Toward MP-safe Networking in NetBSD

Ryota Ozaki <ozaki-r@iij.ad.jp>
Kengo Nakahara <k-nakahra@iij.ad.jp>

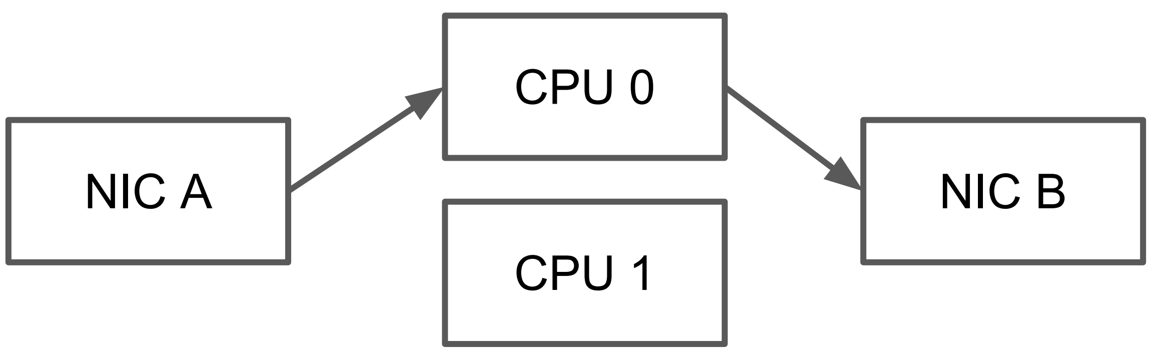
EuroBSDcon 2016
2016-09-25

Contents

- Background and goals
- Approach
- Current status
- MP-safe Layer 3 forwarding
- Performance evaluations
- Future work

Background

- The Multi-core Era
- The network stack of NetBSD couldn't utilize multi-cores
  - As of 2 years ago



Our Background and Our Goals

- Internet Initiative Japan Inc. (IIJ)
  - Using NetBSD in our products since 1999
  - Products: Internet access routers, etc.
- Our goal
  - Better performance of our products, especially

    Layer 2/3 forwarding, tunneling, IPsec VPN, etc.

    → MP-safe networking

Our Targets

- Targets
  - 10+ cores systems
  - 1 Gbps Intel NICs and virtualized NICs
    - wm(4), vmx(4), vioif(4)
  - Layer 2 and 3
    - IPv4/IPv6, bridge(4), gif(4), vlan(4), ipsec(4), pppoe(4), bpf(4)
- Out of targets
  - 100 cores systems and above
  - Layer 4 and above
    - and any other network components except for the above

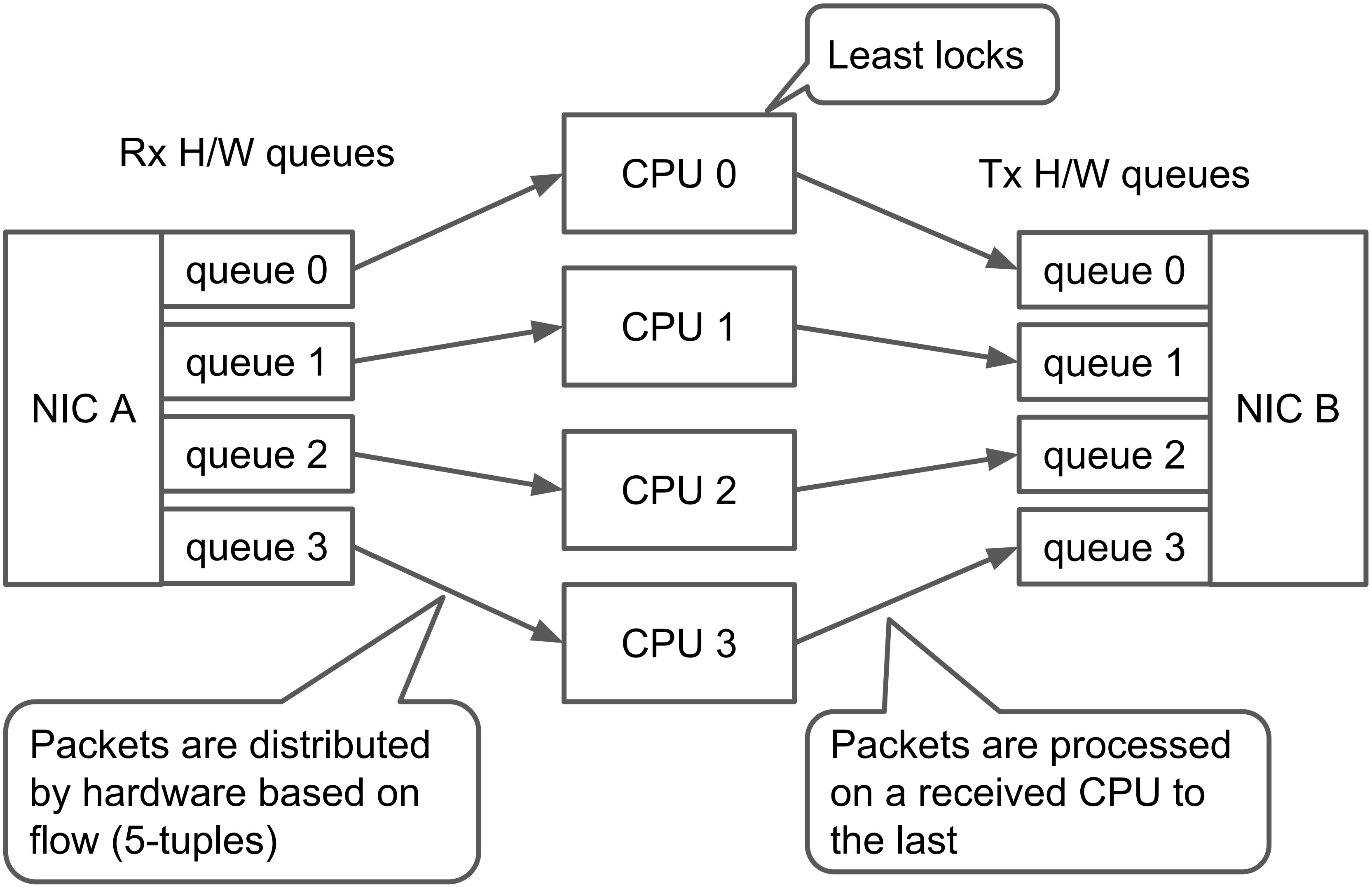
Approach

- MP-safe and then MP-scalable
- Architecture
  - Utilize hardware assists
  - Utilize lightweight synchronization mechanisms
- Development
  - Restructure the code first
  - Benchmark often

Approach : Architecture

- Utilize hardware assists
  - Distribute packets to CPUs by hardware
    - NIC multi-queue and RSS
- Utilize software techniques
  - Lightweight synchronization mechanisms
    - Especially pserialize(9) and psref(9)
  - Existing facilities
    - Fast forwarding and ipflow

Forwarding Utilizing Hardware Assists



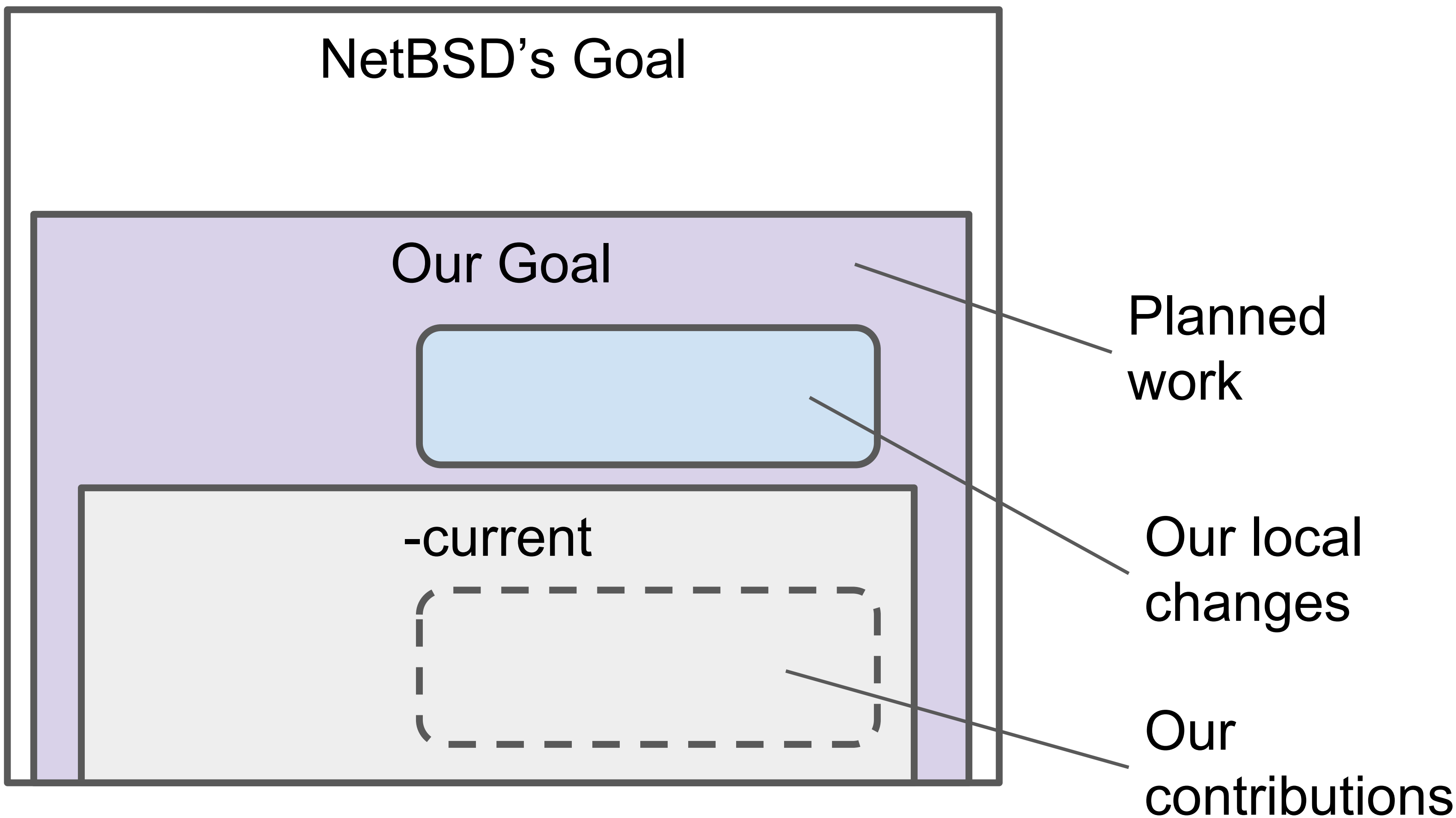
Approach : Development

- Restructure the code first
  - Hard to simply apply locks to the existing code
    - E.g., hardware interrupt context for Layer 2, cloning/cloned routes, etc.
  - Need tests to detect regressions
- ATF tests
  - Automated and isolated tests of the network stack
    - Thanks to rump kernels
  - 320 test cases in total related to networking
    - 130 test cases have been added since NetBSD 7
    - New categories: IP forwarding, ARP/NDP, IPv6, routes (flags and messages), bridge, gif, tun, tap, pppoe, ifconfig (commands/options)
  - Only 2 minutes to run all the test cases

Approach : Development (cont’d)

- Benchmark often
  - Measure speedup
  - Measure (single-thread) overheads
- Performance evaluation environments
  - Easy to retry tests by anyone else
  - Easy to replicate the environment
    - Ansible
- ipgen (https://github.com/iij/ipgen)
  - netmap-based packet generator running on FreeBSD
  - Support RFC 2544 tests

Current Status



Our Contributions in -current : Device Drivers

- MSI/MSI-X support
  - i386 and amd64
- Interrupt distribution / affinity
  - intrctl(8) changes interrupt destination CPUs
- MP-safe network device drivers
  - wm(4), vioif(4) and vmx(4)
- Hardware multi-queue support of wm(4)

Our Contributions in -current : Network Components

- MP-safe bridge(4) and gif(4)
- Partial MP-safe Layer 3
  - Interfaces, IP address, etc.
- Important restructuring
  - Separate ARP/NDP caches from the routing table
    - Based on lltable/llentry of FreeBSD
  - Softint-based packet Rx processing
    - Except for net80211 and bpf(4)
- Lots of ATF tests for the network stack

Check our presentation at AsiaBSDCon 2015 (http://www.netbsd.org/gallery/presentations/)
for details

Our Local Changes

- Experimental MP-safe Layer 3 forwarding
- Packet Rx processing optimization

CAVEAT: the changes don’t get consensus in the community yet and are not guaranteed to be merged

Planned Work

- Complete MP-ification of Layer 3
  - Remaining non MP-safe stuffs: statistic counters, nd_defrouter, nd_prefix, etc.
- MP-ifications
  - vlan(4)
  - ipsec(4) including opencrypto
  - pppoe(4)

MP-safe Layer 3 Forwarding

- Tools
  - Hardware assists
  - Software techniques
- Changes for MP-safe Layer 3 Forwarding

Tools

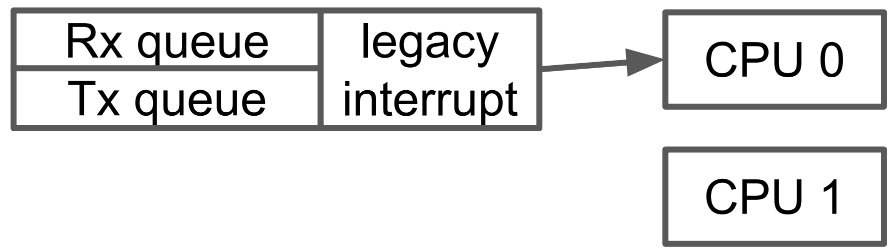
- Hardware assists
  - NIC hardware multi-queues
  - MSI/MSI-X
  - Interrupt distribution / affinity
- Software techniques
  - Lightweight synchronization
  - Fast forwarding and ipflow

Hardware assists

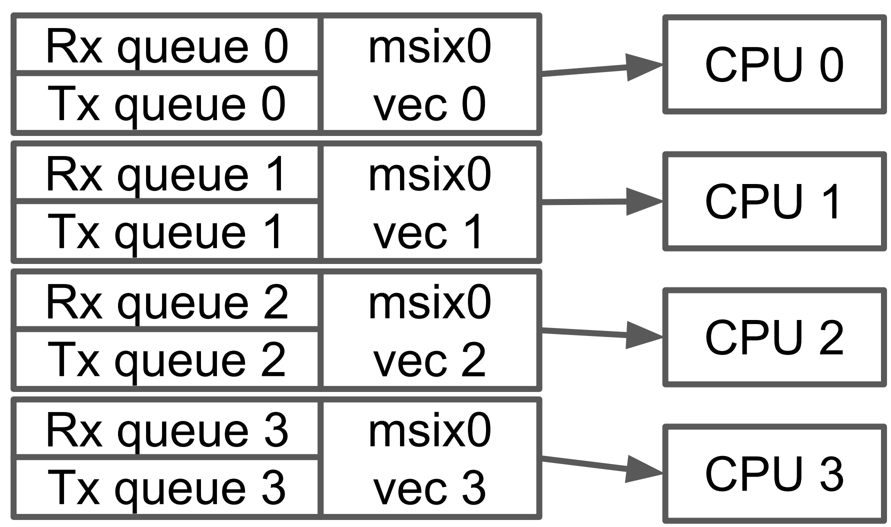
- Recent Ethernet controllers have multiple hardware queues for packet Tx/Rx
- MSI-X allows to have an interrupt on each queue
- We can set an interrupt affinity to a CPU
  - Set by device drivers or intrctl(8)
- We can distribute packets between CPU by RSS (receive-side scaling)
  - Classified by 5-tuples

Interrupt Distributions

Old



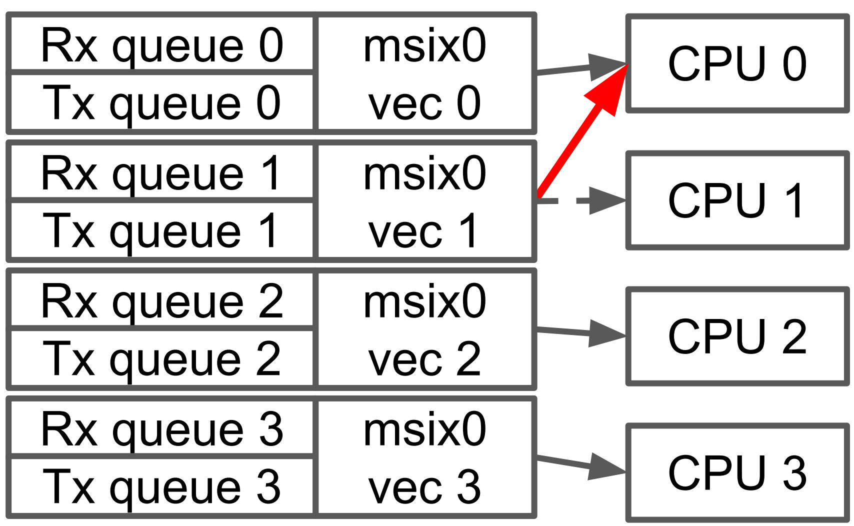
Packet distribution by hardware assists



intrctl(8)

- Enable to change the interrupt affinity
- Support only x86 for now

Example: Direct interrupts of queue 1 to CPU 0




```
intrctl affinity -i 'msix0 vec 1' -c 0
```

intrctl(8) : Screenshots

```
# intrctl list
interrupt id                CPU0              CPU1
ioapic0 pin 9                 0*                 0
msix0 vec 0                1696*                 0
msix0 vec 1                   0               621*
msix0 vec 2                   0                  0
msix0 vec 3                   0                  0
msix0 vec 4                   2*                 0
```

```
# intrctl affinity -i 'msix0 vec 1' -c 0
# intrctl list
interrupt id                CPU0              CPU1
ioapic0 pin 9                 0*                 0
msix0 vec 0                2732*                 0
msix0 vec 1                 177*               621
msix0 vec 2                   0                  0
msix0 vec 3                   0                  0
msix0 vec 4                   2*                 0
```

Synchronization Techniques

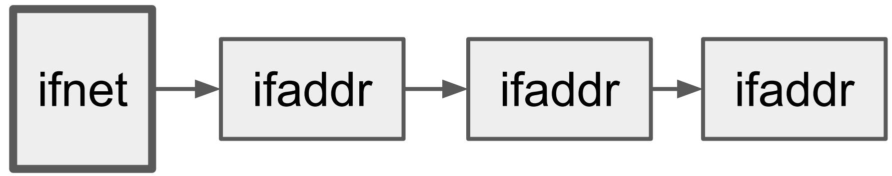
- pserialize(9) and psref(9)
- An example of pserialize(9)
- An example of psref(9)

pserialize(9) and psref(9)

- Lightweight synchronization primitives
  - Sort of *deferred processing* in the literature
    - Cf. RCU of Linux and hazard pointers
  - Lightweight read and heavyweight write
- Reader critical sections
  - pserialize can be used for those that don't sleep
  - psref can be used for those that may sleep
- Writer side
  - Both provide a mechanism that waits until readers release referencing objects

An Example of pserialize(9) : reader

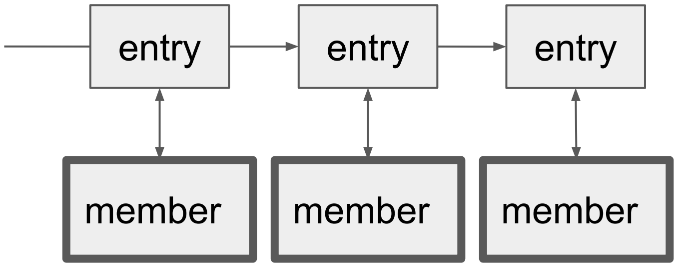
Iterate addresses of an interface with pserialize




```
s = pserialize_read_enter();
IFADDR_READER_FOREACH(ifa, ifp) {

    /* Do something on ifa, which doesn't sleep */

}
pserialize_read_exit(s);
```

An Example of psref(9) : reader

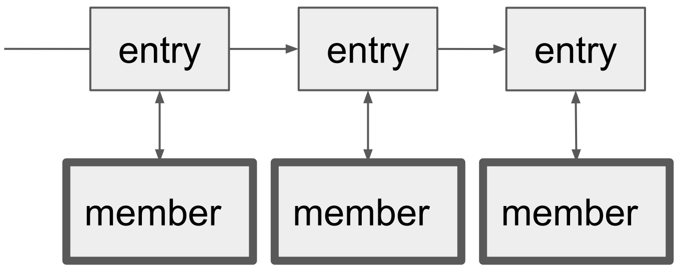
Acquiring a reference of a bridge member entry by psref(9) on an interaction of the bridge member list




```
s = pserialize_read_enter();
BRIDGE_IFLIST_READER_FOREACH(bif, sc) {
    struct psref psref;

    psref_acquire(&psref, &bif->bif_psref, bridge_psref_class);
    pserialize_read_exit(s);

    /* Do something may sleep */

    s = pserialize_read_enter();
    psref_release(&psref, &bif->bif_psref, bridge_psref_class);
}
pserialize_read_exit(s);
```

An Example of pserialize(9) and psref(9) : writer

Remove a member from the list with holding a lock and wait for readers left



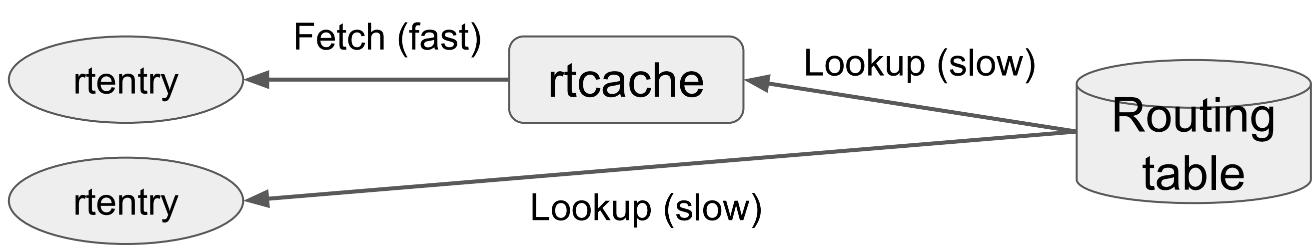

```
BRIDGE_LOCK(sc);

BRIDGE_IFLIST_WRITER_FOREACH(bif, sc) {
    if (strcmp(bif->bif_ifp->if_xname, name) == 0)
        break;
}
PSLIST_WRITER_REMOVE(bif, bif_next);

pserialize_perform(sc->sc_iflist_psref.bip_psz);

BRIDGE_UNLOCK(sc);

psref_target_destroy(&bif->bif_psref, bridge_psref_class);

/* Free bif safely */
```

Fast Forwarding and ipflow

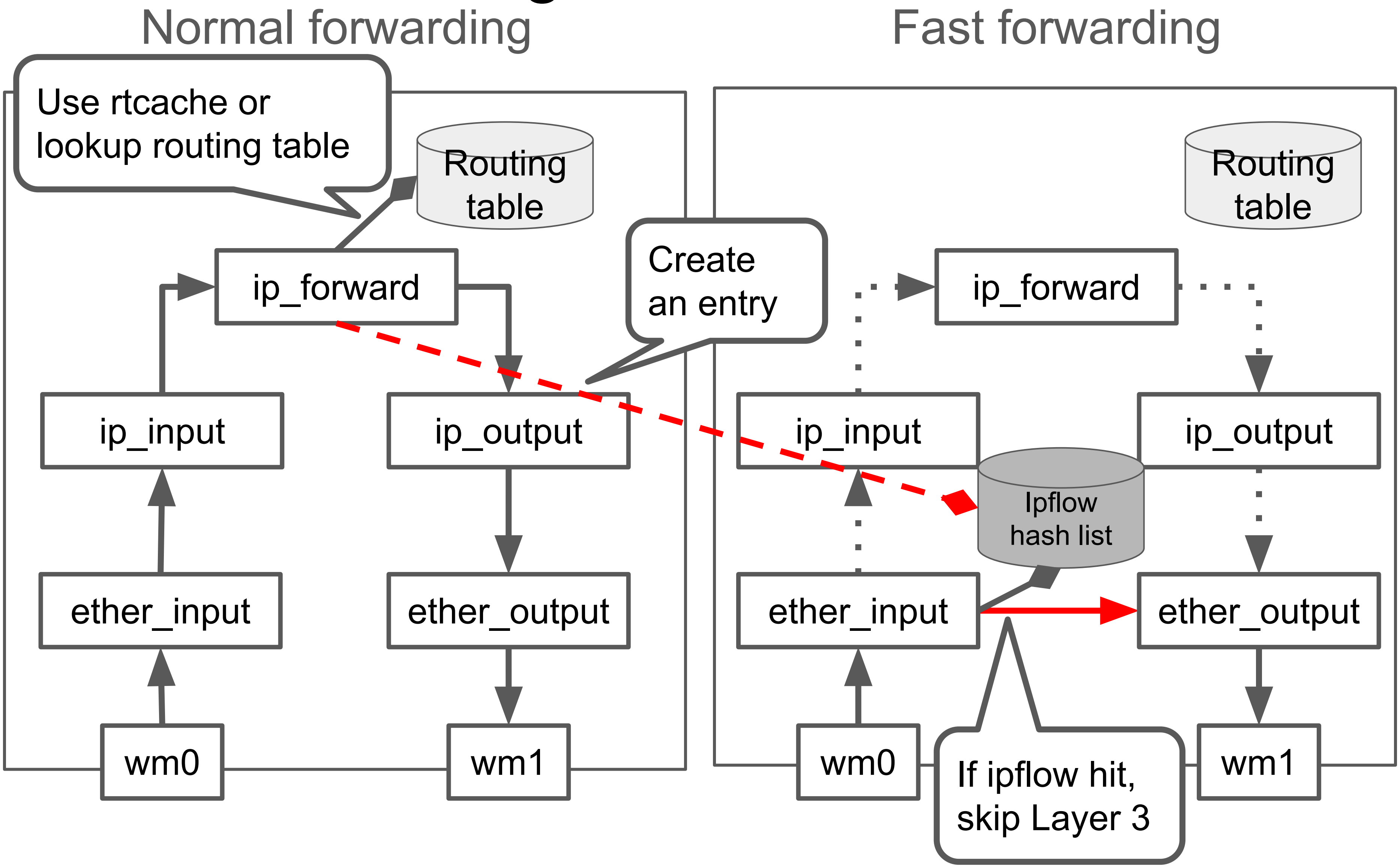
- Data structures for the routing table
- Fast forwarding
- ipflow

Data Structures for the routing table

- The routing table (backend)
  - Radix tree
- rtentry
  - Representation of a route
- rtcache
  - Caches to reduce looking up a route from the radix tree
  - Per-CPU rtcache for Layer 3 forwarding

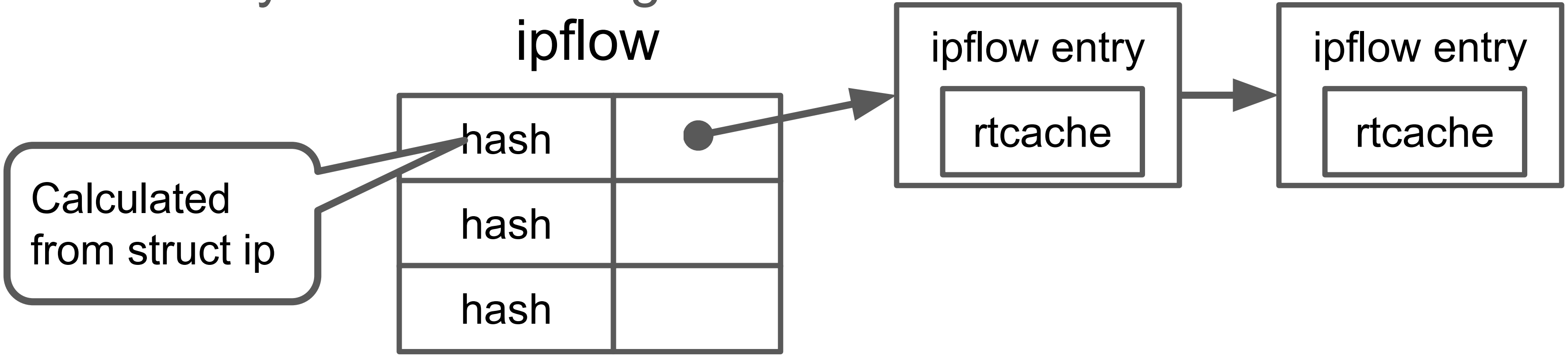


Fast Forwarding



ipflow

- Route caches used by fast forwarding
- ipflow is a hash list
  - Key: struct ip (source and destination addresses)
  - Value: rtcache
- Per-flow rtcaches
  - More scalable compared to per-CPU rtcaches for Layer 3 forwarding



Changes for MP-safe Layer 3 Forwarding

- Packet Rx/Tx processing and queuing
- MP-safe interfaces and addresses
- MP-safe routing table
- Scaling up Layer 3 forwarding
- Optimizing packet Rx processing

Our local changes

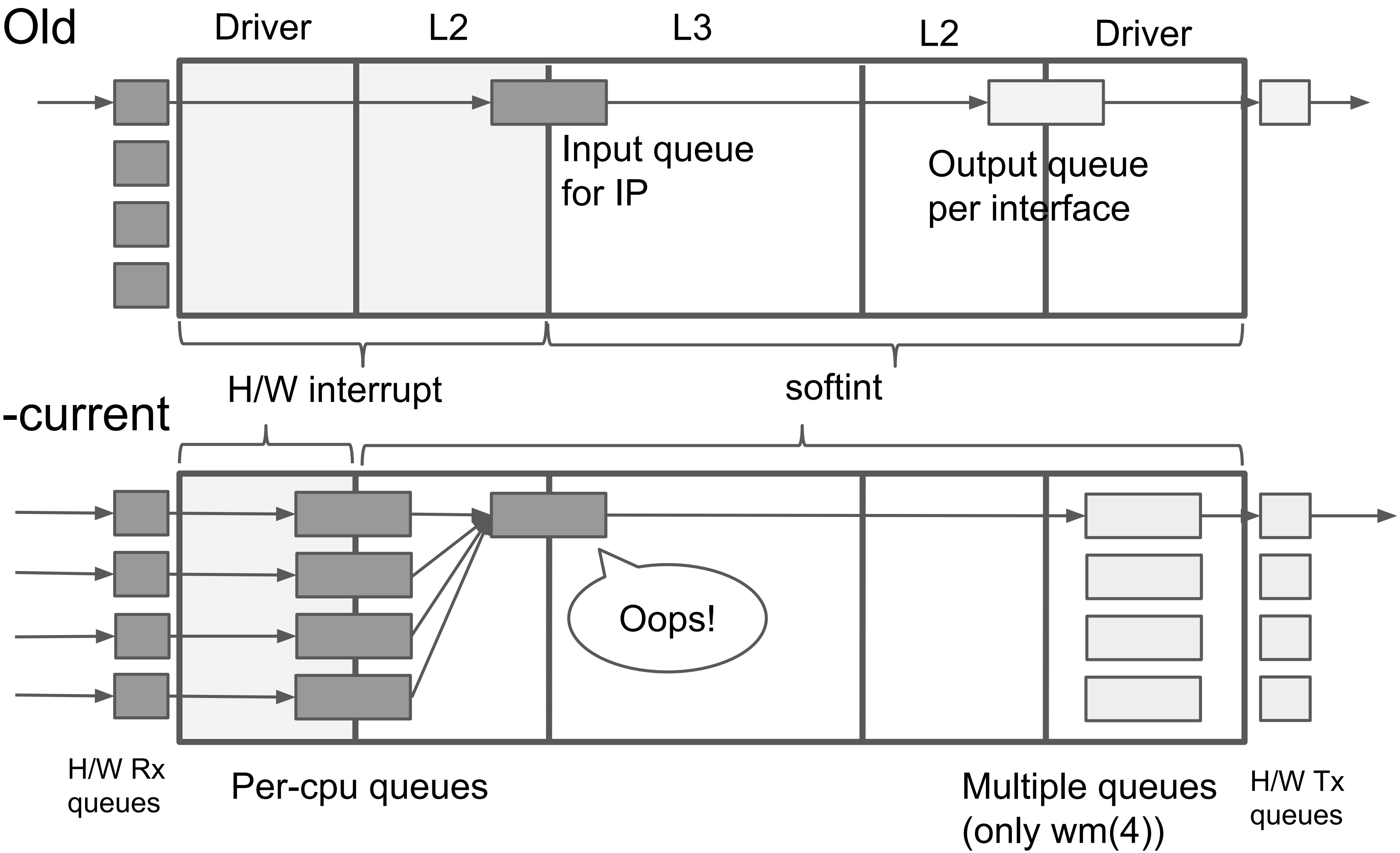
Packet Rx/Tx Processing and Queuing

- Rx processing mess
  - Layer 2 processing including bridge(4), vlan(4), fast forwarding, bpf(4) run in hardware interrupt context
  - Hardware interrupt context is an enemy of MP-ification
    - No sleep is allowed
    - Only spin mutex can be used
- Softint-based Rx processing
  - Run Layer 2 (and above) in softint (per-CPU)
    - Except for bpf(4)...
  - Interrupt handlers of device drivers just put packets to a per-CPU queue and schedule softint

Packet Rx/Tx Processing and Queuing

- Tx processing
  - From Layer 2 to an interface (device driver)
  - If the driver supports hardware multi-queue, the upper layer just passes packets directly
    - If not, it enqueues packets into the traditional if_snd queue of the interface
- Tx processing in wm(4)
  - wm(4) has multiple queues corresponding to hardware queues to temporarily store packets passed from the upper layer

Softint and Queuing on L3 Forwarding



MP-safe Interfaces and addresses

- Applied pserialize(9) and psref(9)
- Interfaces (struct ifnet)
  - Iterating interfaces with pserialize or psref
  - Calling ioctl to an interface with holding psref of it
  - rcvif (*ifp) of mbuf is changed to an interface index to avoid dangling pointers
- Addresses (struct ifaddr)
  - Three data stores for IPv4
    - Global list, global hash list and list per interface
  - Get an address from either with pserialize or psref

MP-safe Routing Table

Local changes

- An experimental design of MP-safe routing table
  - Use rwlock
    - psz and psref are difficult to apply to the routing table because it’s not a lockless data structure
  - Limited scalability
- rwlocks
  - A global rwlock for each the backend and rtcaches
  - A rwlock for each rtentry

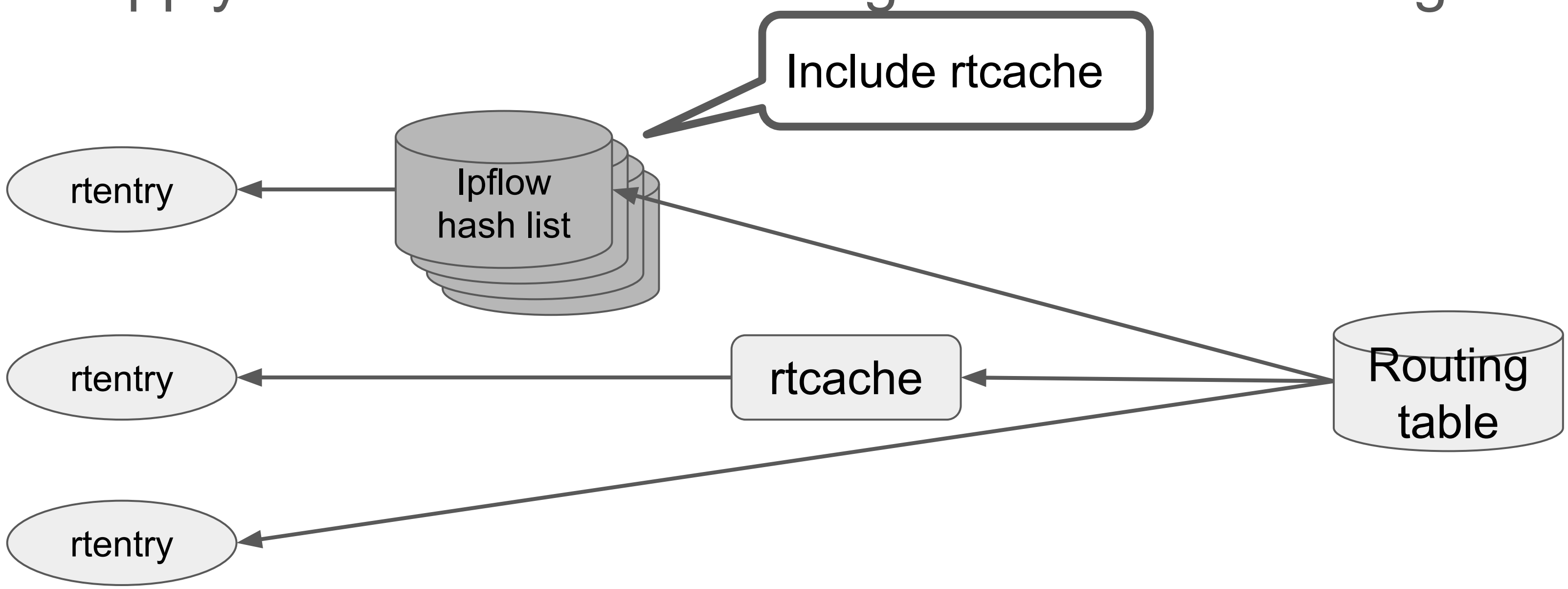
MP-safe Routing Table (cont’d)

- If rtcaches hit:
  - No need to hold any writer locks
  - Resulting in good scalability
- If not:
  - Performance of Layer 3 forwarding decreases heavily
  - It can easily happen because NetBSD has just one rtcache per CPU in -current
    - Multiple flows on one CPU cause contentions on the rtcache

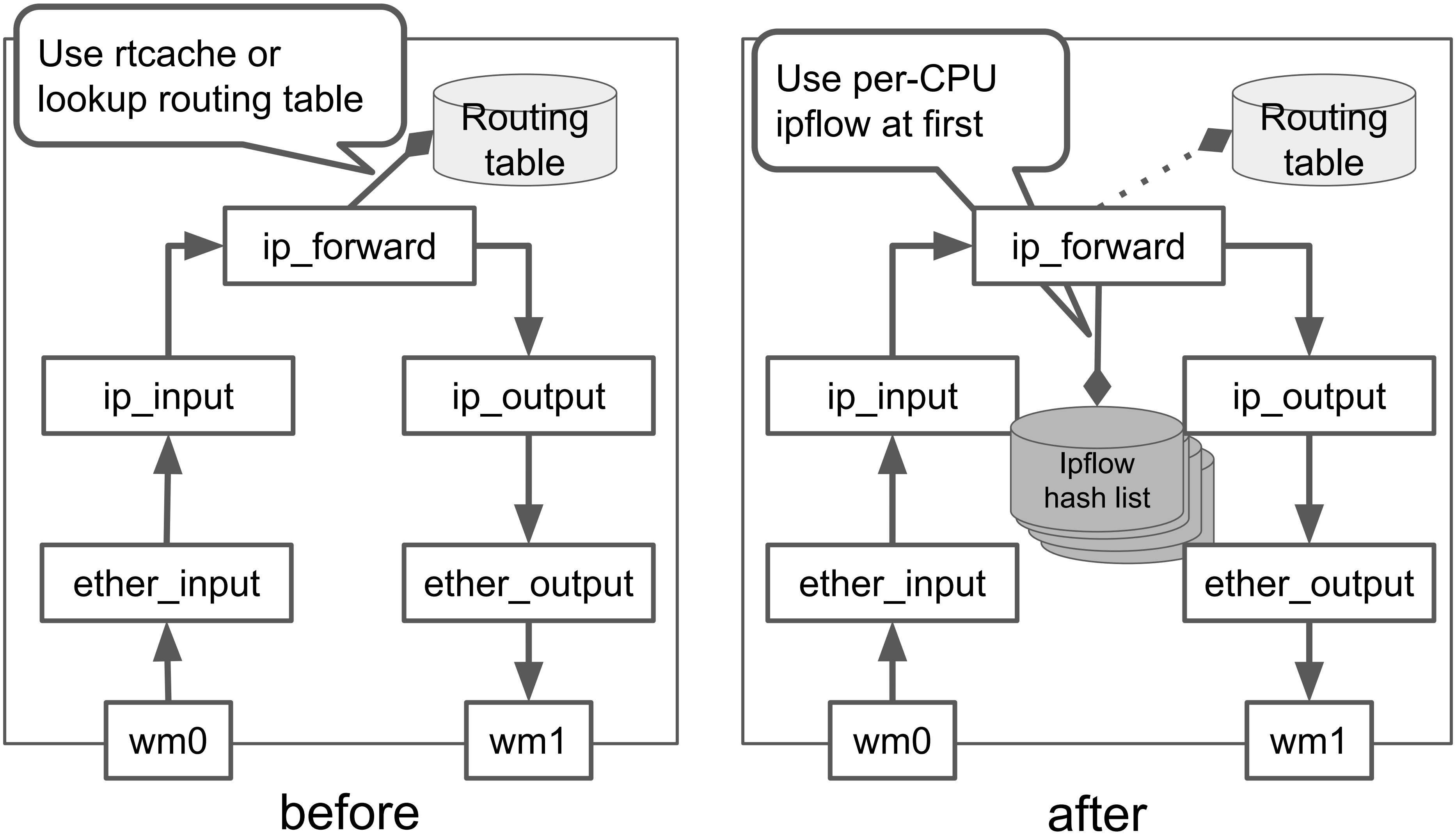
Scaling up Layer 3 Forwarding

Local changes

- Reuse ipflow
  - Apply ipflow to Layer 3 (normal) forwarding as well as fast forwarding
- Make ipflow per-CPU
  - Apply both normal forwarding and fast forwarding



Scaling up Layer 3 Forwarding (cont’d)

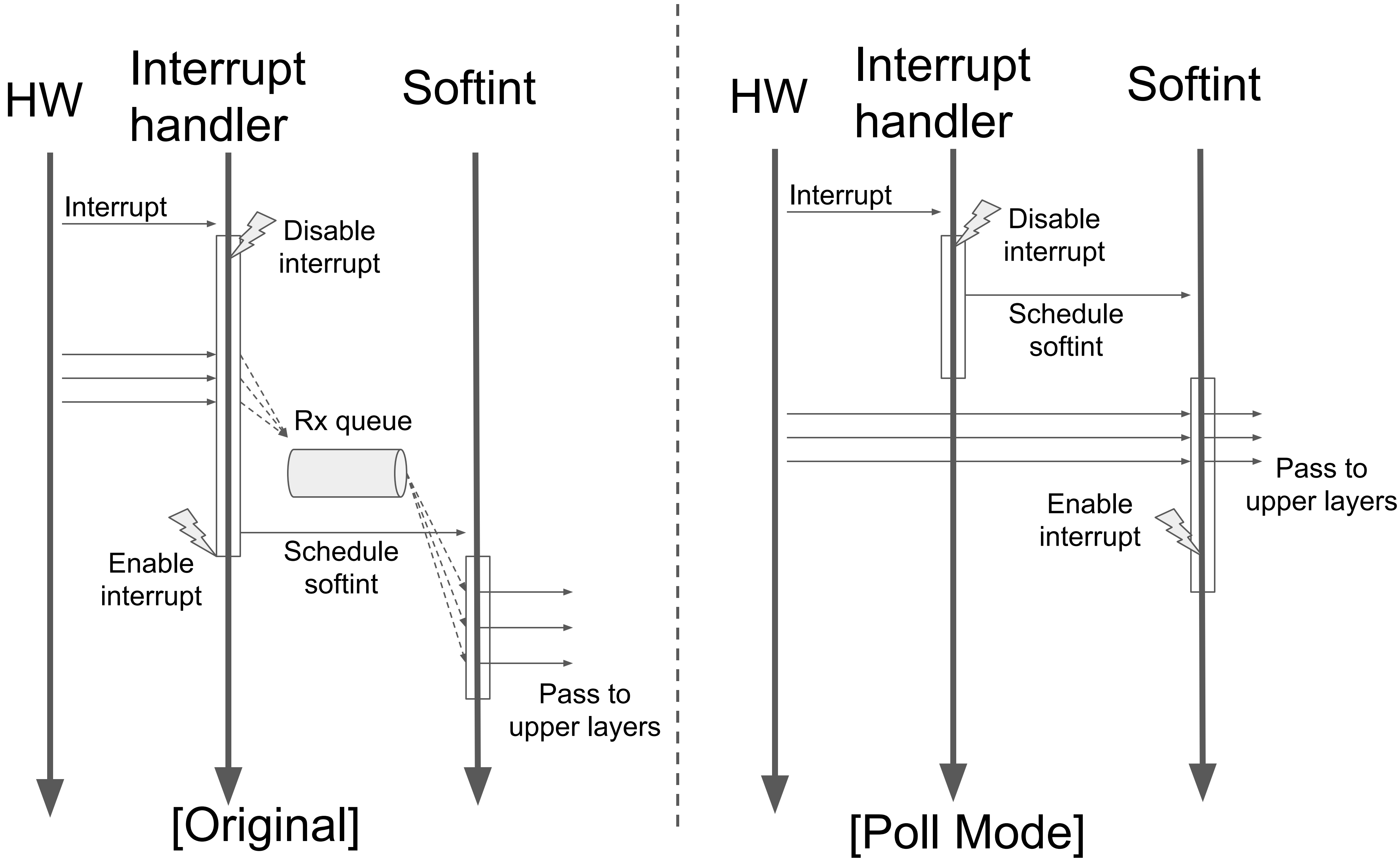


Local changes

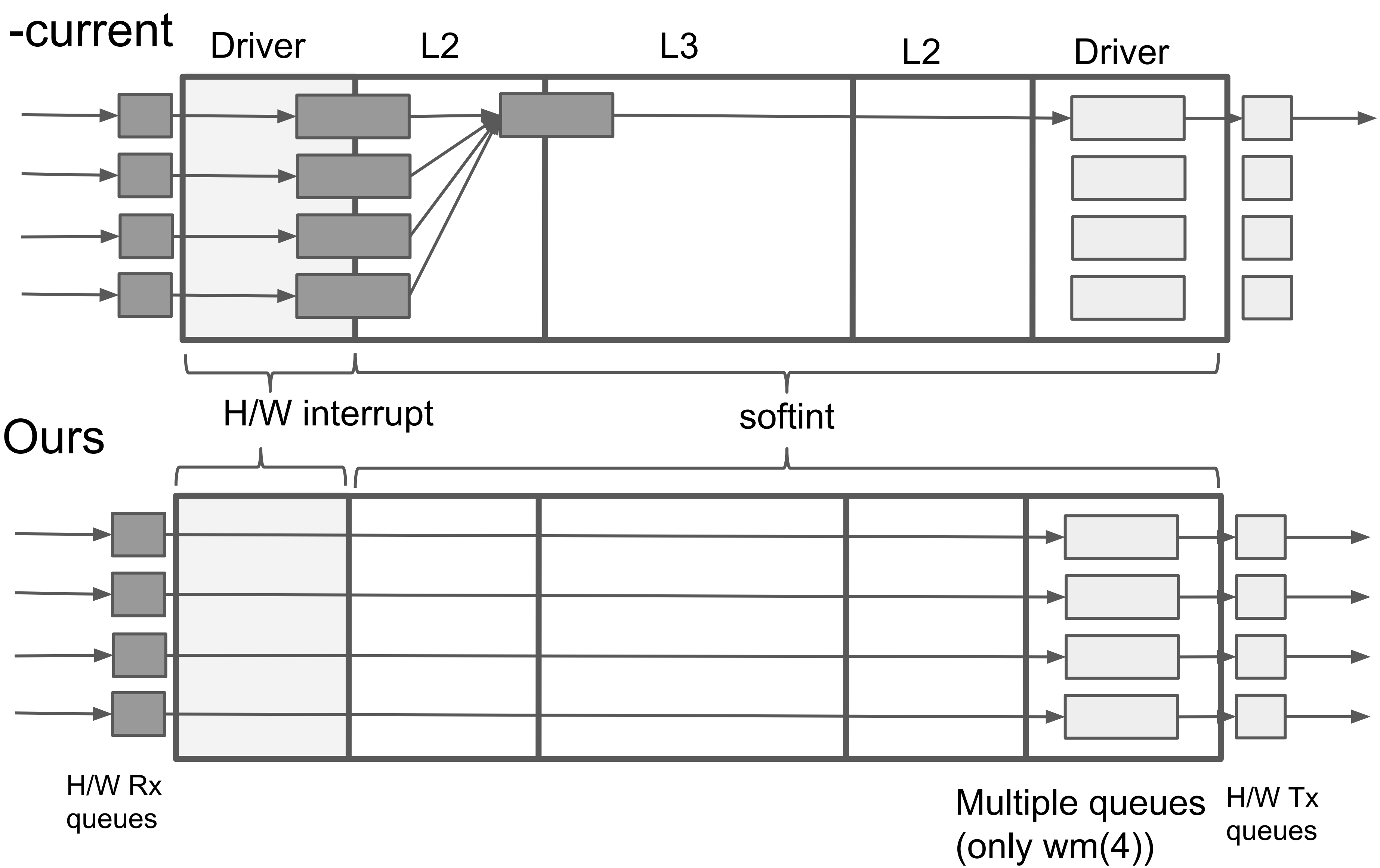
Poll Mode

- An optimization technique of Rx processing
  - Inspired by NAPI of Linux and the like
  - Also one of DoS/livelock mitigation
- Overview
  - Disable interrupts during Rx processing
  - No queuing
- Support only for wm(4) for now

Poll Mode (cont'd)



Softint and Queuing with Poll Mode



Performance Evaluations : Settings

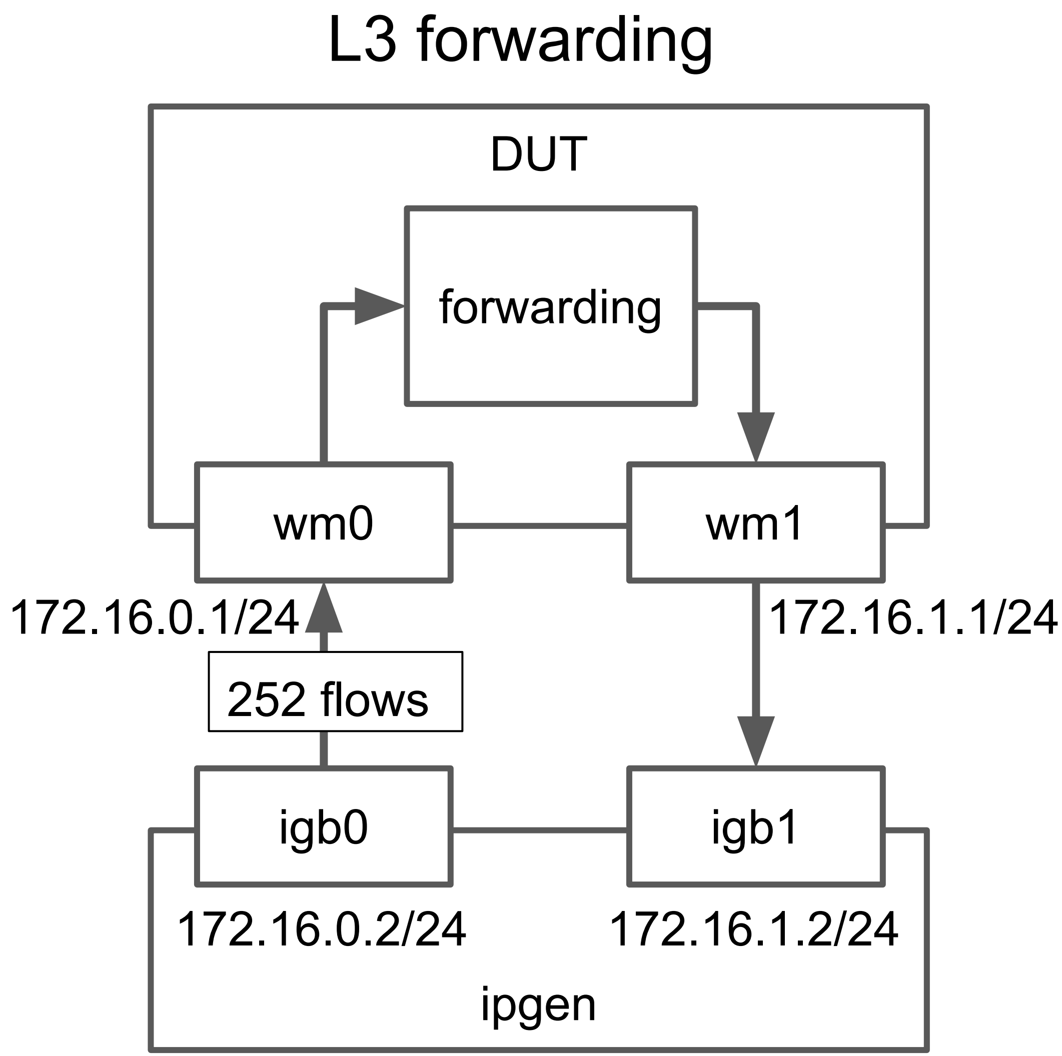
- Hardware
  - DUT (device under test): Supermicro A1SRi-2758F
    - 8 core Atom C2758 SoC (2.4 GHz)
    - 4 port I354 Ethernet adapter (each port has 8 TX/RX queues)
  - Packet generator box: BPV4 (our product)
    - 4 core Atom C2558 SoC (2.4 GHz)
    - 4 port I354 Ethernet adapter (each port has 8 TX/RX queues)
- DUT kernel
  - Based on NetBSD-current at 2016-08-24
    with our local changes

    CAVEAT: the changes are incomplete and resulting performance would degrade by further developments

Performance Evaluations : Settings

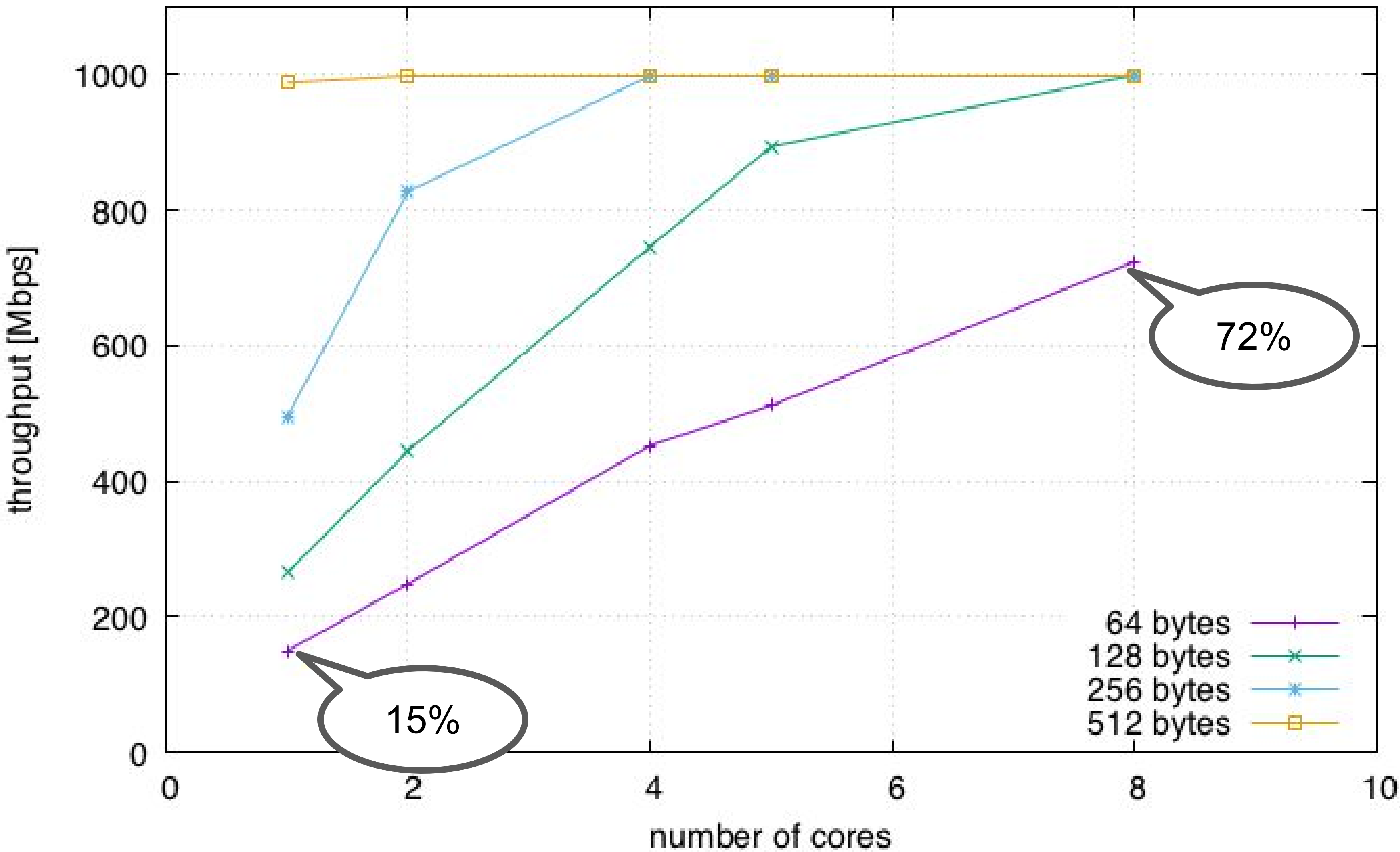
- Targets
  - Layer 3 forwarding
  - 1, 2, 4, 5 and 8 cores
- Tests
  - RFC 2544 throughput by ipgen
  - UDP/IPv4 packets
  - Unidirectional
- Note that packet distributions
  - We adjust IP addresses to distribute packets almost equally between CPUs

Setups for L3 forwarding Evaluation

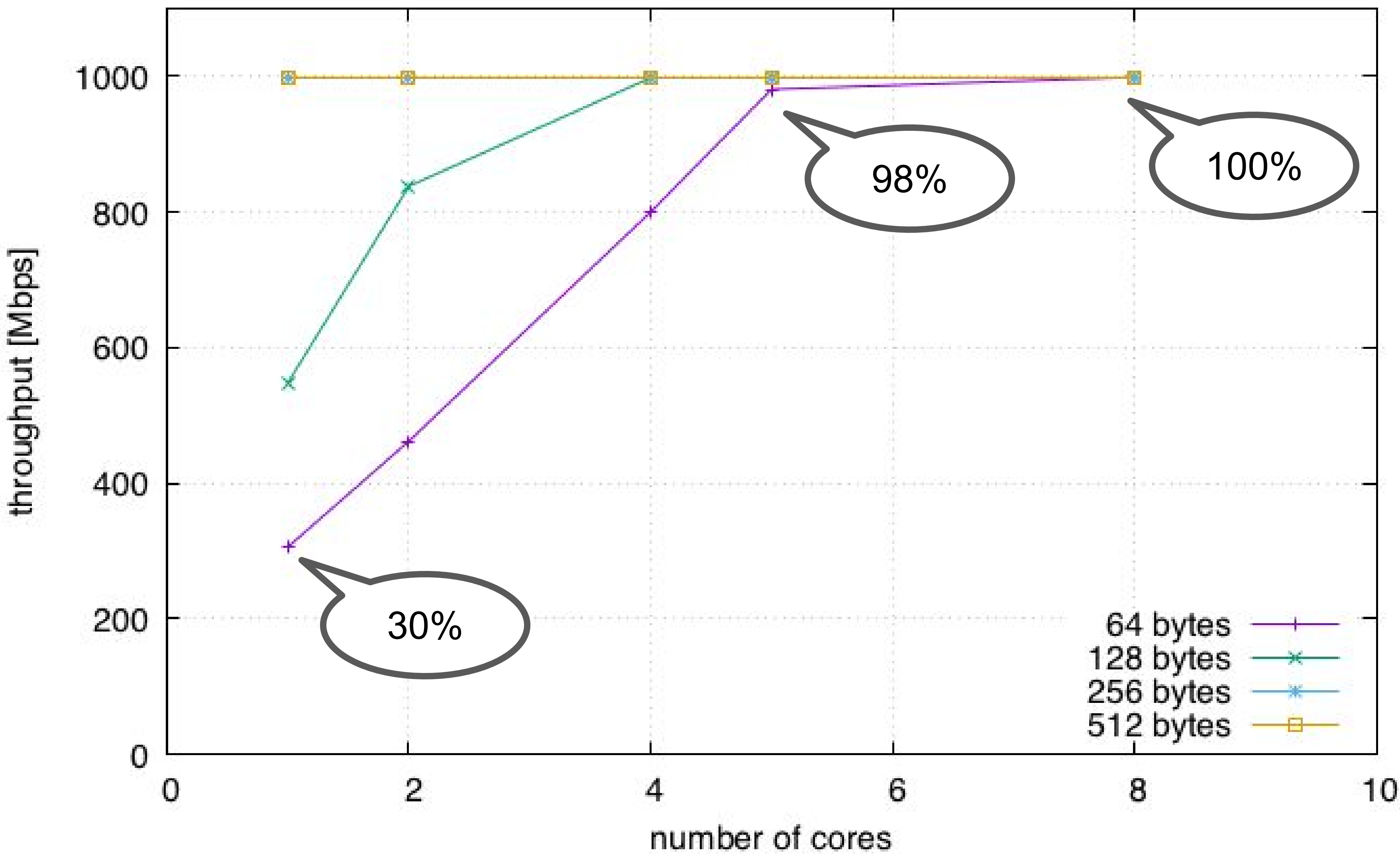


Throughput vs. # of cores : Normal forwarding

Without per-CPU ipflow, throughputs are around 50-60 Mbps



Throughput vs. # of cores : Fast forwarding



Summary of Experimental Results

- Frames per second per # of cores
  - At 64 bytes

	1 core	2 cores	4 cores	5 cores	8 cores
Wire rate	1,488,095	1,488,095	1,488,095	1,488,095	1,488,095
Fast forwarding	455,727 30%	688,241 46%	1,190,617 80%	1,460,193 98%	1,488,095 100%
Normal forwarding	224,375 15%	372,022 24%	674,290 45%	762,646 51%	1,078,865 72%

Future Work

- Evaluate with 10 Gbps NICs
- Explore alternatives of the routing table backend
- Poll mode with either of softint and LWP
  - To prevent userland starvation

Backup

Expected Questions

- Q: Why don’t you measure with 10 GbE?
    - A: Our 10 GbE aren’t MP-safe yet
    - A: Our immediate target is 1 GbE
- Q: Why don’t you use netmap/DPDK if performance really matters?
    - A: Difficult to cooperate with existing tools including ours for our products
- How do you test MP-safe?
    - A: Run ATF with LOCKDEBUG
    - Do ioctl repeatedly while applying fluctuating traffic
        - If there are bugs, the kernel panic for about 10minitues
        - So, when the kernel run completely a few days, it probably ok

Expected Questions

- Q: Why do you use rwlock for the routing table despite NetBSD has pserialize/psref?
  - A: We cannot simply apply serialize/psref to the routing table
    - because the radix tree isn’t a lockless data structure
    - because a route can be deleted in softint but pserialize_perform and psref_target_destroy cannot be used in softint
      - A big restructuring is required
  - A: We don’t have a good alternative to the radix tree yet
  - A: We (IIJ) want to make Layer 3 MP-safe right away
    - To MP-ify other components like ipsec(4)

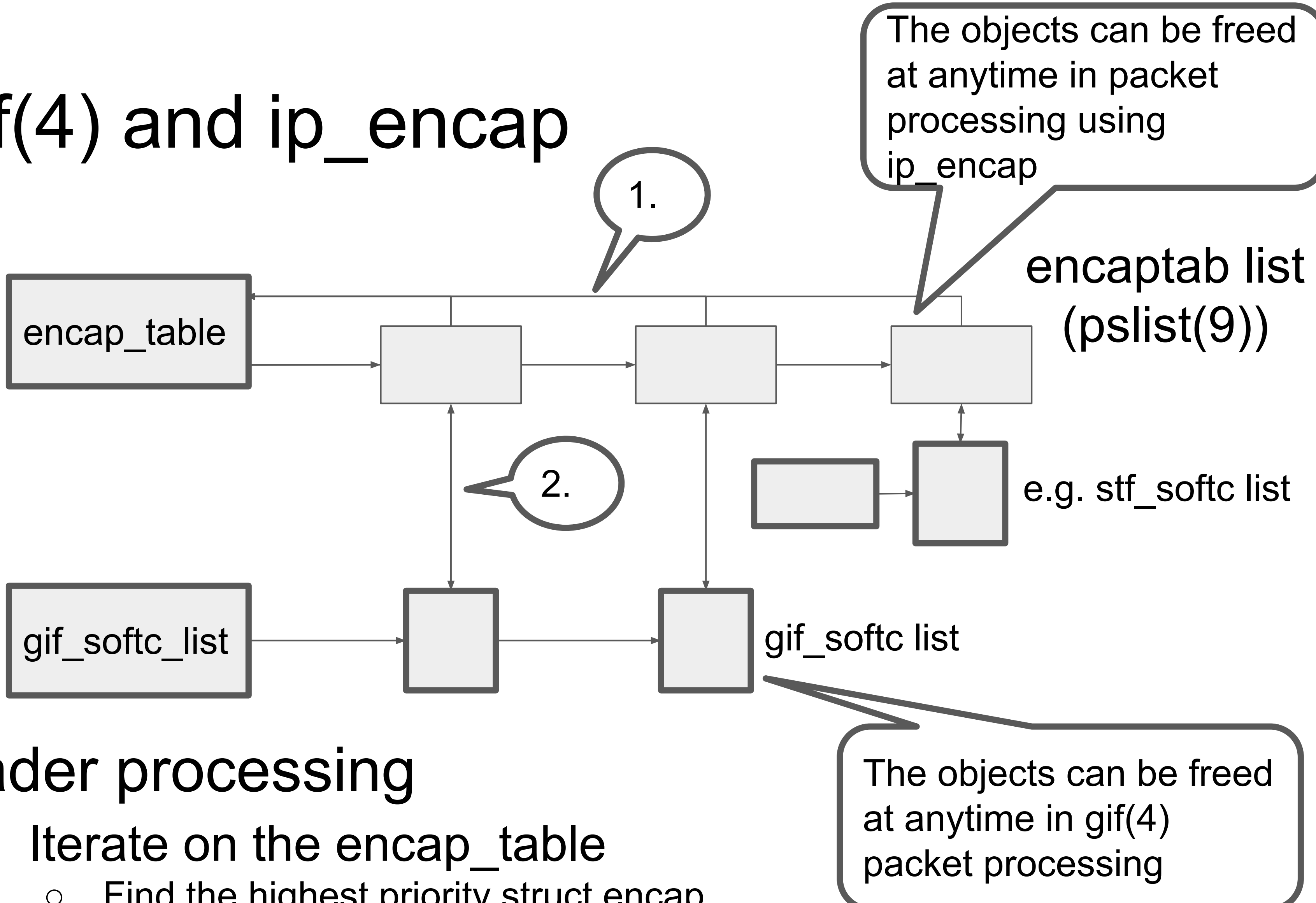
Expected Questions

- Q: What about the overhead of ipflow?
  - A: Not trivial (see the next slide)
  - A: Hash table size is 64 while there are 31 flows

The Case of gif(4)

- What’s gif?
  - A generic tunneling pseudo device
  - IPv[46] over IPv[46]
- Why gif?
  - It’s a good first step prior to other complex tunneling facilities
    - gif(4) is a very basic tunneling device
  - It uses a common IP tunneling utility, ip_encap
    - ip_encap is used by ipsec(4)

gif(4) and ip_encap

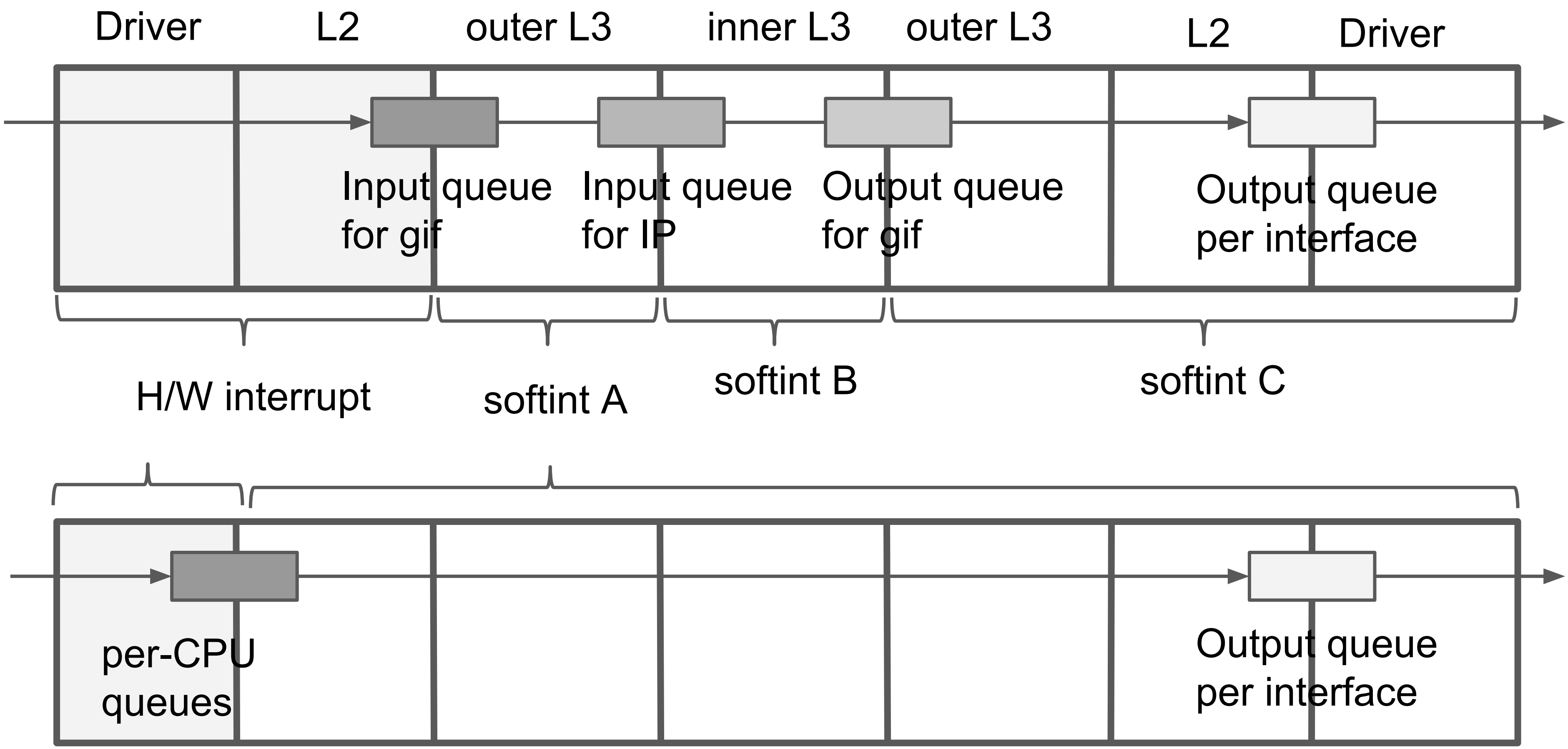


Reader processing

1. Iterate on the encap_table
   - Find the highest priority struct encap
2. Get a gif(4) softc
   - On receiving a packet
   - Not iterate gif_softc_list in fast path

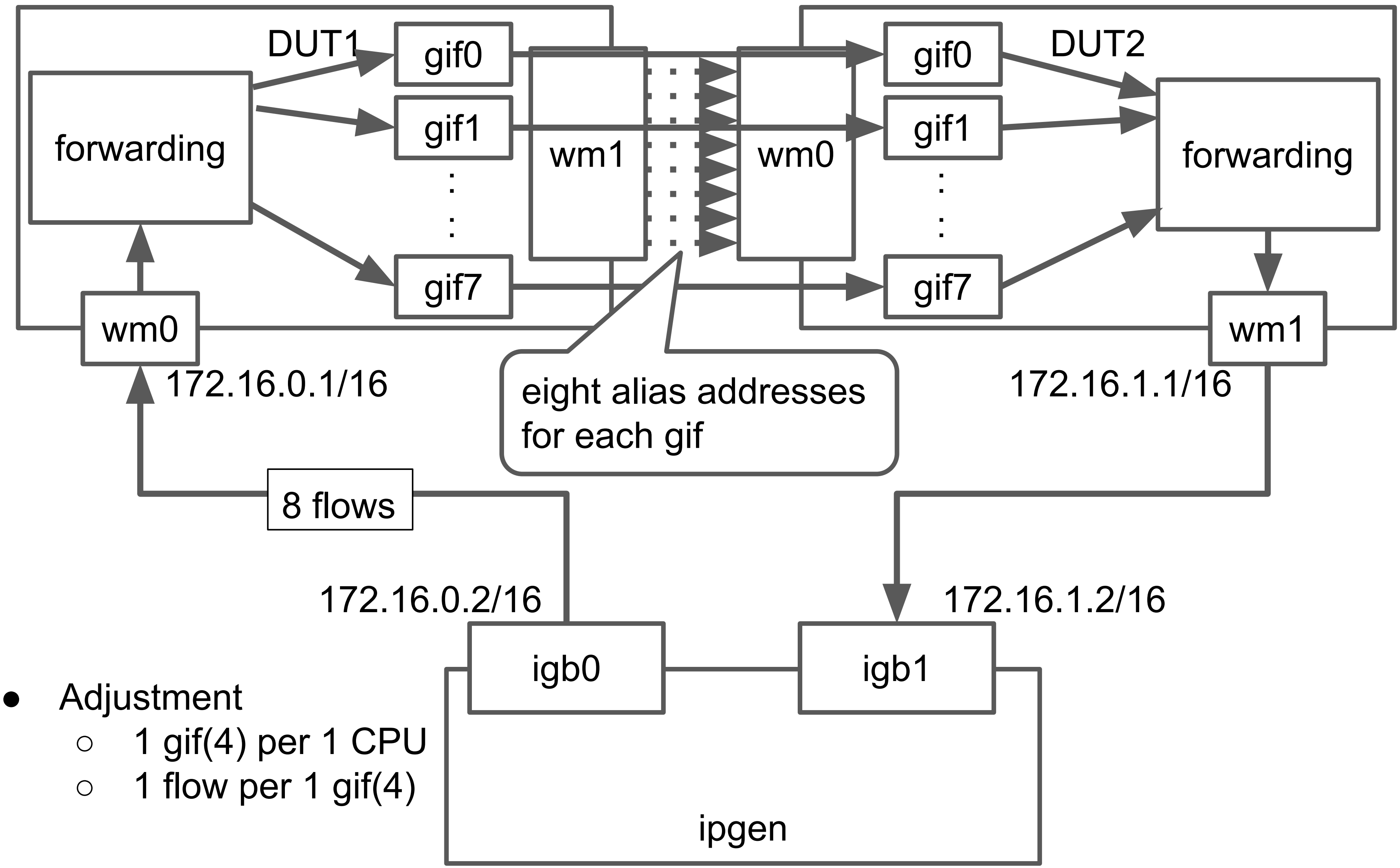
gif(4) to gif(4) Forwarding

Old



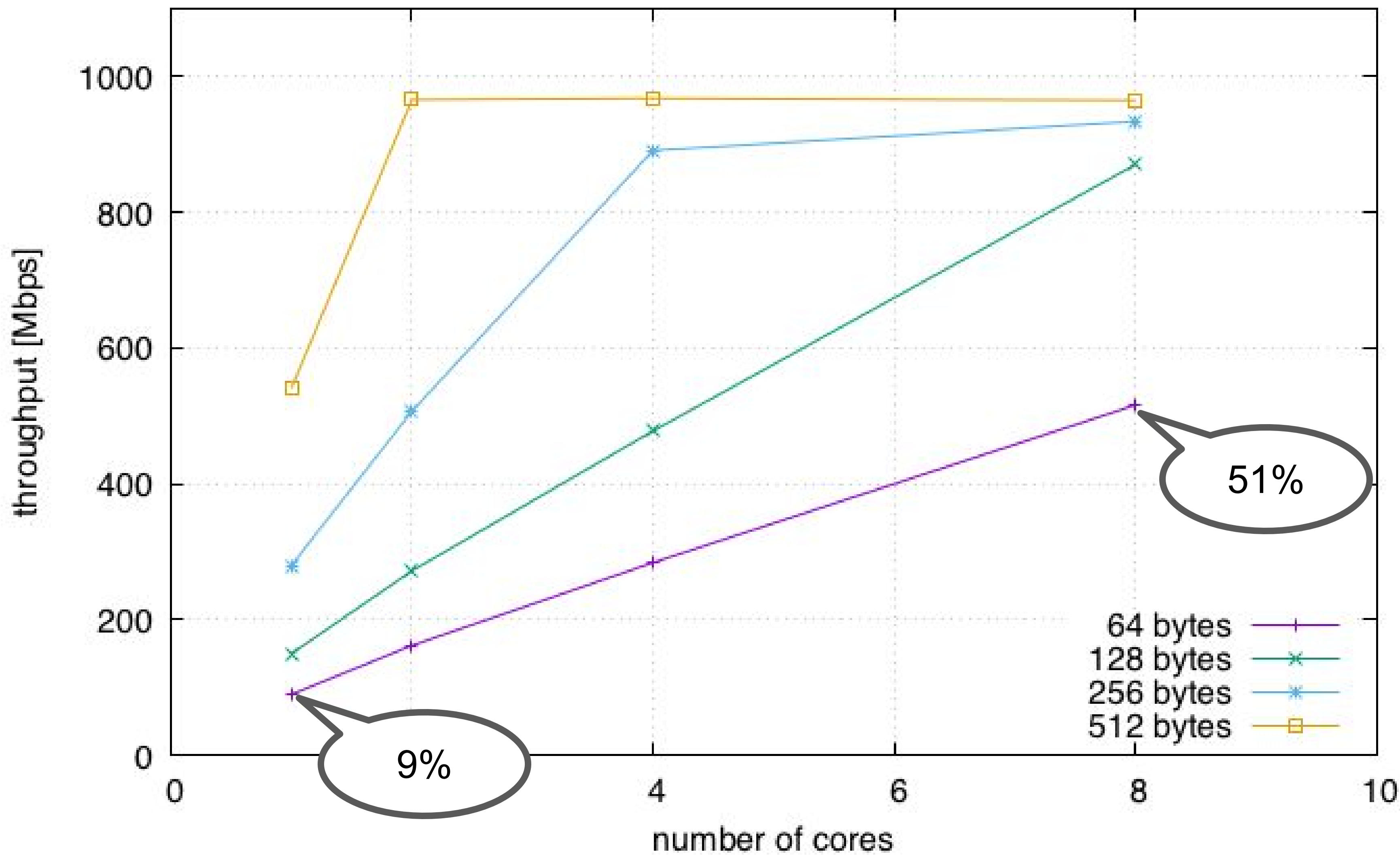
-current + our local changes

Setups for gif(4) Evaluation

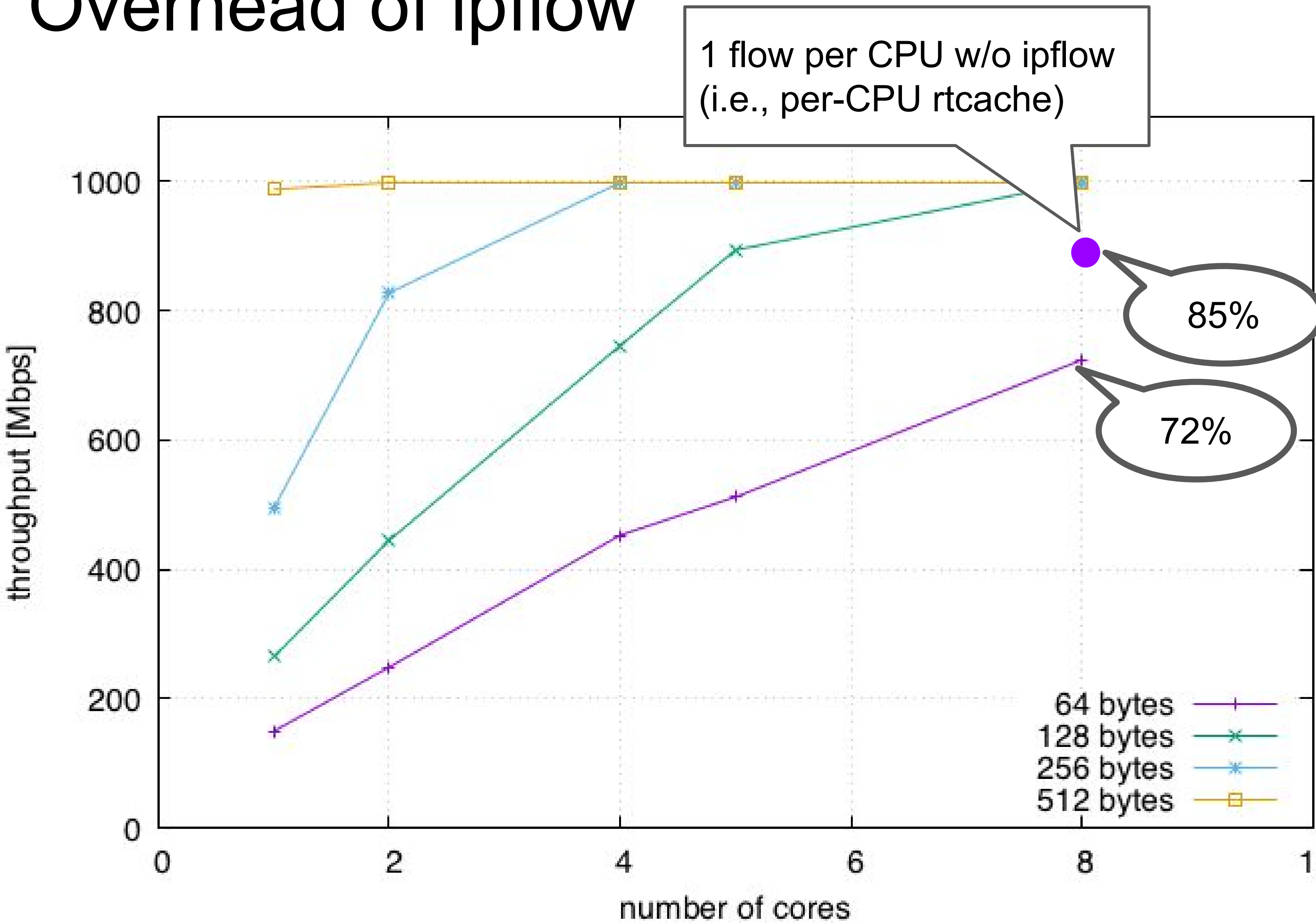


- Adjustment
  - 1 gif(4) per 1 CPU
  - 1 flow per 1 gif(4)

Throughput vs. # of cores : gif(4)



Overhead of ipflow



Summary of Experimental Results with 5 cores

- Frames per second per # of cores
  - at 64 bytes

	1 core	2 cores	4 cores	5 cores	8 cores
Wire rate	1,488,095	1,488,095	1,488,095	1,488,095	1,488,095
bridge(4)	381,322 25%	613,837 41%	1,191,634 80%	1,488,095 100%	1,488,095 100%
Fast forwarding	455,727 30%	688,241 46%	1,190,617 80%	1,460,193 98%	1,488,095 100%
Normal forwarding	224,375 15%	372,022 24%	674,290 45%	762,646 51%	1,078,865 72%
gif(4)	138,492 9%	242,251 16%	425,502 28%		772,528 51%

Dangling Pointers on struct ifnet

- Many structures have a pointer of an ifnet (ifp)
- In the MP-safe world, *ifp can be freed
- Solution
  - Replace a pointer with an interface index and get ifp from the interface database
    - With pserialize(9) or psref(9)
    - It adds some overhead
- Structures we needed the change
  - mbuf (rcvif)
    - Need to gain a reference of ifp on ip_input
  - ip_moptions, ip6_moptions

Dangling Pointers on struct ifnet (cont'd)

- A case when an interface pointer is always valid
  - If an object having ifp always lives shorter than the ifnet object, we can assume that *ifp is always valid
  - IOW, if an referencing object is destroyed on ifnet destruction, *ifp is always valid
  - Examples of this case
    - rtentry->rt_ifp
    - rtentry->rt_ifa (struct ifaddr)