Network Performance in the Linux Kernel

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  - Linux kernel and driver development, system integration, boot time optimization, consulting...
  - Embedded Linux, Linux driver development, Yocto Project & OpenEmbedded and Buildroot training, with materials freely available under a Creative Commons license.
  - `https://bootlin.com`
- Contributions:
  - Worked on network (MAC, PHY, switch) engines.
  - Contributed to the Marvell EBU SoCs upstream support.
  - Worked on Rockchip's Camera interface and Techwell's TW9900 decoder.

Preamble - goals

- Follow the path of packets through the Hardware and Software stack
- Understand the features of modern NICs
- Discover what the Linux Kernel implements to gain performances
- Go through the various offloadings available

The path of a packet

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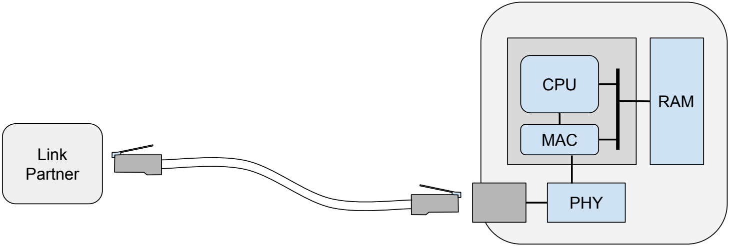
The Hardware

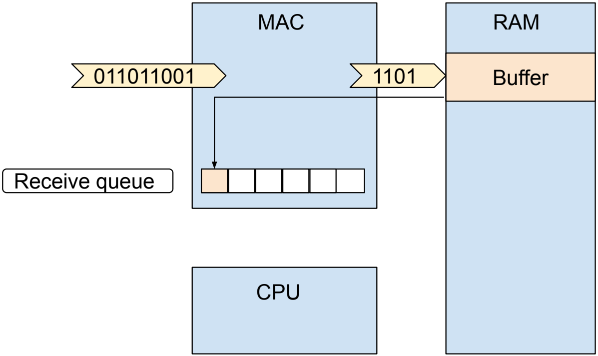


- Link Partner : The other side of the cable
- Connector : 8P8C (RJ45), SFP, etc.
- Media : Copper, Fiber, Radio
- PHY : Converts media-dependent signals into standard data

The NIC

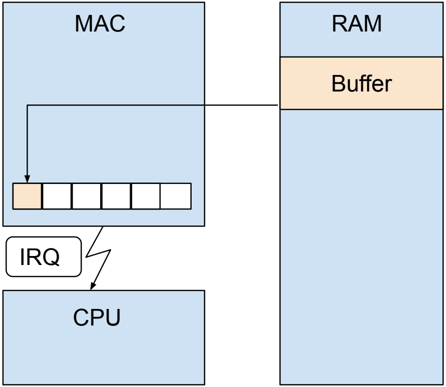
- **N**etwork **I**nterface **C**ontroller
- Sometimes embed a PHY (PCIe networking card)
- The MAC : Handles L2 protocol, transfers data to the CPU

Frame reception



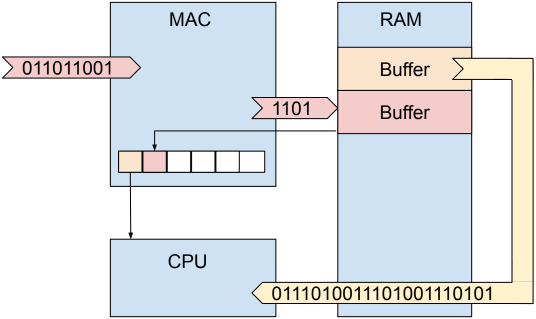
- The MAC received data and writes it to RAM using DMA
- A descriptor is created
- Its address is put in a queue

Frame reception - IRQ



- An interrupt is fired
- One CPU core will handle the interrupt

Frame reception - Unqueue



- The Interrupt handler acknowledges the interrupt
- The packet is processed in `softirq` context
- The next frame can be received in parallel

In the NIC driver

- The CPU : Processes L3 (`packets`) and above, up to the application
- The Interrupt Handler does very basic work, and masks interrupts
- `NAPI` is used to schedule the processing in batches
- Subsequent frames are also dequeued
- `NAPI` stops dequeueing once :
  - The budget is expired (release the CPU to the scheduler)
  - The queue is empty
- `NAPI` re-enables interrupts
  - This avoids having one interrupt per frame

In the kernel networking stack

- The PCAP hook is called, then the TC hook
- The header in unpacked, to decide if :
  - The packet is forwarded
  - The packet is dropped
  - The packed is passed to a socket
- The in-kernel data path is heavily optimized...
- ...But still requires some processing power at very high speeds

Traffic Spreading and Steering

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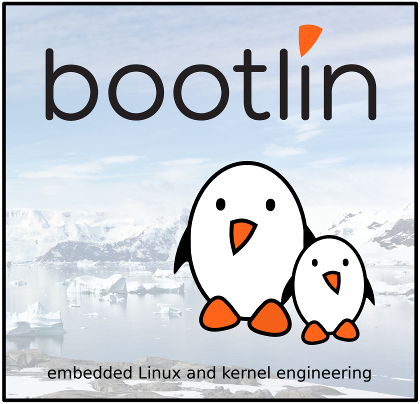
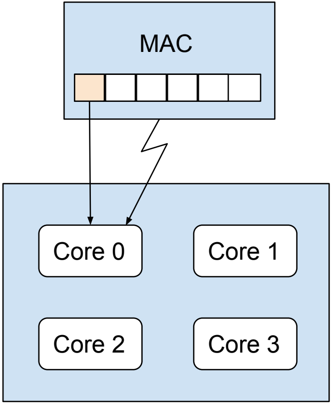


Scaling across queues and CPUs

- Most modern systems have multi-core CPUs
- Modern NICs have multiple RX/TX queues (`rxq`/`txq`)
- Interrupted CPU does all the packet processing
  - If the interrupt always goes to the same core...
  - ...the other ones will stay unused



Hardware and Software techniques exists to scale processing across CPUs

Scaling

Goal : Spread packet across CPU cores

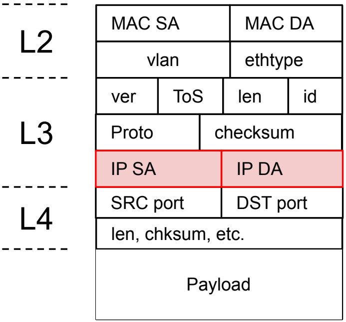
- We can't randomly assign packets to CPUs
- Ordering must be preserved
- Memory domains should be taken into account (L1/L2 caches, NUMA nodes)
- We need to spread packets per-flow

Kernel documentation : `Documentation/networking/scaling.rst`

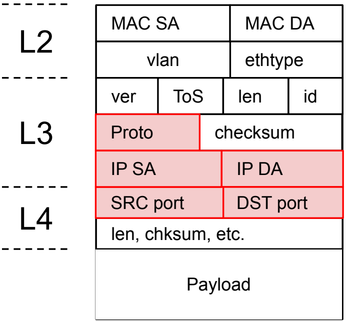
N-tuple Flows

Flow : Packets from the same emitter, for the same consumer

- Flows are identified by data extracted from the headers
- L3 flow : Source and Destination IP addresses → 2-tuple
- L4 flow : src/dst IP + Proto + src/dst ports → 5-tuple



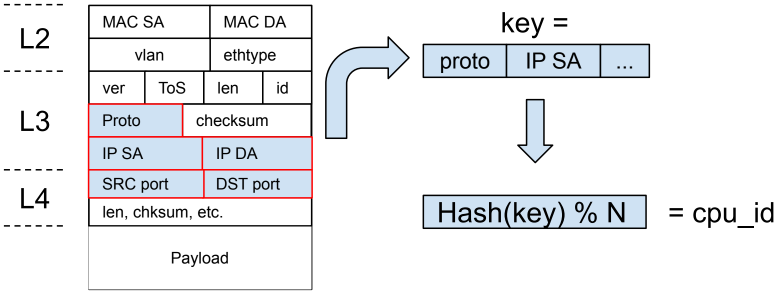
2-tuple



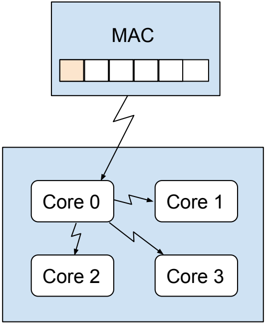
5-tuple

N-tuple Flows

- Other flows can be interesting :
  - Vlan-based flows
  - Destination MAC-based flows
- Most often, these tuples are hashed prior to being used
- Allows to build smaller flow tables
- Advanced NICs are able to keep track of a high number of flows



RPS : Receive Packet Steering

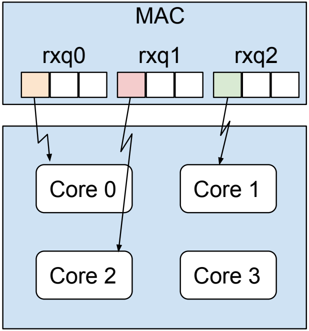


- The interrupted CPU schedules processing on other CPUs
- Key data is extracted from the Headers and hashed
  - The Hash can be computed by the hardware
  - It is then passed in the descriptor
- The CPU is chosen by masking out the first bits of the hash

Using RPS

- Kernel needs to be built with `CONFIG_RPS`
- The set of CPUs used depends on the `rxq` the frame arrives on
- `echo 0x03 > /sys/class/net/eth0/queues/rx-0/rps_cpus`
- `echo 0x0c > /sys/class/net/eth0/queues/rx-1/rps_cpus`
  - → Traffic from rxq 0 is spread on CPUs 0 and 1
  - → Traffic from rxq 1 is spread on CPUs 2 and 3
- Very useful for NICs with fewer `rxqs` than CPU cores !

RSS : Receive Side Scaling



- Offloaded version of RPS
- The NIC is configured to extract the header data and compute the Hash
- The CPU is chosen by means of an Indirection Table
- The NIC actually enqueues the packet into one of its queues
- The interrupt directly comes to the correct CPU !

RSS Tables

- Tables within the `NIC`
- Associates hashes to queues
- Tables commonly have more entries than queues
  - e.g. 128 entries for 4 queues
- Filling the table allows affecting weights to each queue

```
0x00: 0 0 0 0 0 0 0 0
0x08: 0 0 0 0 0 0 0 0
0x10: 1 1 1 1 1 1 1 1
0x18: 2 2 2 2 3 3 3 3
```

- `rxq` 0 has weight 4
- `rxq` 1 has weight 2
- `rxq` 2 and 3 have weight 1

Using RSS

- RSS is configured through ethtool
- Enabling RSS : `ethtool -K eth0 rx-hashing on`
- Configuring the indirection table :
  `ethtool -X eth0 weight 1 2 2 1`
- Dumping the indirection table : `ethtool -x eth0`
- Configuring the hashed fields :
  `ethtool -N eth0 rx-flow-hash tcp4 sdfn`
  - see man ethtool(8) for the meaning of each flow type

```
ethtool -X eth0 equal 4
ethtool -N eth0 rx-flow-hash tcp4 sdfn
ethtool -N eth0 rx-flow-hash udp4 sdfn
ethtool -K eth0 rx-hashing on
```

→ Increased IP forwarding speed by a factor of 3 on the MacchiatoBin

RFS : Receive Flow Steering

- RPS and RSS don't care about who consumes which flow
- This might be bad for cache locality
  - What if RPS/RSS sends a flow to CPU 1...
  - ...but the consumer process lives on CPU 2 ?
- RFS tracks the flows and their consumers
- Internally keeps a table associating flows to consumers/CPUs
- Updates indirection for a flow when the consumer migrates

1. `httpd` lives on CPU 0
2. RFS steers TCP traffic to port 80 onto CPU 0
3. `httpd` is migrated to CPU 1
4. RFS updates the flow table
5. TCP to port 80 traffic now goes to CPU 1 !

Using RFS

- Internally, a **flow table** associates flow hashes to CPUs
- User indicates the size of the table
- `echo 32768 > /proc/sys/net/core/rps_sock_flow_entries`
- `echo 4096 > /sys/class/net/eth0/queues/rx-0/rps_flow_cnt`
- `echo 4096 > /sys/class/net/eth0/queues/rx-1/rps_flow_cnt`
- `...`
- We configure $(32768/N(rxqs))$ in each queue
- These values are recommended in the Kernel Documentation

aRFS : Accelerated Receive Flow Steering

- Advanced NICs can steer packets to `rxqs` in Hardware
- `aRFS` asks the driver to configure steering rules for each flow
- Rules are updated upon migration of the consumer
  - Packets always come to the right CPU !
  - Kernel handles outstanding packets upon migration
- Needs support in HW, and a specific implementation in the driver
- The driver determines how to build the steering rule (n-tuple)

Using aRFS

- Kernel needs to be built with `CONFIG_RFS_ACCEL`
- Enable N-tuple filtering offloading :
  `ethtool -K eth0 ntuple on`
- The `NIC` and the driver needs to support aRFS

Flow Steering : Ethtool and TC flower

- Manually steering flows can be interesting for proper resource assignment
- This is also helpful to dedicate queues to flows, e.g. `AF_XDP`
- Two interfaces exists : `tc flower` and `ethtool`
  - Internally, both `ethtool` and `tc` interfaces are being merged...
  - ... But for now the 2 methods coexist and can conflict
- We insert **steering rules** in the `NIC`, with priorities
- Rules associate :
  - Flow types : `TCP4`, `UDP6`, `IP4`, `ether`, etc.
  - Filters : `src-ip`, `proto`, `vlan`, `dst-port`, etc.
  - Actions : Target `rxq`, drop, `RSS context`
  - Location : Priority of the rule

Using tc flower and ethtool rxnfc

ethtool examples

- `ethtool -K eth0 ntuple on`
- `ethtool -N eth0 flow-type udp4 dst-port 1234 action 2 loc 0`
  - Steer IPv4 UDP traffic for port 1234 to rxq 2
- `ethtool -N eth0 flow-type udp4 action -1 loc 1`
  - Drop all UDP IPv4 traffic (except for port 1234)

TC flower example

- `ethtool -K eth0 hw-tc-offload on`
- `tc qdisc add dev eth0 ingress`
- `tc flower protocol ip parent ffff: flower ip_proto tcp \`
  `dst_port 80 action drop`
  - Drop all IPv4 TCP traffic for port 80
- `tc flower` falls back to software filtering if needed

RSS contexts

- Flows can also be steered to multiple queues at once
- RSS is then used to spread traffic accross queues
- This is achieved through RSS contexts
- An RSS context is simply an indirection table
- An RSS context is created with ethtool :
  - `ethtool -X eth0 equal 4 context new`
- The RSS context is uses as a destination for the flow :
  `ethtool -N eth0 flow-type udp4 dst-port 1234 context 1 loc 0`

XPS : Transmit Packet Steering

- Upon transmitting packets, the driver executes **completion** code
- Transmitting using a single CPU can also lead to cache misses
- `XPS` is used to select which `txq` to use for packet sending
- We can assign `txqs` to **CPUs**
  - The `txq` is chosen according to the CPU the sender lives on
- We can also assign `txqs` to **rxqs**
  - Make sure that we use the same CPU for RX and TX
- The `NIC` driver assigns `txqs` to CPUs

Using XPS

- Per-CPU mapping :
  - `echo 0x01 > /sys/class/net/eth0/queues/tx-0/xps_cpus`
  - `echo 0x02 > /sys/class/net/eth0/queues/tx-1/xps_cpus`
  - Assign `txq` 0 to CPU 0
  - Assign `txq` 1 to CPU 1
- Per-rxq mapping :
  - `echo 0x01 > /sys/class/net/eth0/queues/tx-0/xps_rxqs`
  - `echo 0x02 > /sys/class/net/eth0/queues/tx-1/xps_rxqs`
  - Assign `txq` 0 to `rxq` 0
  - Assign `txq` 1 to `rxq` 1

Other offloading

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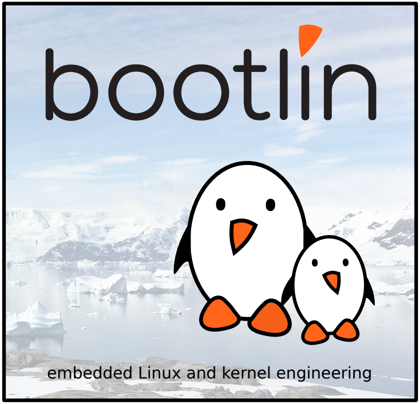

Checksumming

- IPv4 and IPv6 include a checksum in the header
- NICs can compute checksums on the fly in TX mode
- The Kernel leaves the checksum fields empty
- tcpdump will show egress packets with a wrong checksum !!

Filtering

- Some NICs are capable of early dropping and filtering
- Frames are dropped by the NIC, no interrupt is ever fired
- MAC filtering :
  - Drop frames with an unknown MAC address
  - The NIC keeps information about multicast domains
  - The NIC must also keep an updated list of unicast addresses
  - `MAC Vlans` allows attaching multiple addresses to one NIC
- VLAN filtering :
  - Drop frames for unknown VLANs
  - The NIC keeps track of VLANs attached to the interface
  - `ethtool -K eth0 rx-vlan-filter on`

Data insertion and segmentation

- Some NICs can also insert the VLAN tag on the fly
- `ethtool -K eth0 txvlan on`
  - The NIC will insert the VLAN Tag automatically
- `ethtool -K eth0 rxvlan on`
  - The NIC will strip the VLAN tag
  - The VLAN tag will be in the descriptor
- Some NICs can also deal with packet segmentation
- `ethtool -K eth0 tso on`
  - Offload TCP segmentation, the `NIC` will generate segments
- `ethtool -K eth0 ufo on`
  - Offload UDP frafgentation, the `NIC` will generate fragments

XDP

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Principle

- Execute a BPF program from within the NIC driver
- Executed as early as possible, for fast decision making
- Can be used to `Pass`, `Drop` or `Redirect` frames
- Also used for fine-grained statistics

BPF

- Berkley Packet Filter
- Programming language that can be formally verified
- Designed to write filtering rules
- Lots of hooks in the Networking Stack, XDP being the earliest

AF_XDP

- Uses a combination of `XDP` and flow steering
- Response to `DPDK` : Userspace does the full packet processing
- Allows for heavily optimized and customized processing
- Special sockets that will directly receive raw buffers
- Thanks to `XDP`, we can select only part of the traffic for `AF_XDP`
- The kernel stack is therefor not entirely bypassed...
- ...and this is a fully upstream solution !

Documentation and sources

- In the Kernel source code : `Documentation/networking/scaling.rst`
- RedHat tuning guide: `https://access.redhat.com/documentation/en-us/red_hat_enterprise_linux/6/html/performance_tuning_guide/main-network`

Thank you !