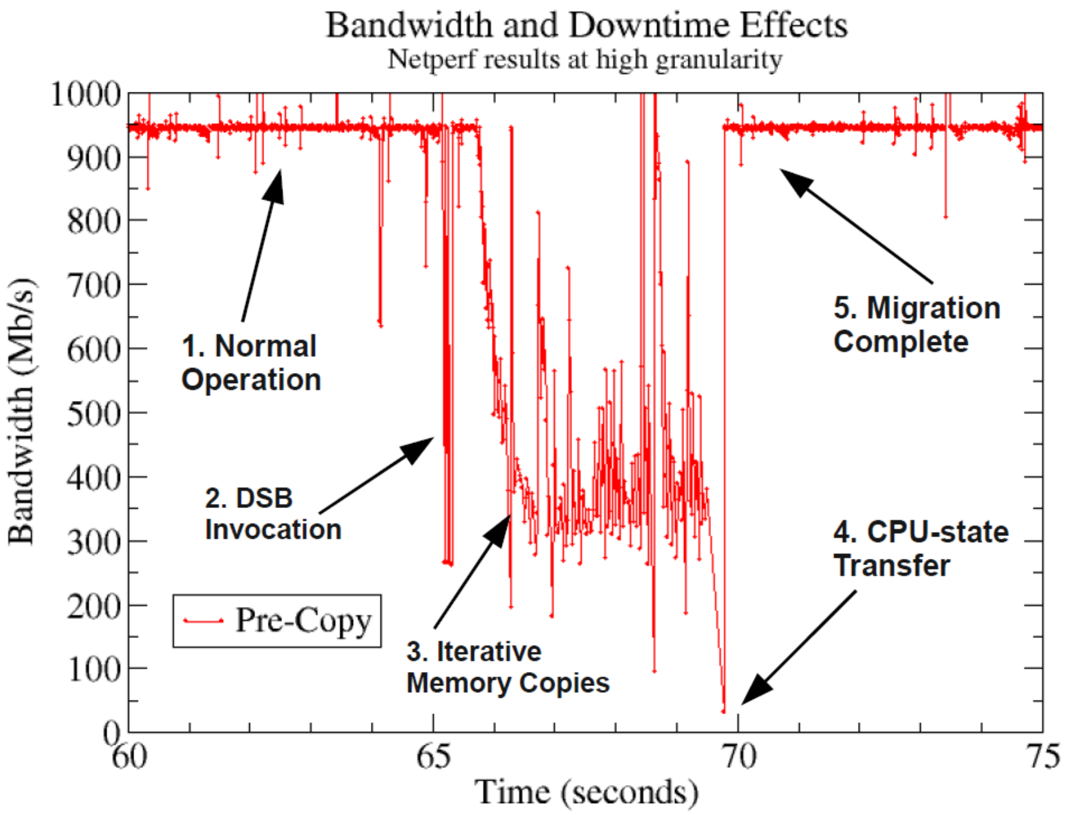
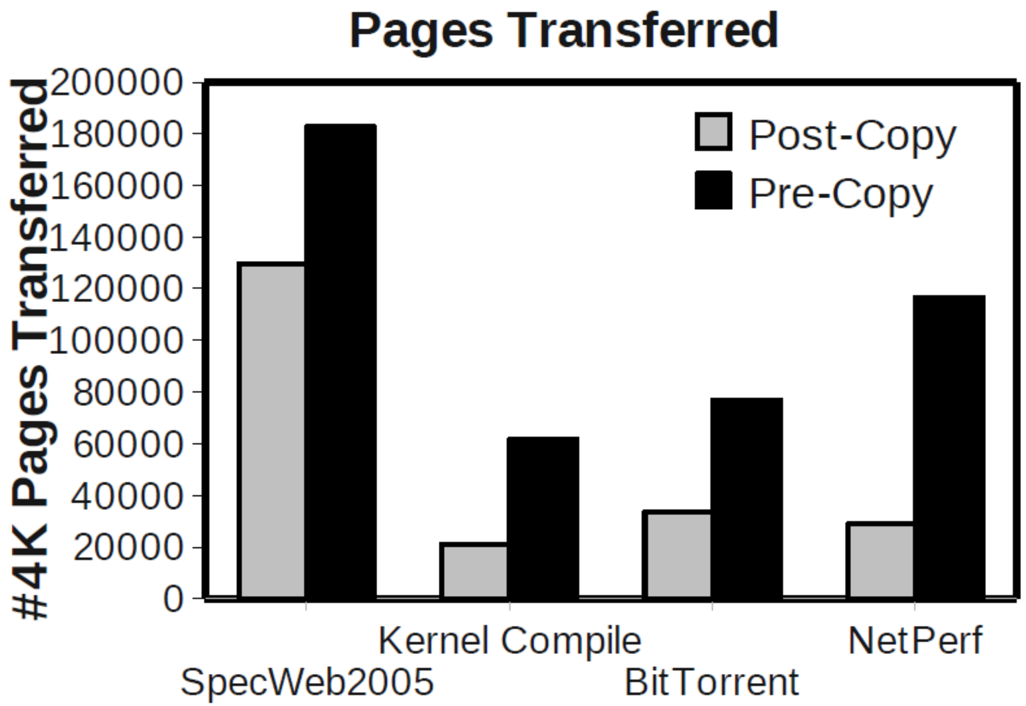
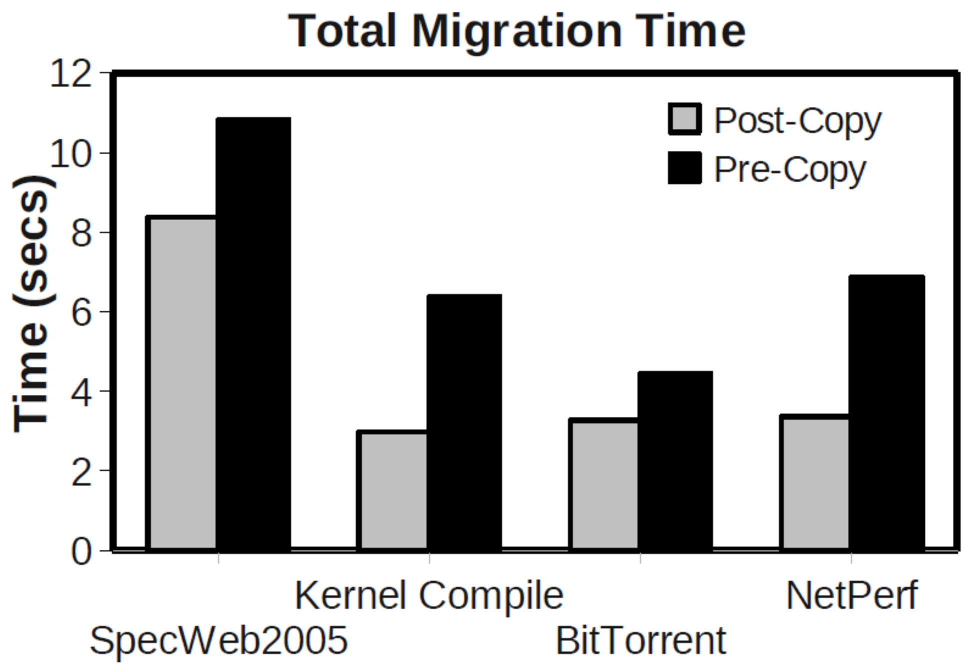
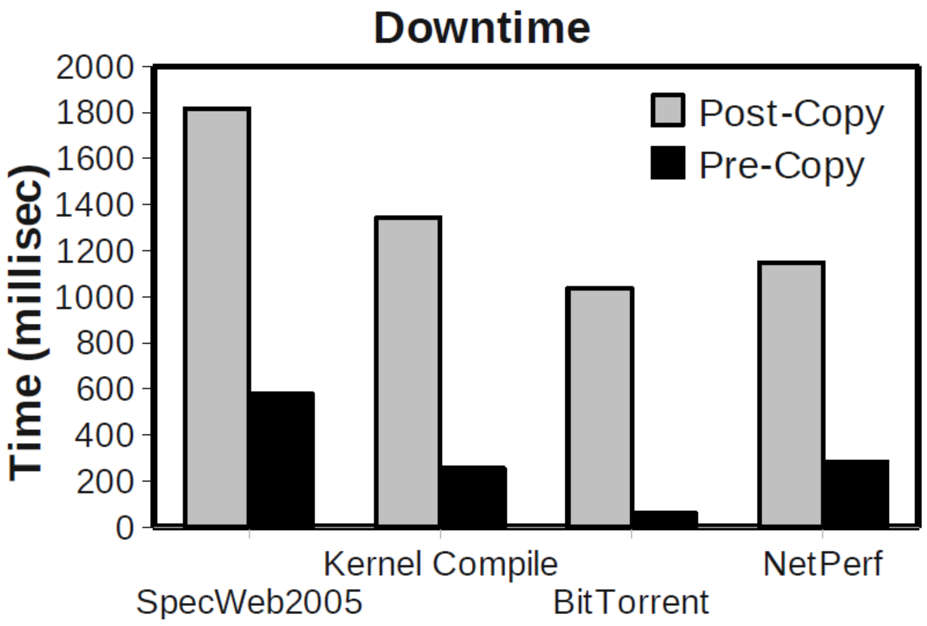


Figure 10. Impact of pre-copy on NetPerf bandwidth.


Pages Transferred
#4K Pages Transferred
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Post-Copy
Pre-Copy
SpecWeb2005
Kernel Compile
BitTorrent
NetPerf


Total Migration Time
Time (secs)
12
10
8
6
4
2
0
Post-Copy
Pre-Copy
SpecWeb2005
Kernel Compile
BitTorrent
NetPerf


Downtime
Time (millisec)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Post-Copy
Pre-Copy
SpecWeb2005
Kernel Compile
BitTorrent
NetPerf

Summary

- VM live migration techniques
  - Iterative pre-copy vs post-copy via demand paging
  - Implementation details on Xen
  - Performance comparison
- Which is better?
  - Pre-copy suited for interactive application
  - Post copy is better for memory-intensive applications with large WWS
  - Hybrid techniques are also used