ClickOS and the Art of Network Function Virtualization

(NSDI 2014 Paper)

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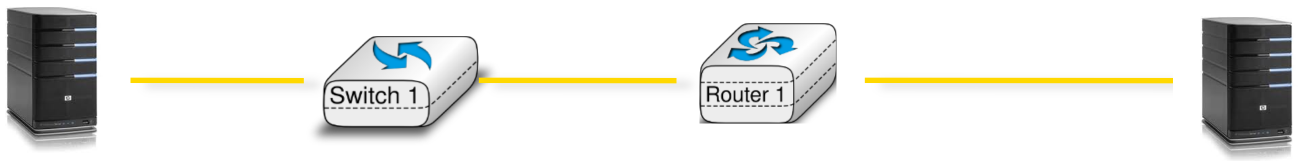
The Idealized Network



Application			Application
Transport			Transport
Network		Network	Network
Datalink	Datalink	Datalink	Datalink
Physical	Physical	Physical	Physical

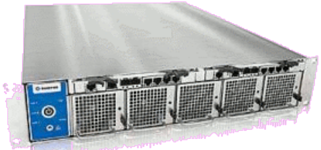
A Middlebox World

ad insertion

WAN accelerator

BRAS

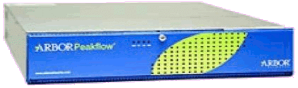
carrier-grade NAT


transcoder

session border controller

IDS

load balancer



DDoS protection

firewall

QoE monitor

DPI

Hardware Middleboxes - Drawbacks

- **Expensive equipment/power costs**

- **Difficult to add new features (vendor lock-in)**

- **Difficult to manage**

- **Cannot be scaled on demand (peak planning)**

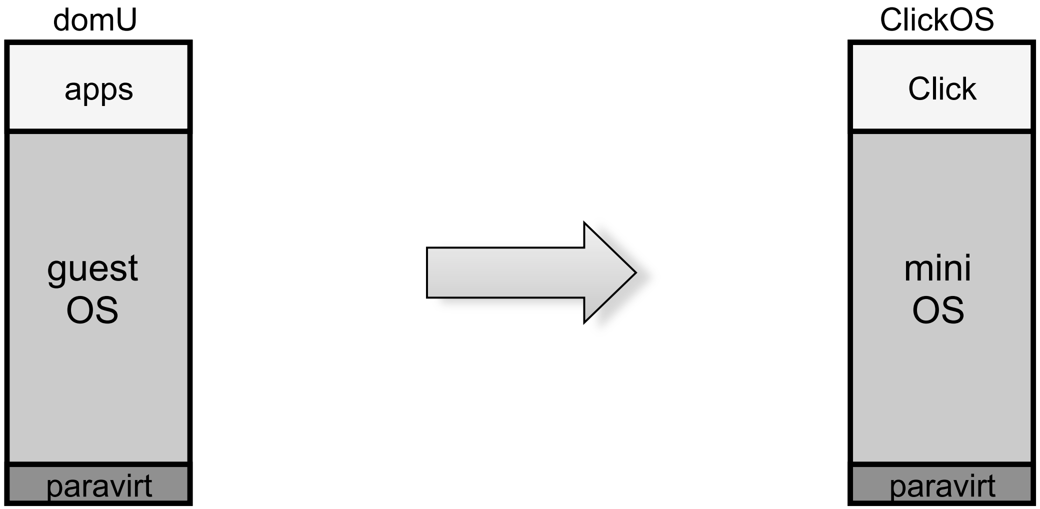
Shifting Middlebox Processing to Software

- **Can share the same hardware across multiple users/tenants**
- **Reduced equipment/power costs through consolidation**
- **Safe to try new features on a operational network/platform**
- But can it be built using commodity hardware while still achieving high performance?
- ClickOS: **tiny Xen-based virtual machine that runs Click**

From Thought to Reality - Requirements

	ClickOS
Fast Instantiation	✓ 30 msec boot times
Small footprint	✓ 5MB when running
Isolation	✓ provided by Xen
Performance	✓ 10Gb/s line rate* 45 µsec delay
Flexibility	✓ provided by Click

What's ClickOS ?

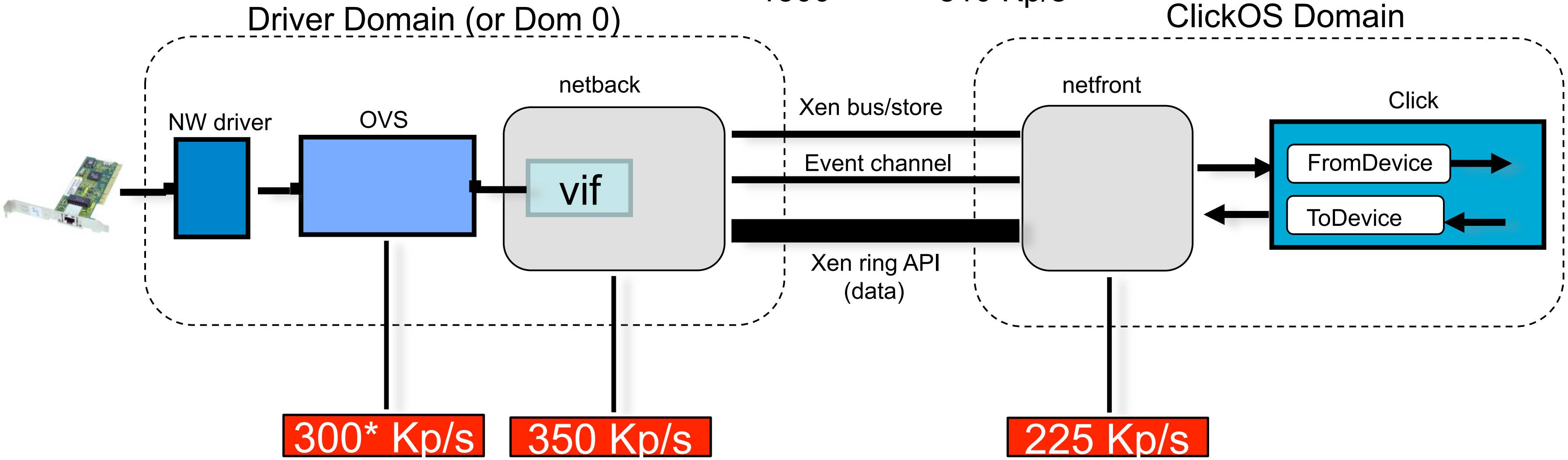


Work consisted of:

- **Build system to create ClickOS images (5 MB in size)**
- **Emulating a Click control plane over MiniOS/Xen**
- **Reducing boot times (roughly 30 milliseconds)**
- **Optimizations to the data plane (10 Gb/s for almost all pkt sizes)**
- **Implementation of a wide range of middleboxes**

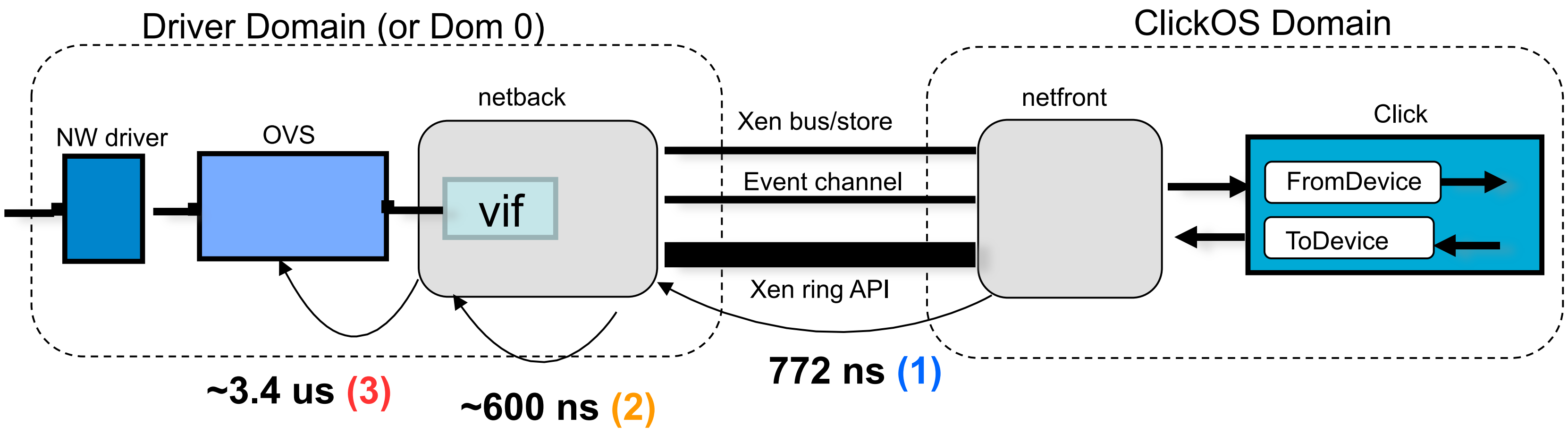
Performance analysis

packet size (bytes)	10 Gbit/s rate
64	14.88 Mp/s
128	8.4 Mp/s
256	4.5 Mp/s
512	2.3 Mp/s
1024	1.2 Mp/s
1500	810 Kp/s



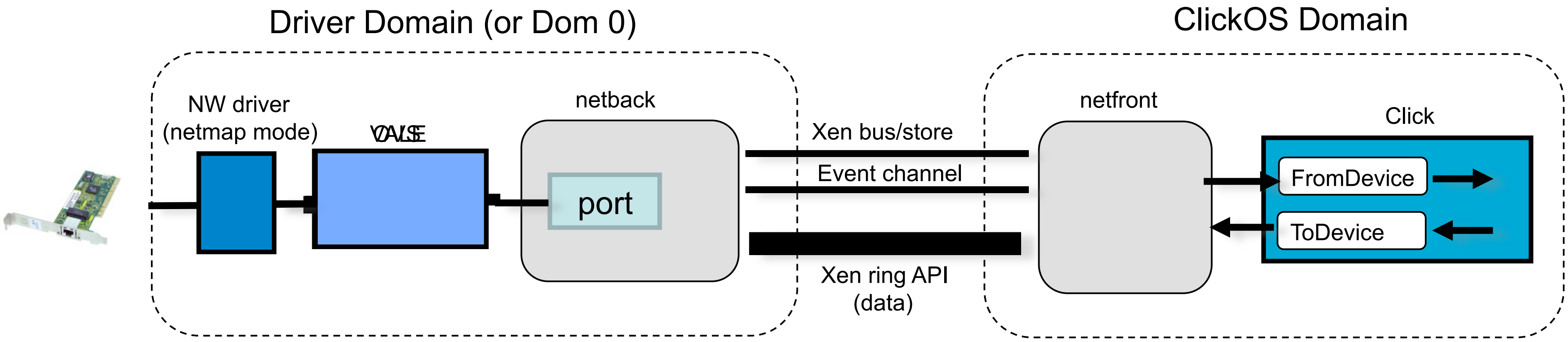
* - maximum-sized packets

Performance analysis

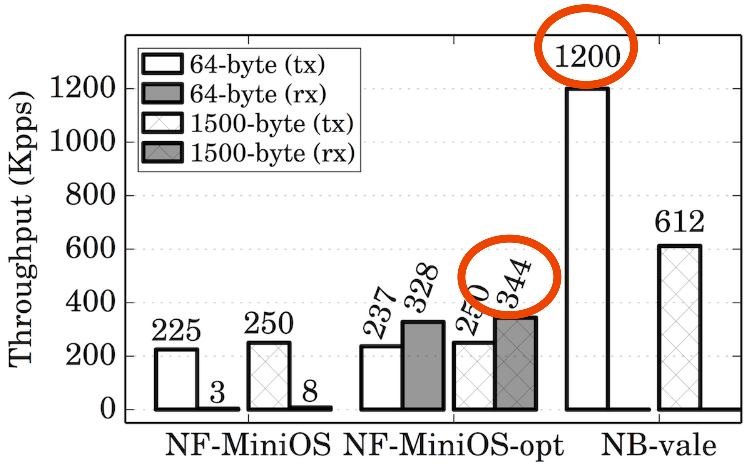


- **Copying packets between guests greatly affects packet I/O (1)**
- **Packet metadata allocations (2)**
- **Backend switch is slow (3)**
- **MiniOS netfront not as good as Linux**

Optimizing Network I/O – Backend Switch

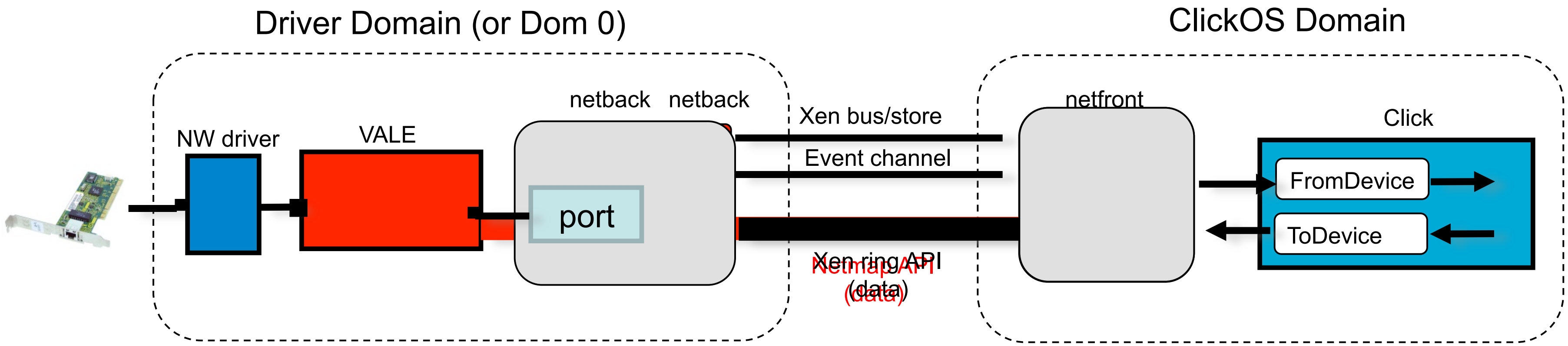


- Reuse Xen page permissions (frontend)
- Introduce VALE[1] as the backend switch
- Increase I/O requests batch size



[1] VALE, a switched ethernet for virtual machines, ACM CoNEXT'2012
Luigi Rizzo, Giuseppe Lettieri
Universita di Pisa

Optimizing Network I/O



Minimal memory requirements

- For max. throughput a guest only needs 2 MB of memory

Breaks other (non-MiniOS) guests

- **But we have implemented Linux netfront driver**

slots	KB (per ring)	# grants (per ring)
64	135	33
128	266	65
256	528	130
512	1056	259
1024	2117	516
2048	4231	1033

ClickOS Prototype Overview

- **Click changes are minimal ~600 LoC**
- **New toolstack for fast boot times**
- **Cross compile toolchain for MiniOS-based apps**
- **`netback` changes comprise ~500 LoC**
- **`netfront` (Linux/MiniOS) around ~600 LoC**
- **VALE switch extended to:**
  - **Connect NIC ports and modular switching**

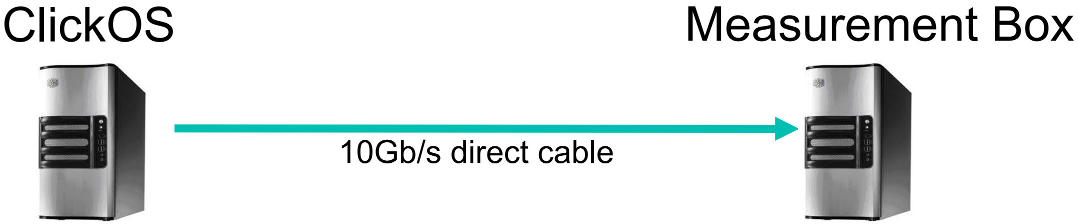
EVALUATION

Experiments

- ClickOS Instantiation
- State reading/insertion performance
- Delay compared with other systems
- Memory footprint

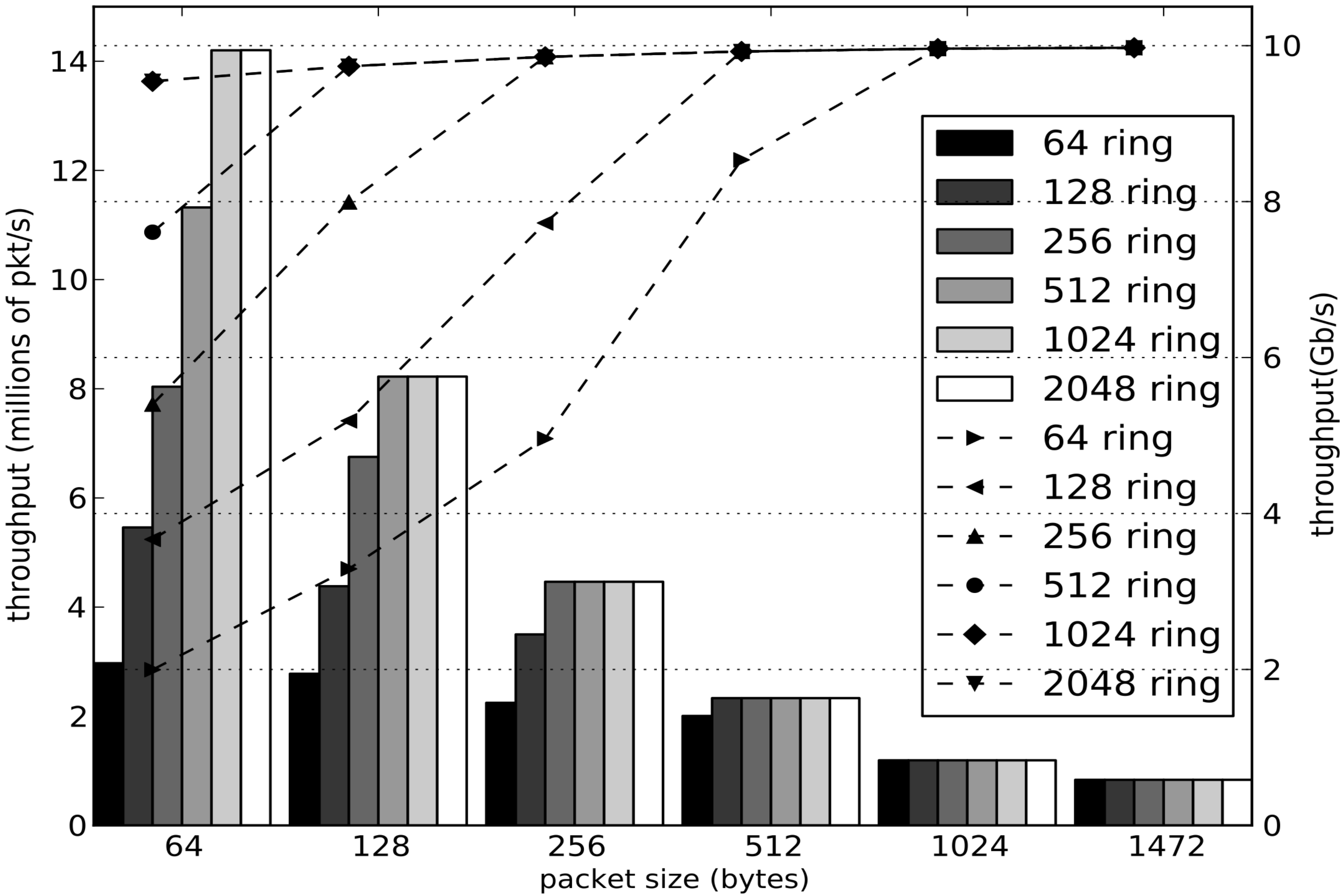
- Switch performance for 1+ NICs
- **ClickOS/MiniOS performance**
- Chaining experiments
- Scalability over multiple guests
- Scalability over multiple NICs
- **Implementation and evaluation of middleboxes**
- **Linux Performance**

ClickOS Base Performance

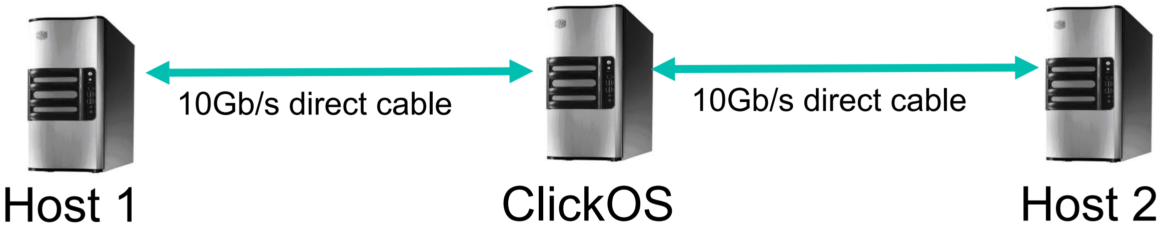


Intel Xeon E1220 4-core 3.2GHz (Sandy bridge)
16GB RAM, 1x Intel x520 10Gb/s NIC.
One CPU core assigned to VMs, the rest to the Domain-0
Linux 3.6.10

ClickOS Base TX Performance

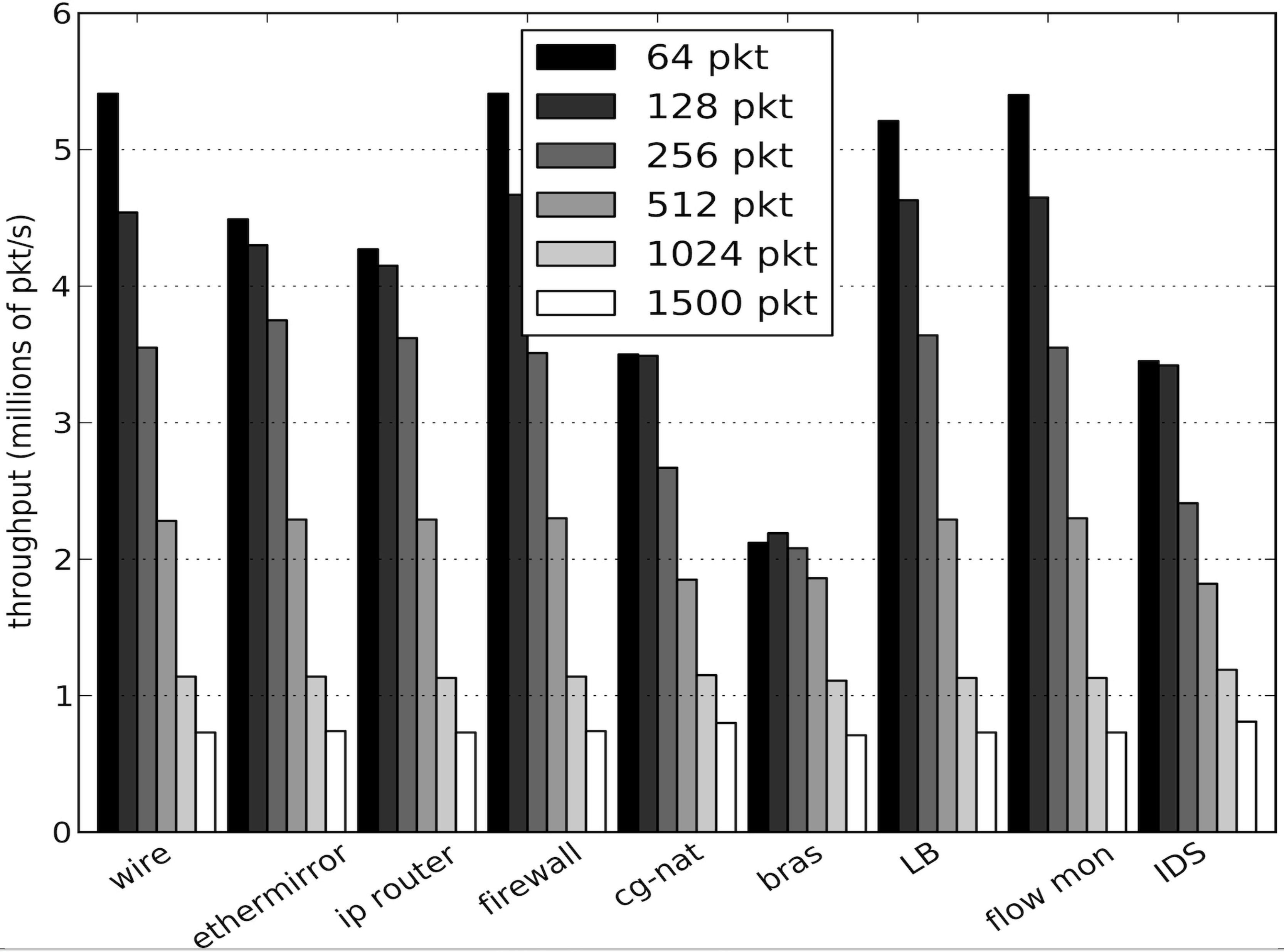


ClickOS (virtualized) Middlebox Performance

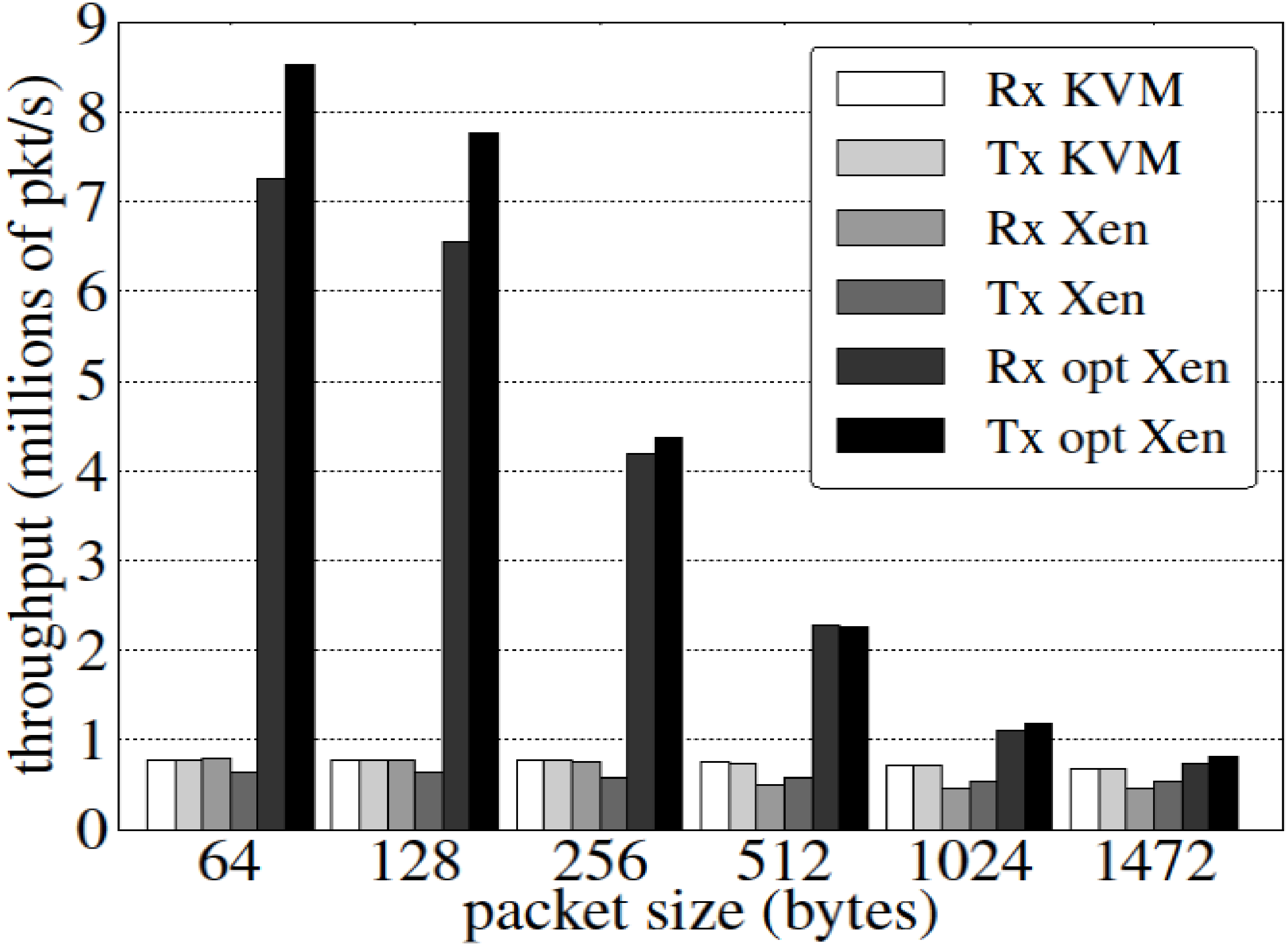


Intel Xeon E1220 4-core 3.2GHz (Sandy bridge)
16GB RAM, 2x Intel x520 10Gb/s NIC.
One CPU core assigned to Vms, 3 CPU cores Domain-0
Linux 3.6.10

ClickOS (virtualized) Middlebox Performance



Linux Guest Performance



- Note that our Linux optimizations apply only to netmap-based applications

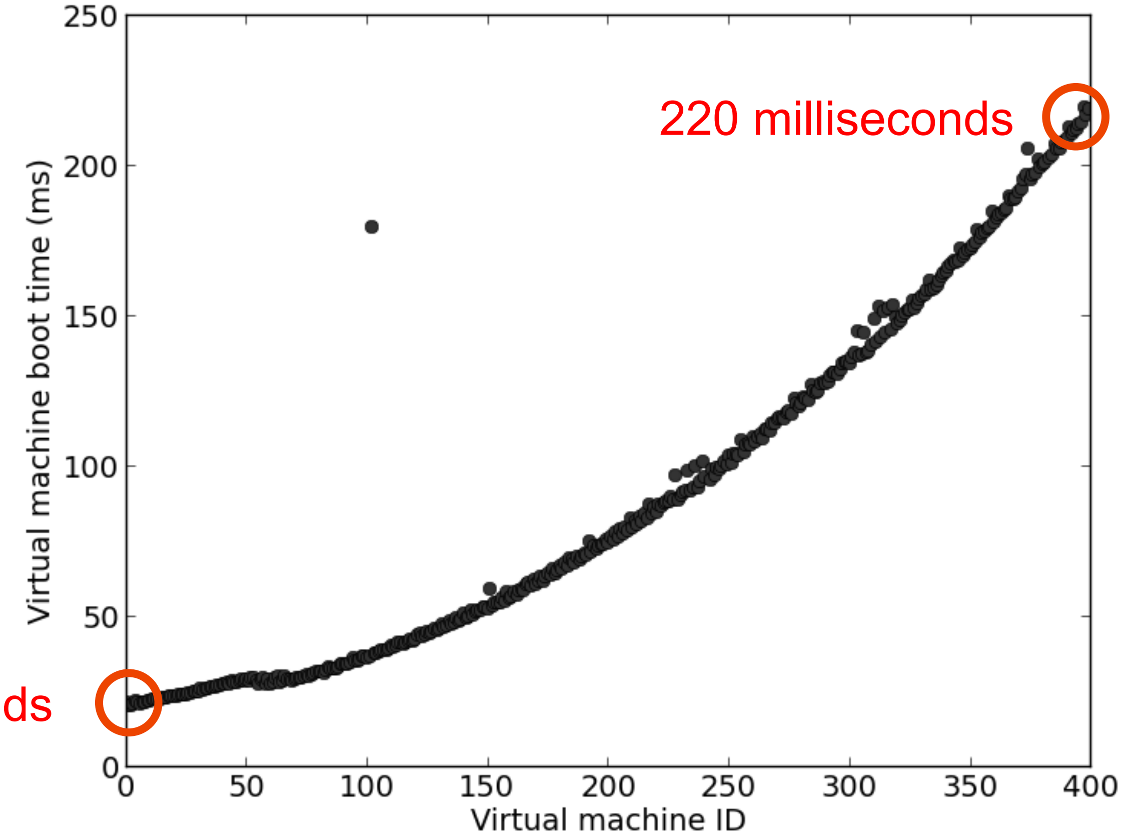
Conclusions

- Virtual machines can do flexible high speed networking

- ClickOS: **<u>Tailor-made operating system</u> for network processing**
  - Smaller is better: **Low footprint is the key to heavy consolidation**
  - Memory footprint: **5MB**
  - Boot time: **30ms**

- Future work:
  - **Massive consolidation of VMs (thousands)**
  - **Improved Inter-VM communication for service chaining**
  - **Reactive VMs (e.g., per-flow)**

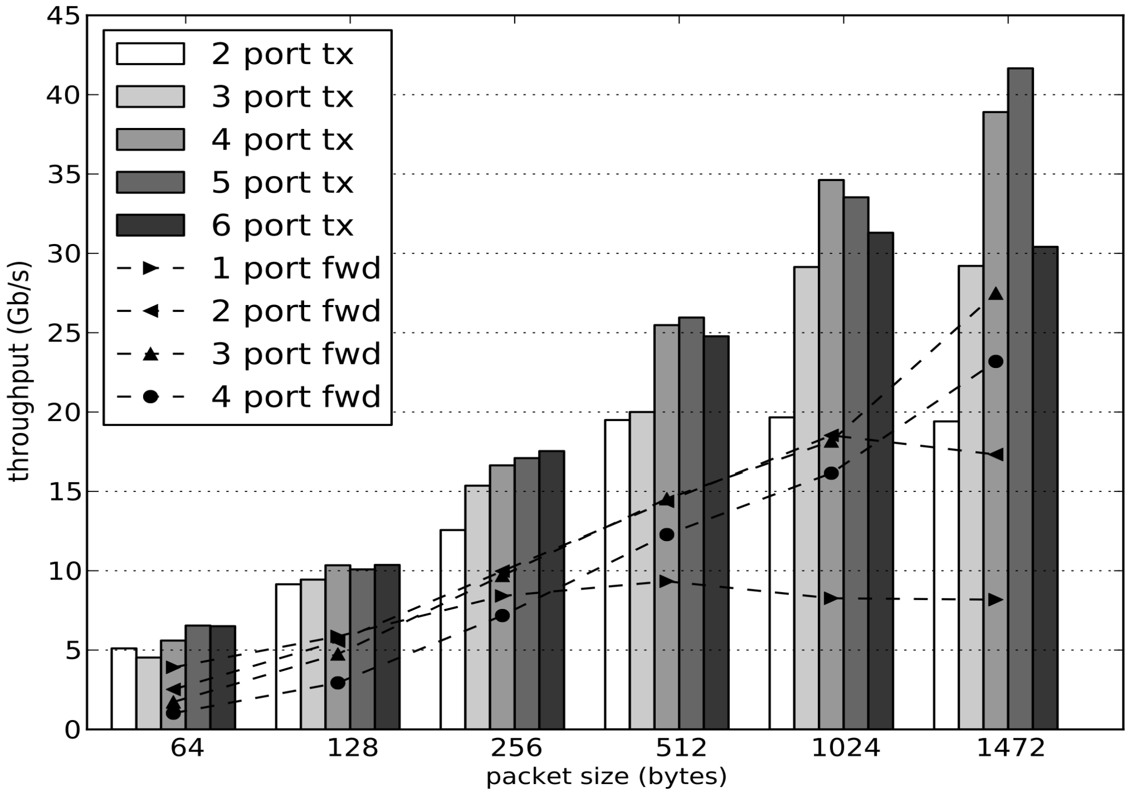
ClickOS Boot times

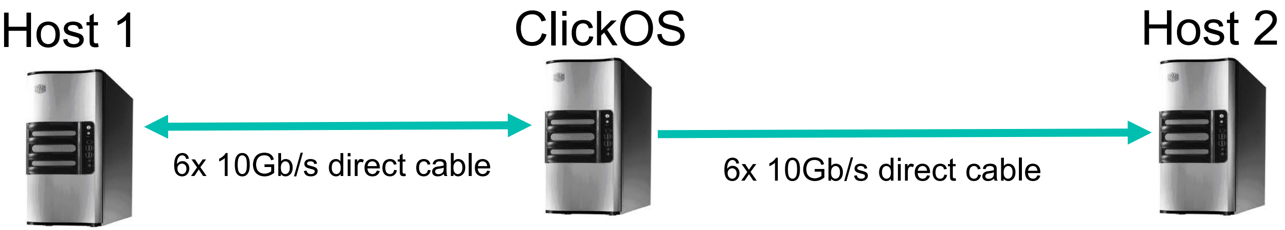


220 milliseconds

30 milliseconds

Scaling out – Multiple NICs/VMs





Host 1

ClickOS

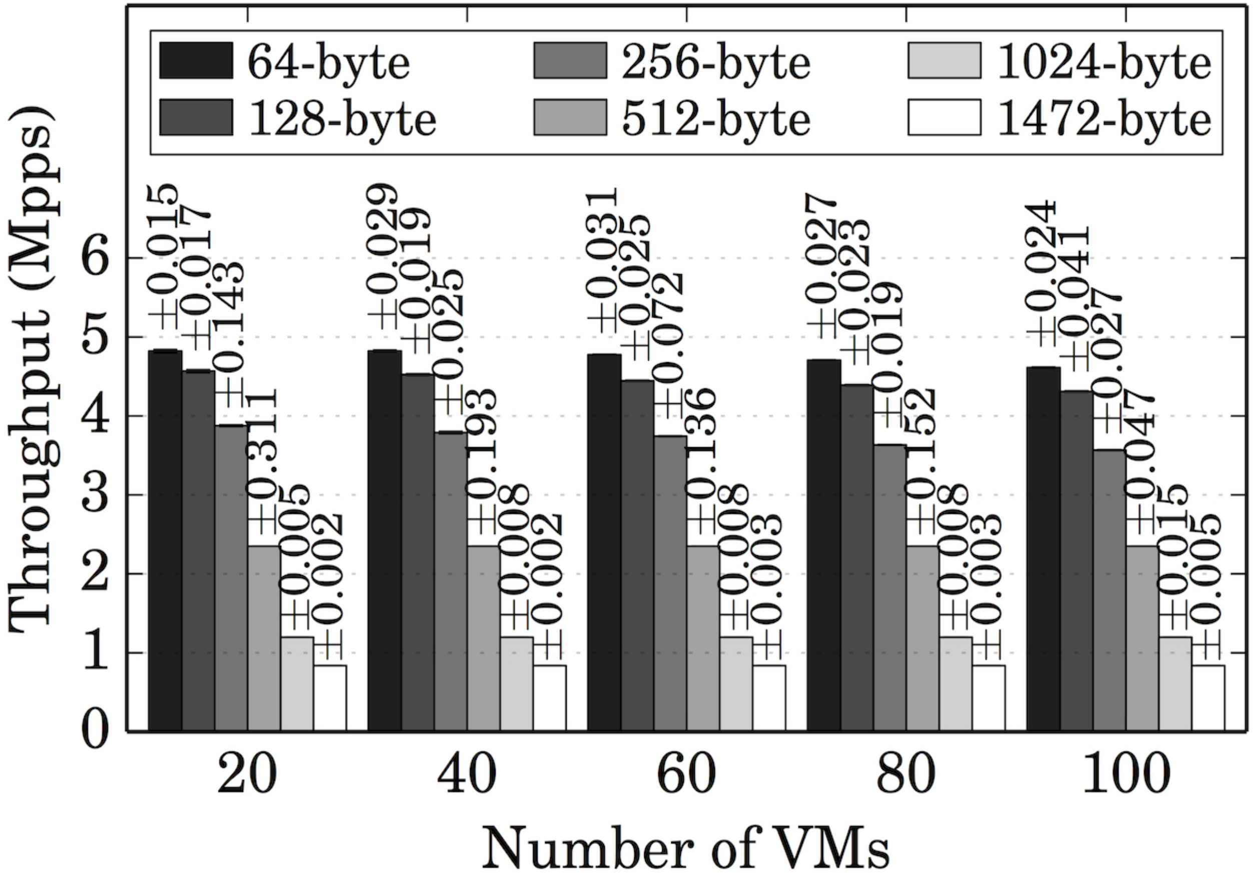
Host 2

6x 10Gb/s direct cable

6x 10Gb/s direct cable

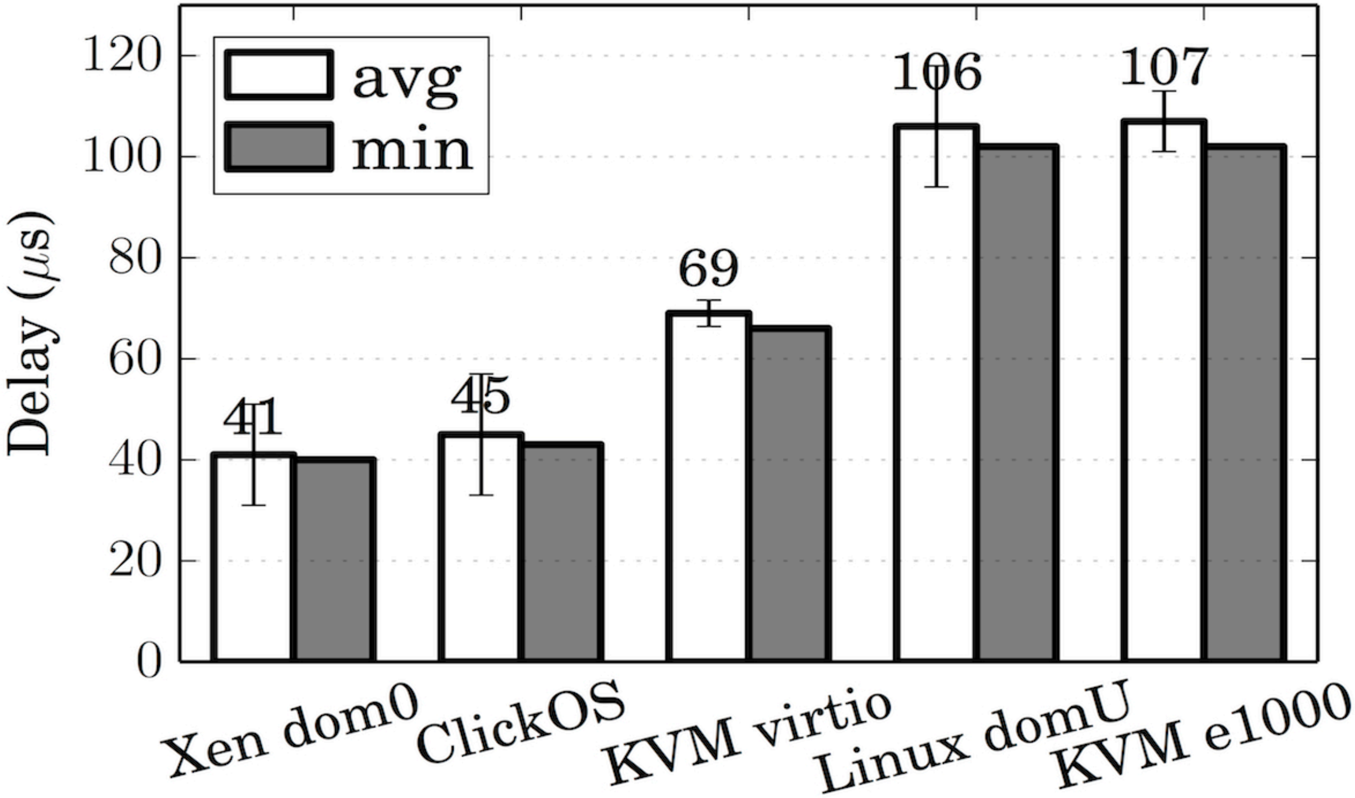
Intel Xeon E1650 6-core 3.2GHz, 16GB RAM, dual-port Intel x520 10Gb/s NIC.
3 cores assigned to VMs, 3 cores for dom0

Scaling out – 100 VMs Aggregate Throughput



Intel Xeon E1650 6-core 3.2GHz, 16GB RAM, dual-port Intel x520 10Gb/s NIC.
3 cores assigned to VMs, 3 cores for dom0

ClickOS Delay vs. Other Systems



Towards Massive Server Consolidation

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NEC Europe Ltd.

Xen Developer Summit 2014

The Super Fluid Cloud

- Target: remove barriers in current cloud deployments
  - Extremely flexible infrastructure
  - **Milliseconds** instantiation and migration of resources
  - **Thousands** of concurrent units running
- This would allow new use cases
  - On the fly deployment of middleboxes
  - Flash crowds
  - Energy consumption reduction
  - Your use case here...

Recent trend: specialized guests

- ClickOS, OSv, Mirage, Erlang on Xen, etc
  - Small memory footprints
  - Relatively fast boot times
  - Provide the basic functionality to make use cases a reality

- Our work focuses on ClickOS
  - Targets network processing using the Click modular router software

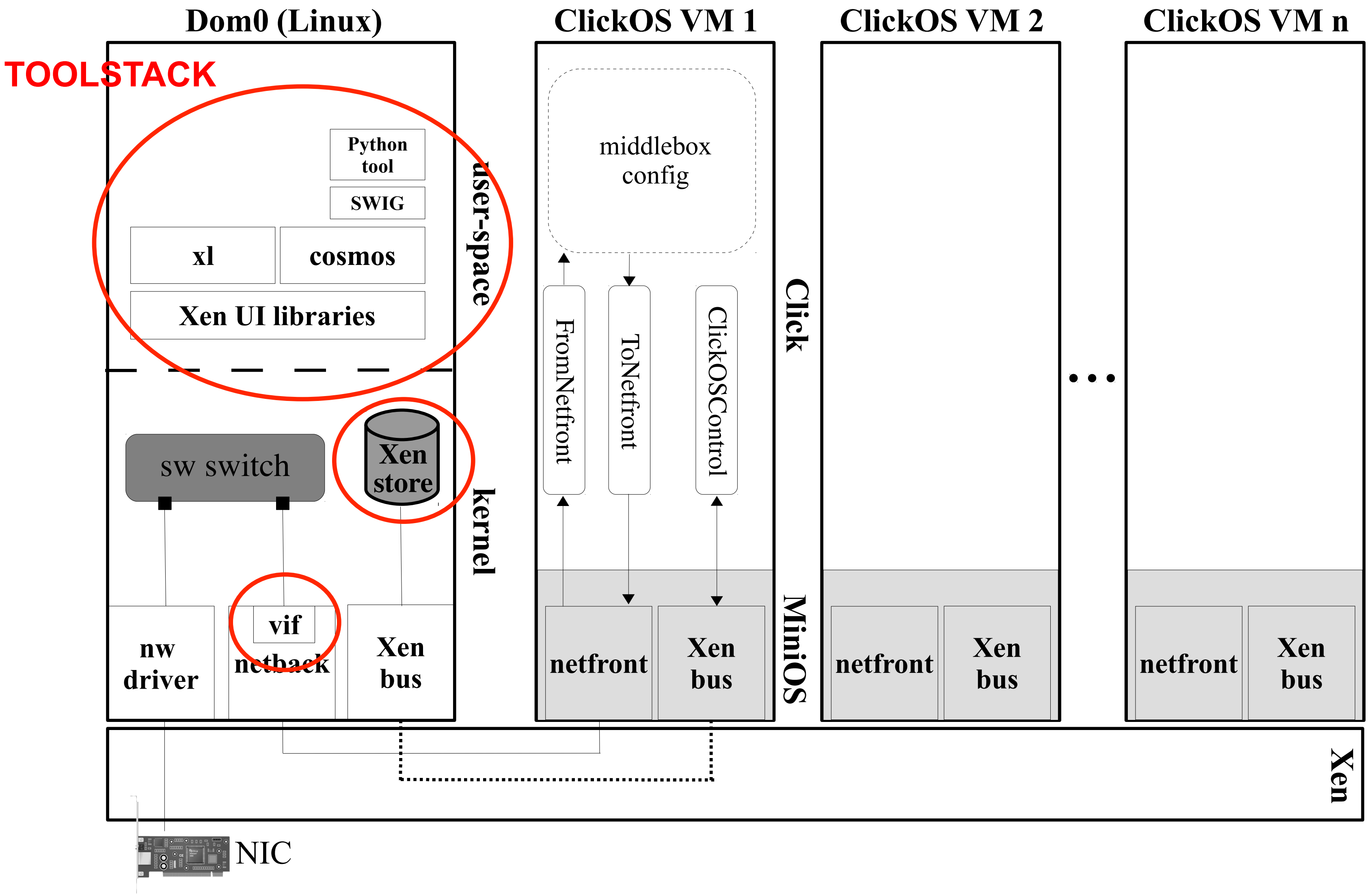
Wouldn't it be Nice if...

- Thousands of guests on a **single server**
  - Short-term target: **10K**
  - Medium-term target: **100K**
- Extremely fast domain creation, destruction and migration
  - **Tens of milliseconds**
  - Constant as number of guests increases

Experiment Setup

- Freshly installed Xen/Debian system
  - Xen 4.2
  - Linux 3.6.10
  - Debian squeeze
- Commodity server
  - 64 Cores @ 2.1GHz [4 x AMD Opteron 6376]
  - 128GB RAM DDR3 @ 1333MHz

Xen and ClickOS Architecture



Baseline Test

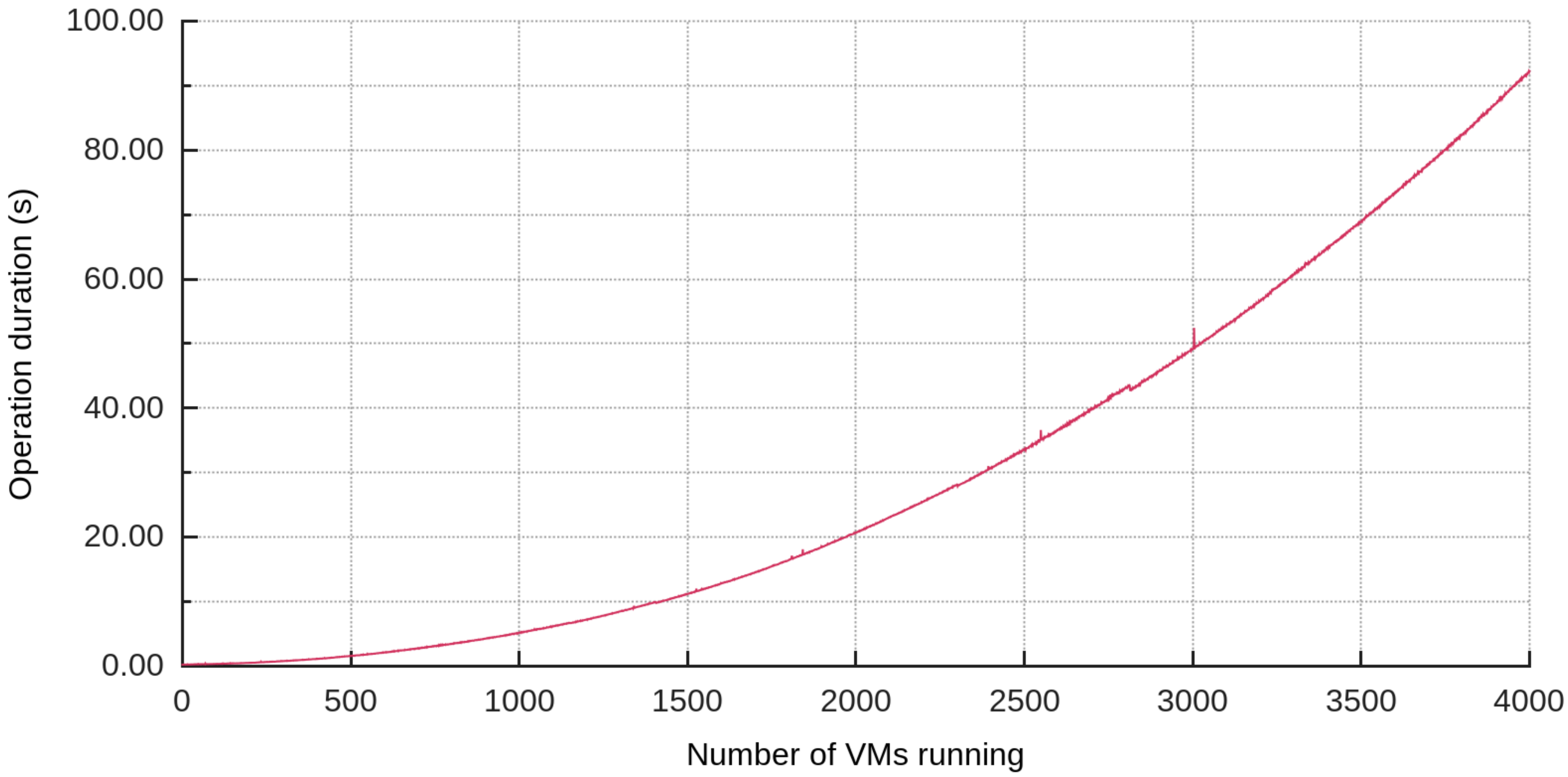
Boot as many guests as possible before system breaks

- Using ClickOS guests
  - 8 MB of RAM
  - 1 VIF
- Guests are mostly idle
  - Running arp responder configuration
  - Only *arping* guests to check they're working

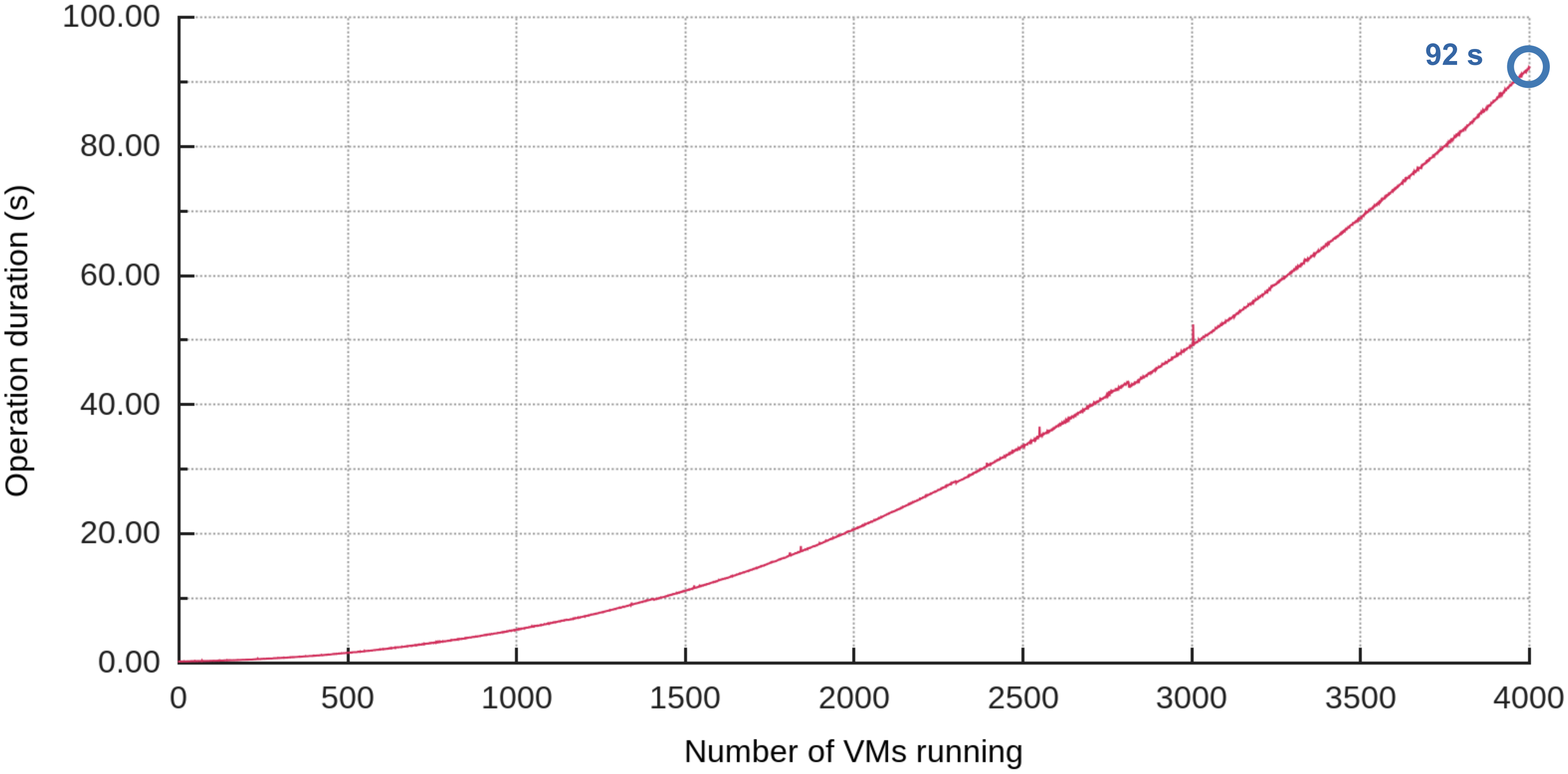
Didn't Work Quite Well...

- Stopped test after 4K guests
  - Took ~ 5 days
  - Up to ~ 100 seconds for creation of last guest (normally ClickOS boots in ~30 milliseconds)
- All the domains were running, but:
  - Only first ~300 guests fully functional
- System got extremely slow
  - Dom0 unusable

Domain Creation Time



Domain Creation Time



Two Types of Problems

- Hard limitations
  - Prevent guests from booting correctly
  - Only ~300 guests fully usable
- Performance limitations
  - Decreasing system performance
  - System unusable after just a few hundred guests

HARD LIMITATIONS

Issues

- Cannot access guests' console
  - Only first ~300 guests have accessible console
- Guests' VIF is not created
  - Only first ~1300 guests have usable VIF
- Guests cannot access the Xenstore
  - Only first ~1300 guests have access to it
- The back-end switch doesn't provide enough ports
  - Only 1024 available

Number of File Descriptors

- `xenconsoled` opens 3 FD per guest
  - `/dev/xenbus`; `/dev/ptmx`; `/dev/pts/<id>`;
- Fix
  - Linux can easily handle > 300K FD
  - Tune `fs.file-max; nofile ulimit;`

Number of PTYs

- `xenconsoled` opens 1 PTY per guest
- Fix
  - Linux can easily handle > 100K PTY
  - Tune `kernel.tty.max`
- Future
  - Only create PTY when user connects to console
  - This also reduces number of FD to 1 per guest

Number of Event Channels

- 3 Interdomain evtchn per guest
  - xenstore; console; VIF
  - 64bit Dom0: `NR_EVTCHNS == 4096`
  - Dom0 runs out after ~1300 guests
- Fix
  - Upgrade to Xen 4.4 + Linux 3.14:
    - `NR_EVTCHNS == 128K`
  - Split services into stub domains

Number of IRQs

- Linux runs out of IRQs to map evtchn
  - Limited by `NR_CPUS`
- Fix
  - `Build with: MAXSMP=y; NR_CPUS=4096`
  - `NR_IRQS == 256K`

vSwitch Ports

- Currently back-end switch supports up to few thousand ports
  - Linux bridge: 1K
  - Open vSwitch: 64K
- Workaround
  - Create multiple bridges
- Longer-term fix
  - Develop a purpose-built back-end switch

Summarizing

- Xen 4.4; Linux 3.14
- `fs.file-max; nofile ulimit`
- `kernel.tty.max`
- `MAXSMP=y; NR_CPUS=4096`

- Not yet fixed:
  - Back-end switch ports

PERFORMANCE LIMITATIONS

Issues

- Overall system becomes too slow
  - `oxenstored`
    - CPU fully utilized after a few dozen guests
  - `Xenconsoled`
    - CPU limited after ~ 2K guests
- Domain creation takes too long
  - Affects migration too

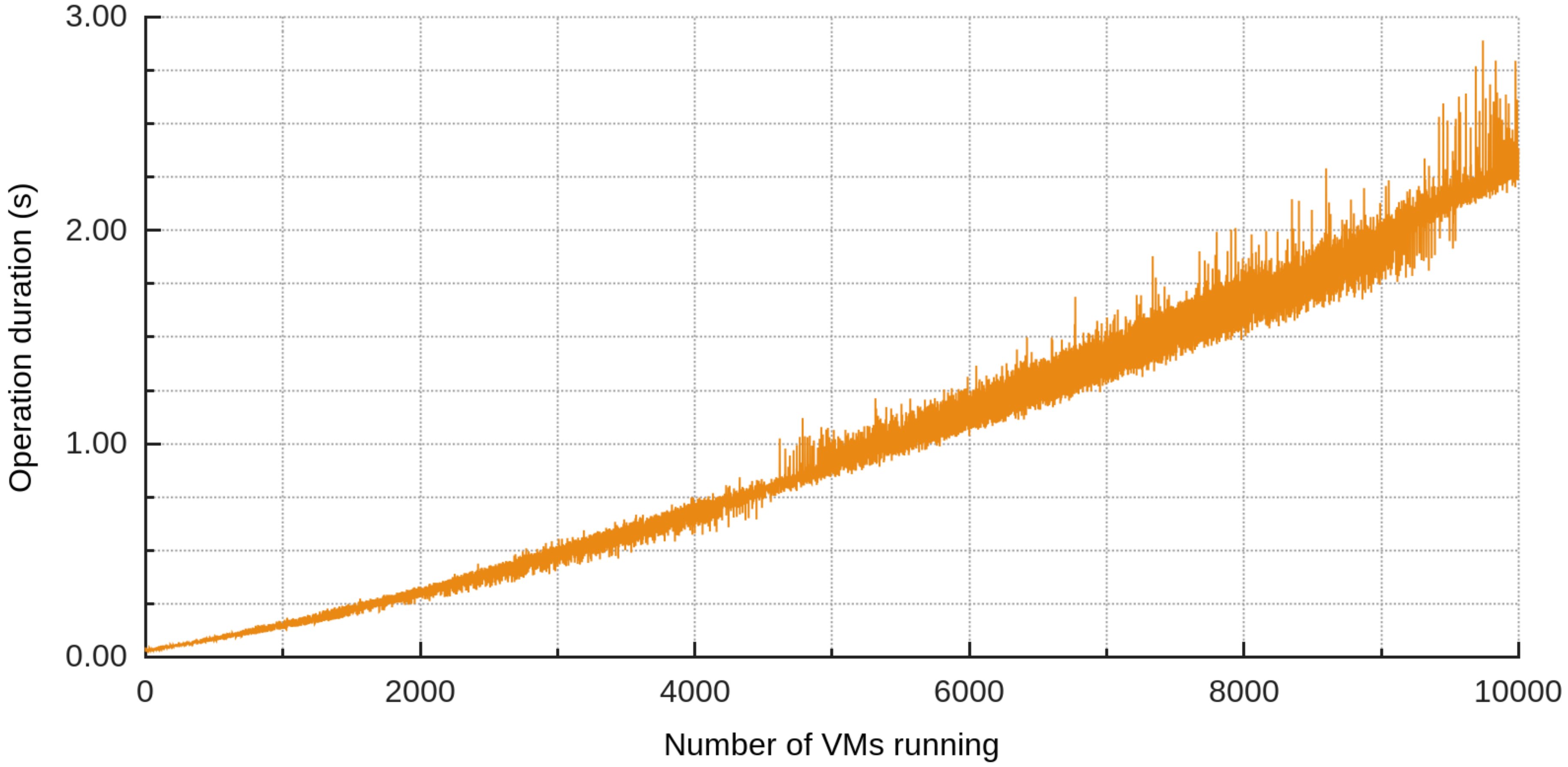
“Blind” optimizations

- 4 Core Dom0
  - 1 core for `oxenstored`
  - 1 core for `xenconsoled`
  - 2 cores for remaining processes
- Pin all vCPUs to pCPUs
- Round robin remaining 60 cores for guests
- Put everything in a ramfs

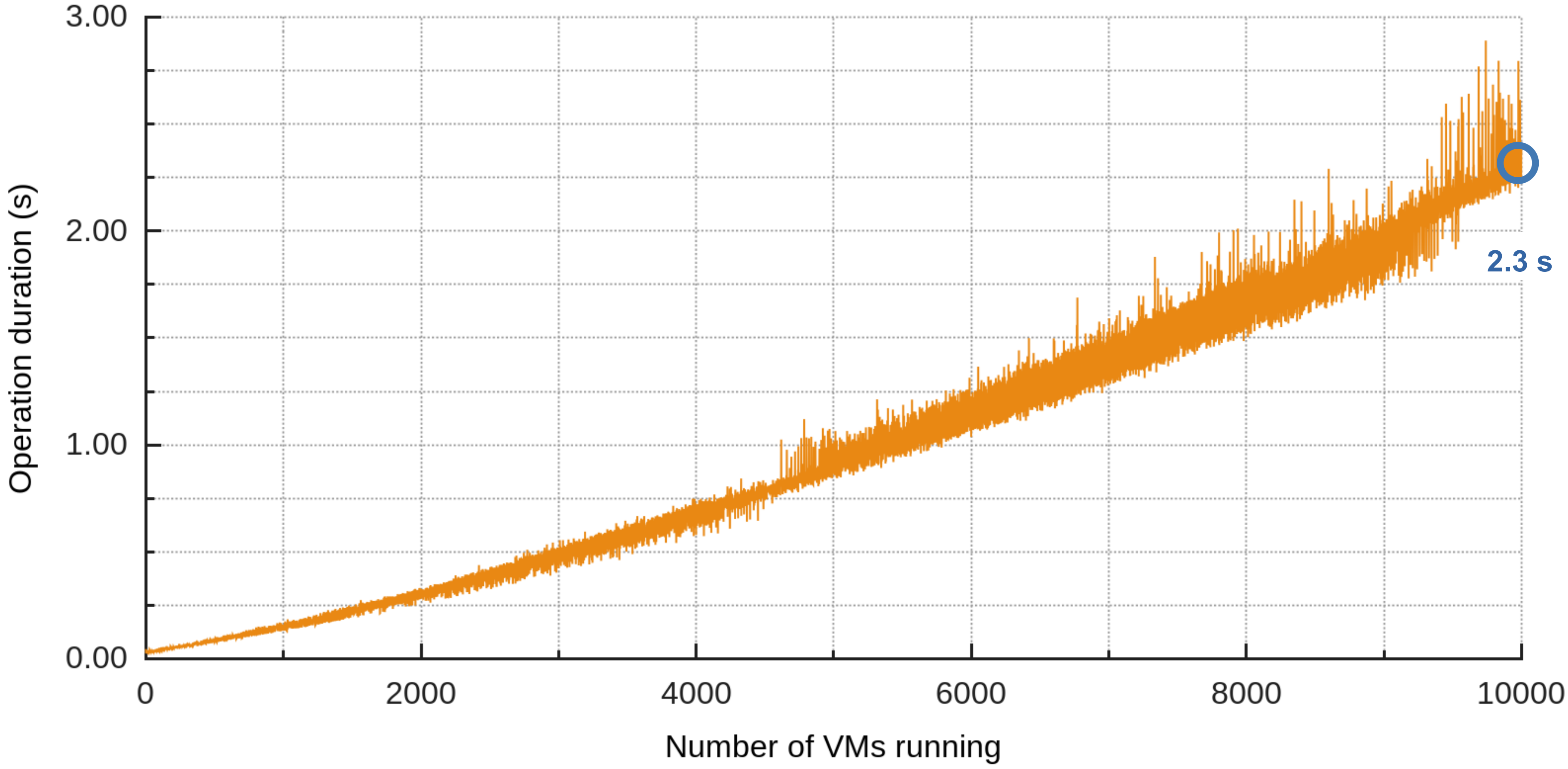
Tools' Optimizations

- xl toolstack
  - Disable xl background process (`xl create -e`)
  - Disable memory ballooning on Dom0
  - Never use domain name
    - This causes xl to retrieve all guest names from the Xenstore
  - Use specialized VIF hotplug script
  - Don't retrieve domain list on creation [PATCH]
- oxenstored
  - Use more recent version of Xenstore from:
    - https://github.com/mirage/ocaml-xenstore

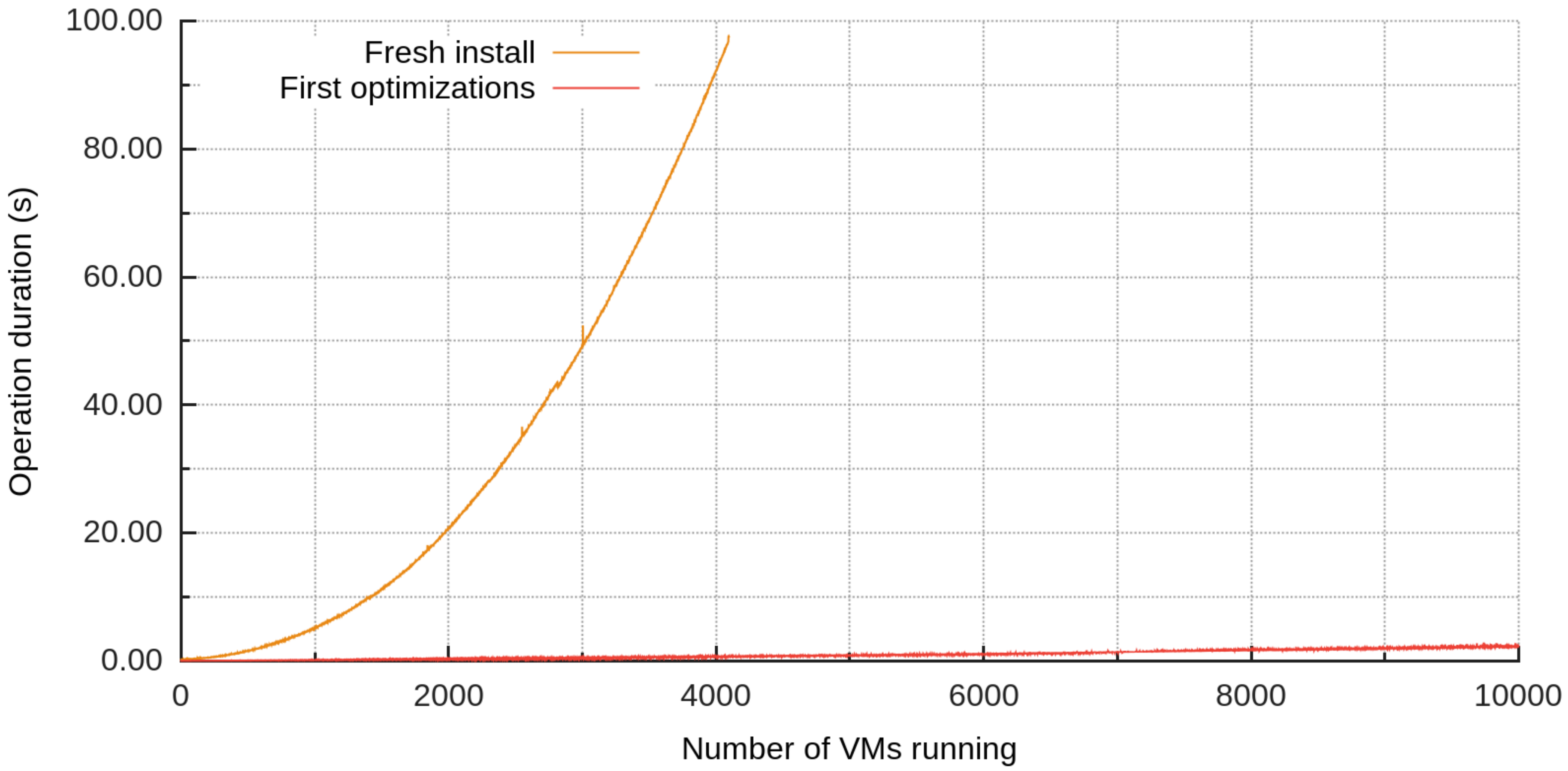
Creation Times with Optimizations



Creation Times with Optimizations



How much better is it?



With Optimizations

- Improvement: system is still usable after 10K guests
  - Although domain creation time is far from ideal

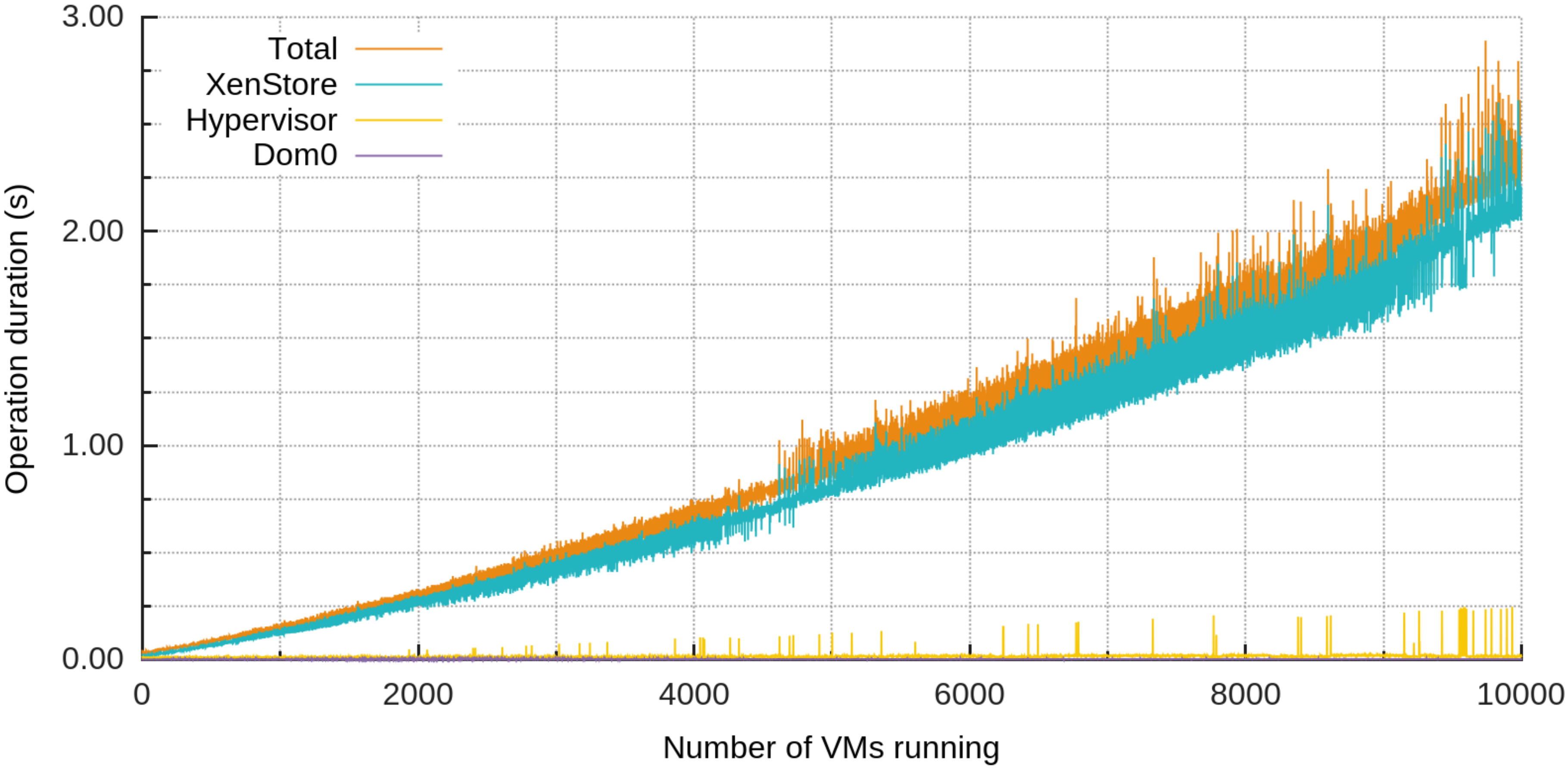
- However...
  - xenstored still CPU heavy
  - xenconsoled still CPU heavy

xenconsoled

- Two major optimizations
  - Move from `poll` to `epoll`
  - On INTRODUCE_DOMAIN, search from last domid
    - Avoid listing all existing domains
- CPU usage down to ~ 10% max.

What Bottlenecks Remain?

Domain Creation Breakdown



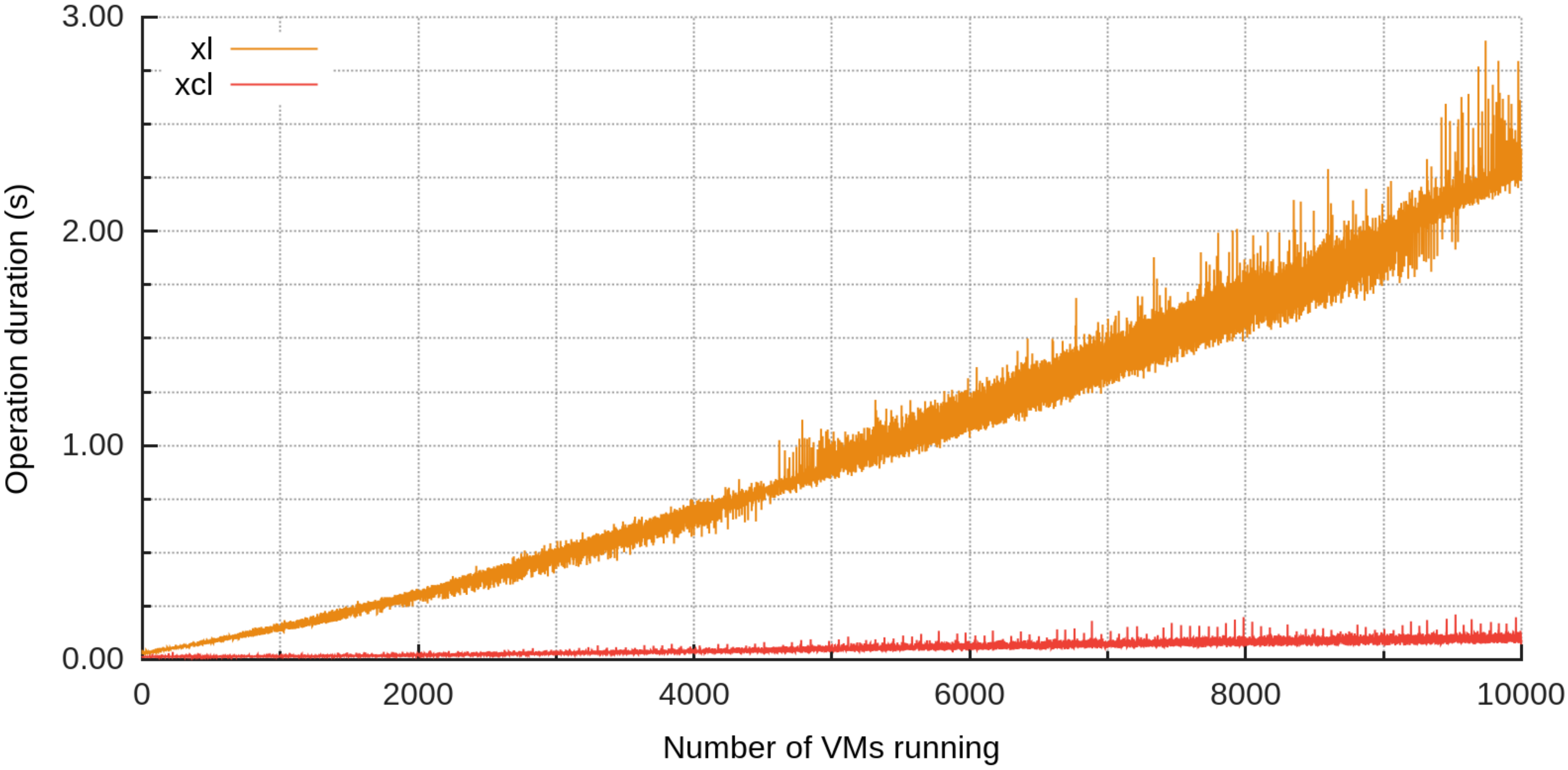
Let's Look at the Toolstack Again

- The domain creation process is too complex for our specialized VMs
  - Also makes the profiling really difficult and inaccurate
  - A lot of unnecessary Xenstore entries
- Some checks take a lot of time
  - Mainly checking for duplicate names

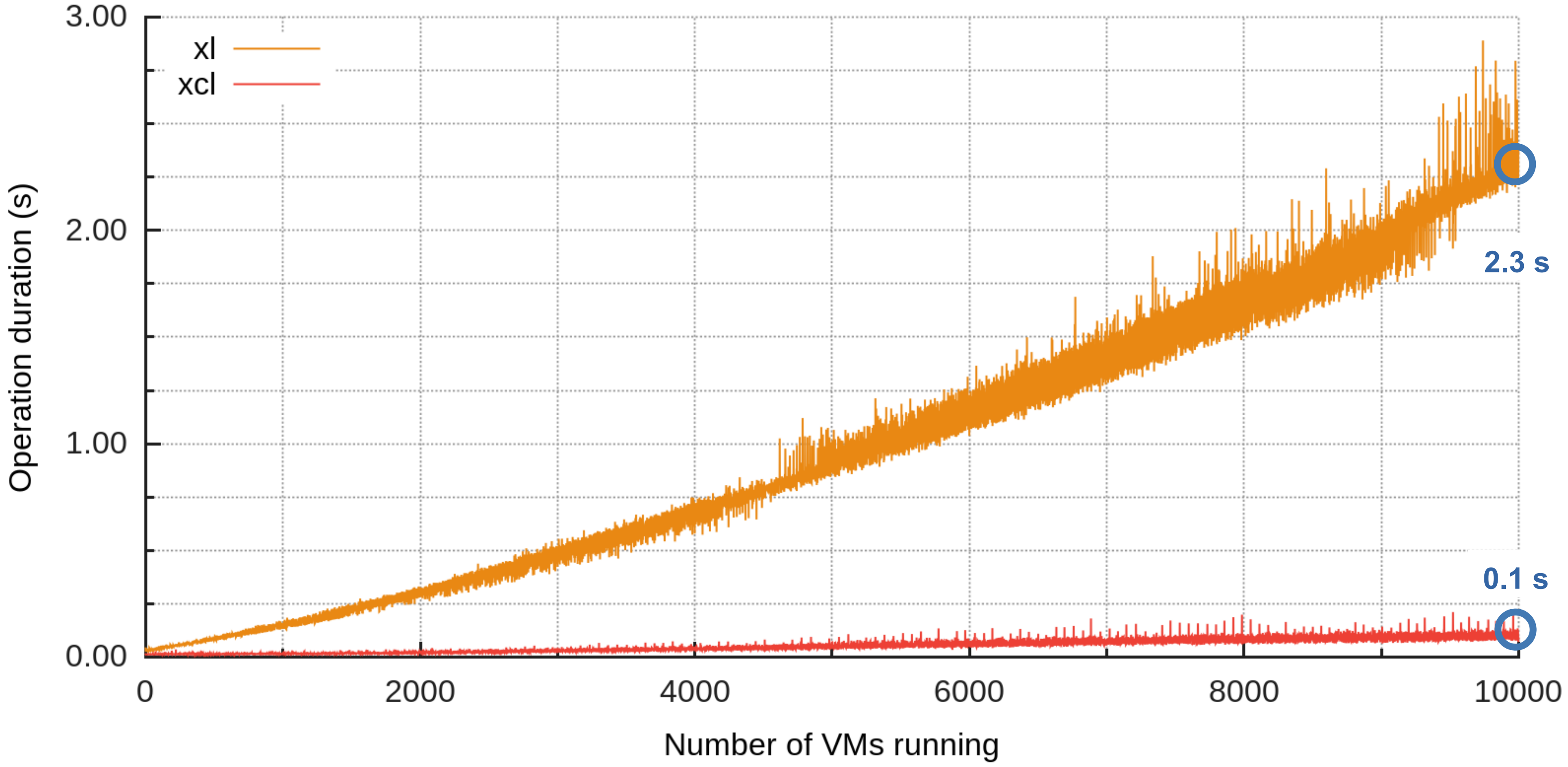
xcl: XenCtrl Light

- A very simplified toolstack
- Small abstraction on top of libxc (~600 LOC)
  - Optimized for our use case
    - Only boots PV and PVH domains
    - Only supports VIFs
  - **Reduced Xenstore usage**
    - From 37 to 17 entries per guest
    - Less Xenstore operations
  - **Doesn't check domain name**

xl vs xcl

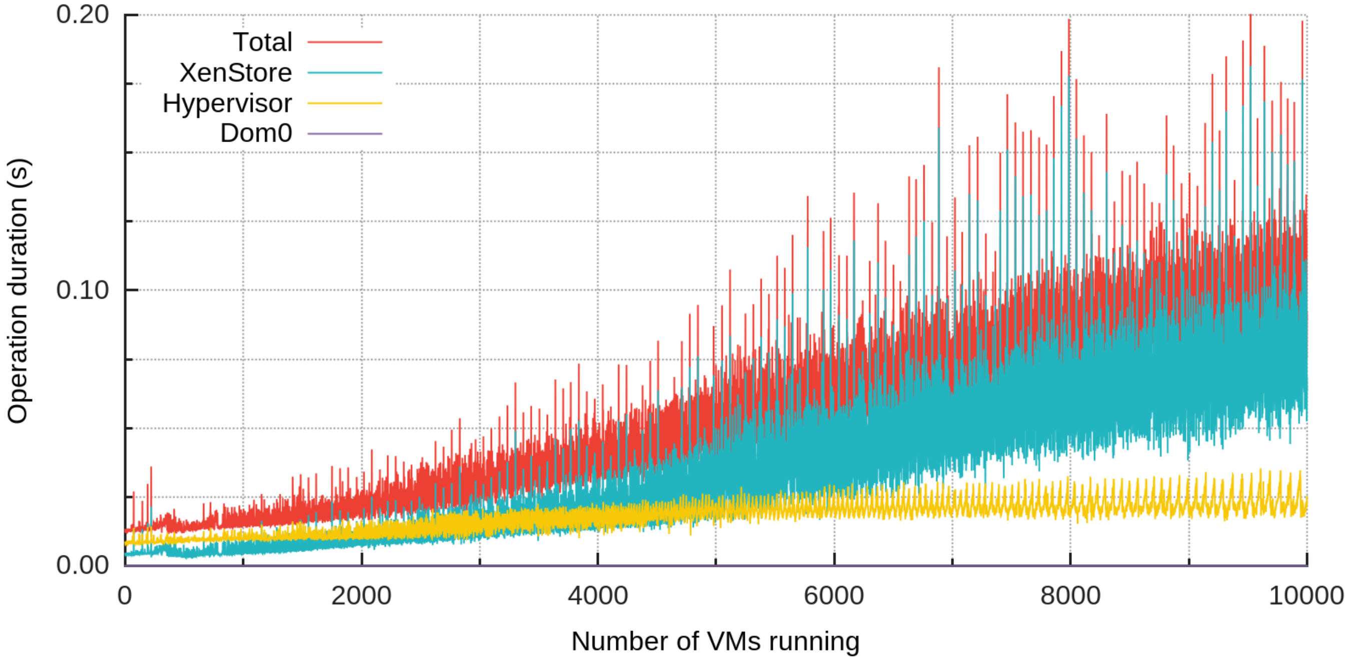

xl
xcl
3.00
2.00
1.00
0.00
Operation duration (s)
0
2000
4000
6000
8000
10000
Number of VMs running

xl vs xcl


3.00
2.00
1.00
0.00
Operation duration (s)
0
2000
4000
6000
8000
10000
Number of VMs running
xl
xcl
2.3 s
0.1 s

With xcl

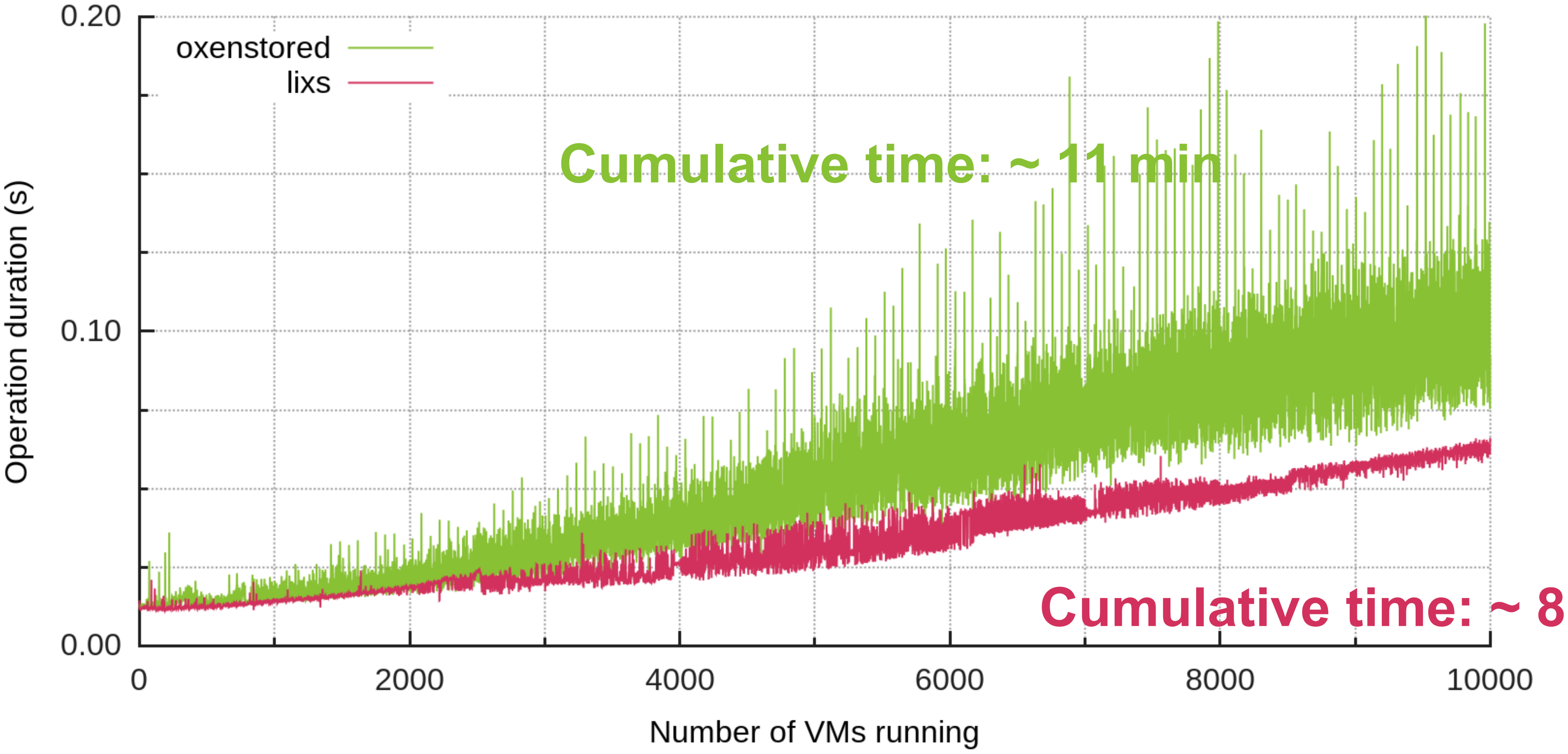
- Much better
- But reducing the number of Xenstore entries is only a palliative
  - Eventually the issue will come back as we increase the number of guests
    - Xenstore remains a major bottleneck



lixs: LIghtweight XenStore

- Work in progress (about 1 month)
- Written from scratch but compatible with the Xenstore protocol
- Currently ~1800 LOC
- C++

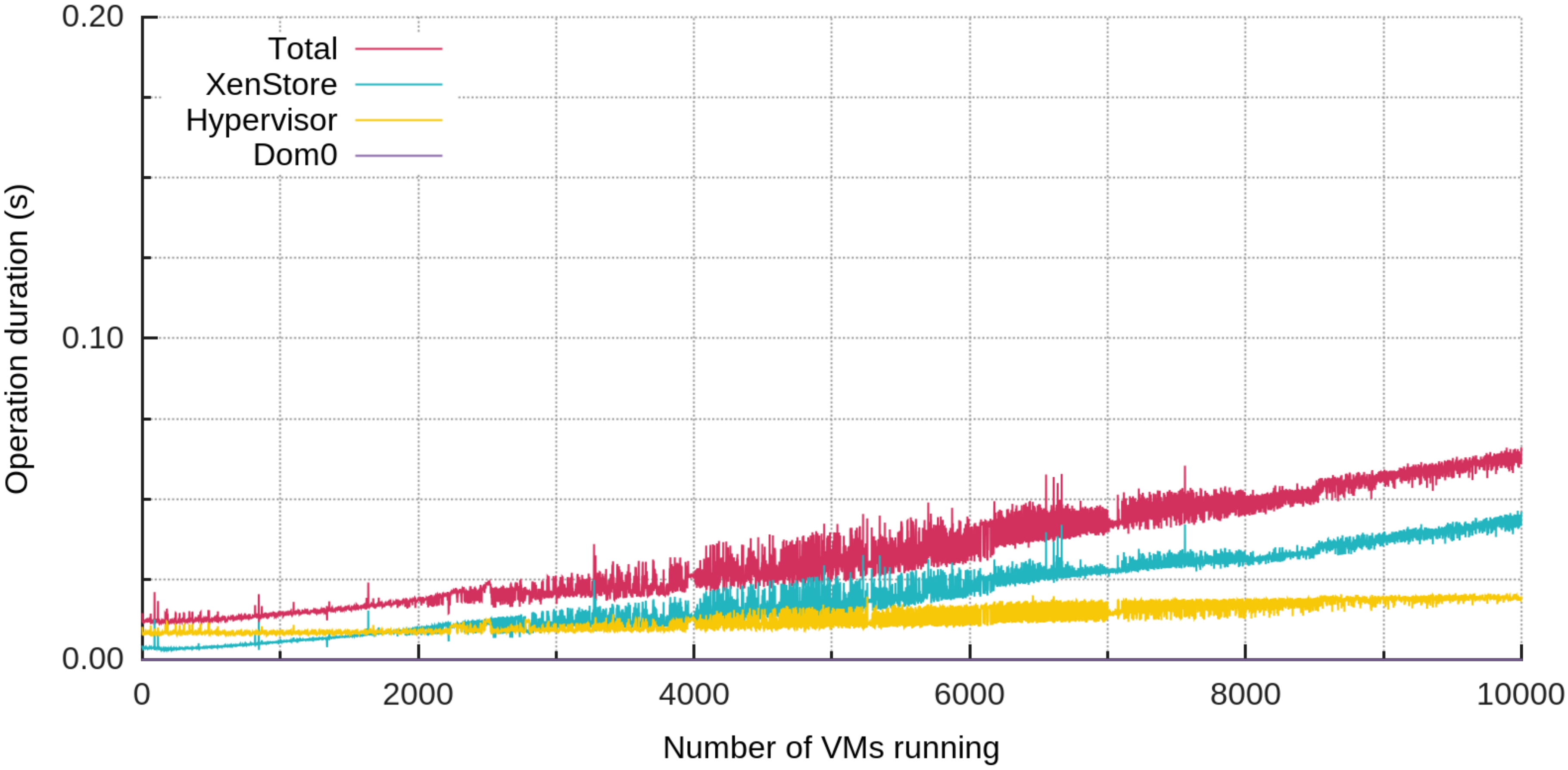
lixs vs oxenstored



Cumulative time: ~ 11 min

Cumulative time: ~ 8

Breakdown with lixs



lixs: Future Work

- Optimize protocol
  - Make Xenstore more specialized
  - Avoid all possible listing operations
- Optimize implementation
  - Remove unix sockets
  - Generic storage backend
    - std::map; noSQL DB; <your backend here>;
    - 10K guests with `std::map` took **10m 3s**
    - 10K guests with `boost::unordered_map` took **7m 54s**

Where are we?

- Usable system running **10K** guests
- 10K guests actually working
  - Although idle most of the time
- Lower domain creation times
  - First domain: **< 10ms**
  - With 10K domains: **< 100ms**

- Recent test: 1,000 VMs running ICMP responder configuration, plus one running content cache (Minicache)
  - **All 1,001 VMs work as expected!**

Will it work? Can we reach 100K?

- There are no fundamental issues with Xen
  - But we only tested it up to 10K guests
- Xenstore protocol needs work
  - Make Xenstore more specialized
  - With 10K+ guests we need to avoid listings

Future work

- Improve lixs and Xenstore protocol
- Multi thousand-port vSwitch
- Have guests doing useful work
- Scheduling
  - Number of guests much bigger than number of cores
  - With that many guests we'll have scheduling issues
- Reducing Memory Usage
  - Smaller image sizes
  - Share memory between guests booting same image

Xenstore Entries: xl vs xcl

XL

```
1 = ""
 vm = "/vm/2baefa82-612c-4e5b-a52d-396a91d5ad7b"
 name = "proxy"
 cpu = ""
  0 = ""
   availability = "online"
 memory = ""
  static-max = "8192"
  target = "8193"
  videoram = "-1"
 device = ""
  suspend = ""
   event-channel = ""
  vif = ""
   0 = ""
    backend = "/local/domain/0/backend/vif/46/0"
    backend-id = "0"
    state = "1"
    handle = "0"
    mac = "00:16:3e:32:ca:23"
   1 = ""
    backend = "/local/domain/0/backend/vif/46/1"
    backend-id = "0"
    state = "1"
    handle = "1"
    mac = "00:16:3e:2e:22:7c"
 control = ""
  shutdown = ""
  platform-feature-multiprocessor-suspend = "1"
  platform-feature-xs_reset_watches = "1"
 data = ""
 domid = "46"
 store = ""
  port = "1"
  ring-ref = "3188551"
 console = ""
  backend = "/local/domain/0/backend/console/46/0"
  backend-id = "0"
  limit = "1048576"
  type = "xenconsoled"
  output = "pty"
  tty = "/dev/pts/1"
  port = "2"
  ring-ref = "3188550"
```

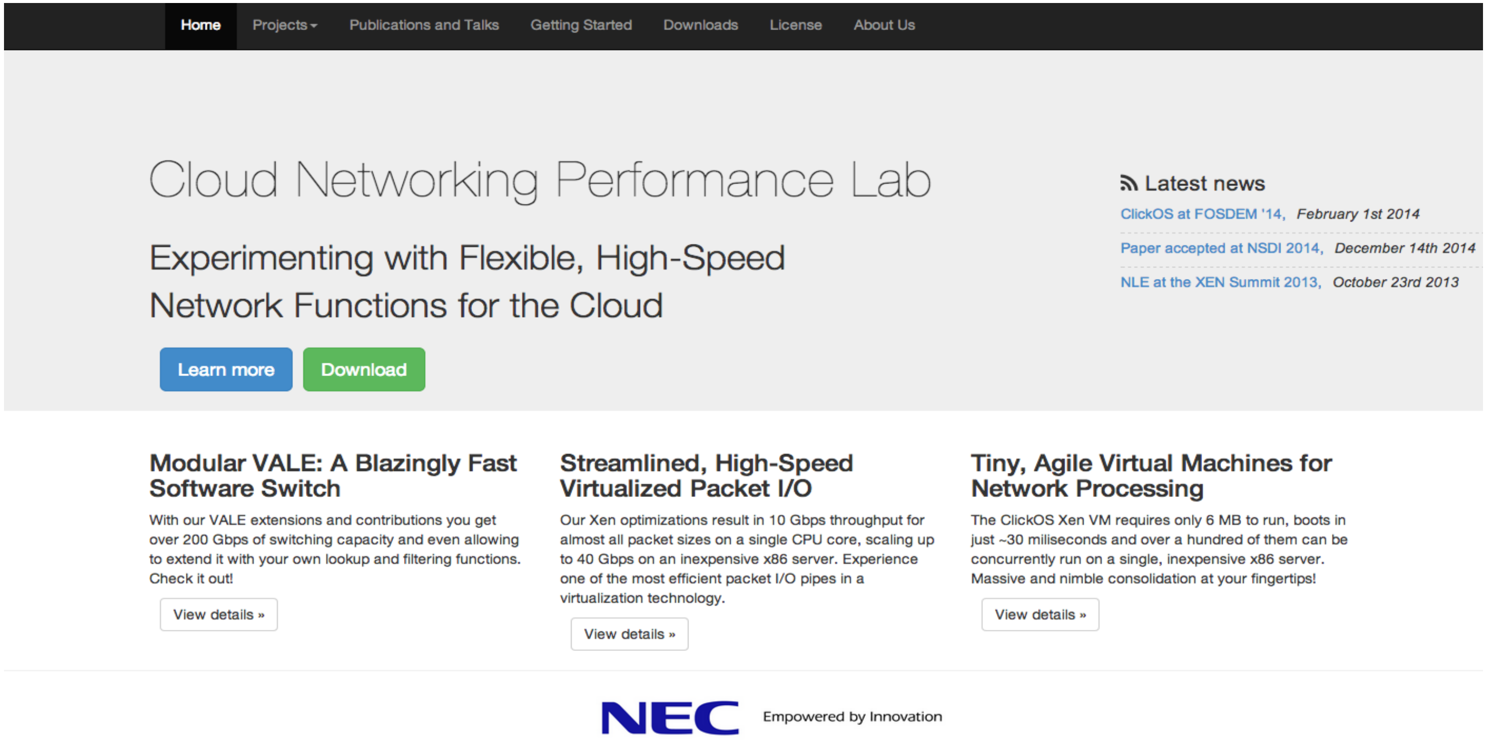
XCL

```
1 = ""
 control = ""
  shutdown = ""
 vm = "/vm/4c3f2a04-e39f-4ad8-9d7f-1b5556f02b34"
 name = "proxy"
 domid = "48"
 console = ""
  port = "2"
  ring-ref = "3157830"
  type = "xenconsoled"
  tty = "/dev/pts/1"
 device = ""
  vif = ""
   0 = ""
    backend = "/local/domain/0/backend/vif/48/0"
    backend-id = "0"
    state = "1"
    handle = "0"
    mac = "00:00:00:00:00:00"
   1 = ""
    backend = "/local/domain/0/backend/vif/48/1"
    backend-id = "0"
    state = "1"
    handle = "1"
    mac = "00:00:00:00:00:00"
```

Number of grants

- 2 grants per domain
  - xenstore; xenconsole;
  - With v1: 512 grants per frame
  - `DEFAULT_MAX_NR_GRANT_FRAMES == 32`
    - Maximum of (512 * 32) / 2 == 8K
- Fix
  - Boot xen with `max_nr_grant_frames=512`
    - Up to 128K domains

It's Open Source!



Cloud Networking Performance Lab

Experimenting with Flexible, High-Speed Network Functions for the Cloud

Latest news

ClickOS at FOSDEM '14, *February 1st 2014*

Paper accepted at NSDI 2014, *December 14th 2014*

NLE at the XEN Summit 2013, *October 23rd 2013*

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