Chair of Network Architectures and Services
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High-Performance Packet Processing Experiments

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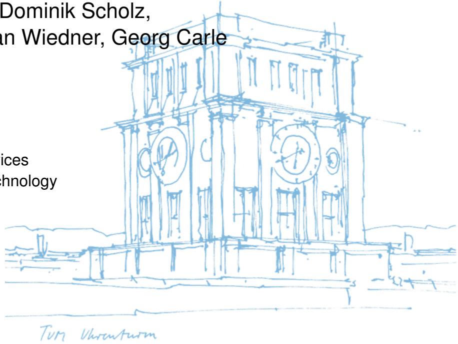
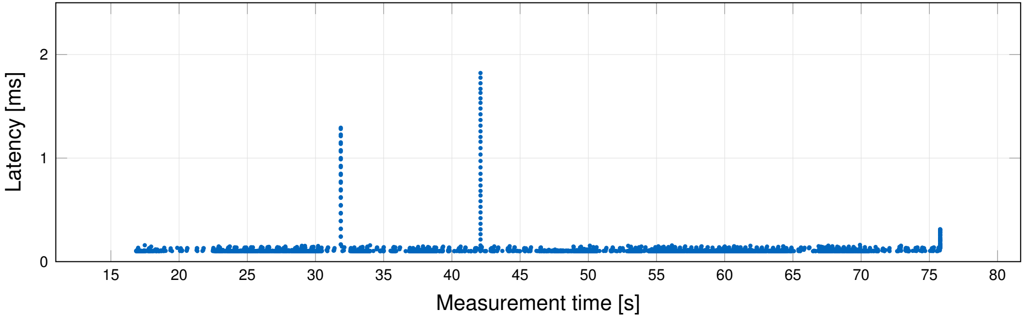


Motivation

Latency of a Network Function



Suricata forwarder worst-case latencies

- Latency spikes are caused by the OS network stack (happen for any application)

➔ Why should we care about 1 or 2 ms?

Motivation

Why should we care about latency?

IEEE standard	TX Rate [Gbit/s]	Serialization Delay [ns]	Impacted Packets [#/ms]
802.3z	1	672.0	1488
802.3ae	10	67.2	14 880
802.3bm	100	6.7	149 253
802.3bs	400	1.7	588 235
P802.3dj	1600	0.4	2 500 000

1-ms transmission for different Ethernet bandwidths

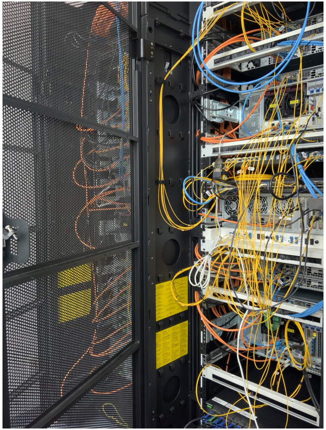
- Using minimum-sized Ethernet packets (64 B incl. FCS) at full line rate
- Impact increases for every new standard
- For 1.6 Tbit/s a 1-ms delay 2.5 M packets are impacted (approx. 150 MB)

→ High-performance packet processing needs to pay attention to delays

Motivation

Main challenges

1. Measurement methodology that can handle the latency
   - How to measure reproducibly?
   - How to measure at high bandwidths?
   - How to measure latency precisely and accurately?
2. Low-latency measurement examples[1]
   - What is causing latency on software packet processing systems?
   - What is the impact of specific components on software packet processing?



High-performance network testbed

[1] [3] S. Gallenmüller, F. Wiedner, J. Naab, and G. Carle. "How Low Can You Go? A Limbo Dance for Low-Latency Network Functions". In: J. Netw. Syst. Manag. 31.1 (2023), p. 20

Measurement Methodology

Reproducible Measurements—The Plain Orchestrating Service (pos)

Our solution to create reproducible research

1. Create a testbed management system
2. Create a well-defined experiment workflow

[2] [2] S. Gallenmüller, D. Scholz, H. Stubbe, and G. Carle. “The pos framework: a methodology and toolchain for reproducible network experiments”. In: CoNEXT. ACM, 2021

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Achieving Repeatability

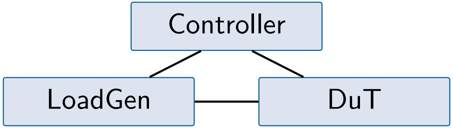
- Automation
- Live images
  - Researchers **must** automate configuration
  - No residual state between reboots

➔ Experiments become repeatable

Achieving Reproducibility

- Providing access to experiment infrastructure
- Other researchers can easily (re-)run experiment

➔ Experiments become reproducible



Minimal pos[2] experiment topology

[2] [2] S. Gallenmüller, D. Scholz, H. Stubbe, and G. Carle. "The pos framework: a methodology and toolchain for reproducible network experiments". In: CoNEXT. ACM, 2021

Reproducible Measurements—pos Experiment Workflow

Setup phase

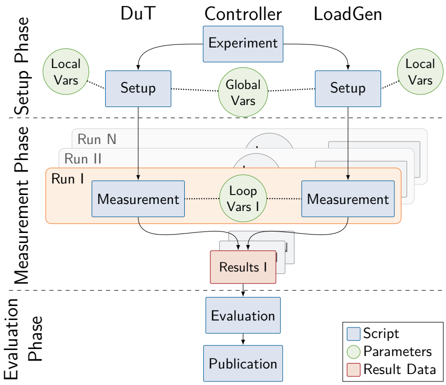
- Controller manages experiment
- Controller configures experiment nodes (DuT, LoadGen)
- Global / local variables (vars) parametrize setup

Measurement phase

- Repeated execution of measurement script
- Loop variables parameterize each measurement run
  - e.g., different packet rates
  - data of each run is connected to a specific set of loop vars

Evaluation phase

- Collected results / loop vars used for experiment evaluation
- Automated experiment release (git repository, website)



pos workflow

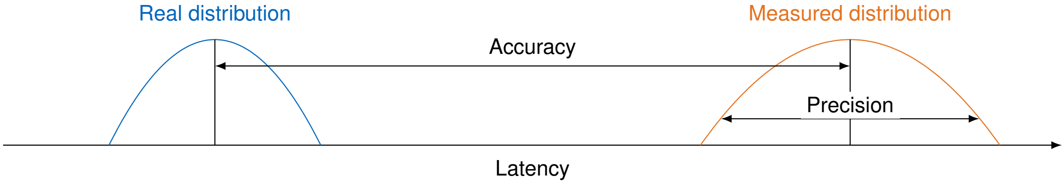
High-Performance Measurement and Generation of Traffic—MoonGen

MoonGen[3] features

- Software packet generator
  - Easy to adapt (via Lua scripting language)
  - High-performance (up to 100 Gbit/s or 100 million packets per second)
- Important features for measurements with high bandwidths
  1. Precise rate control
     - Traffic patterns can have a significant impact on measurement results
     - MoonGen allows to precisely control traffic patterns (via software and with hardware support)
  2. Timestamping
     - NICs typically offer precise clocks for PTP (Precise Time Protocol)
     - MoonGen uses these clocks for hardware timestamping

[3] [1] P. Emmerich et al. “MoonGen: A Scriptable High-Speed Packet Generator”. In: ACM IMC, Tokyo, Japan, 2015

Measuring Latency—High-Accuracy and High-Precision Timestamping



Accuracy vs. precision

- Accuracy: *"closeness of agreement between a test result and the accepted reference value"*
- Precision: *"closeness of agreement between independent test results"*
- Accuracy can be improved if timestamps are taken early in the processing path
- Precision can be improved if measurements are not impacted by jitter, e.g., caused by interrupts

➔ Hardware timestamping on NIC (high accuracy) not impacted by interrupts (high precision)

Measuring Latency—High-Accuracy and High-Precision Timestamping

Three-node setup

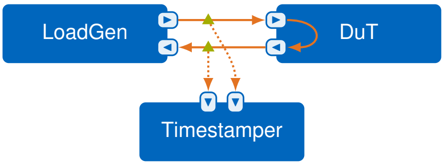
LoadGen

- Flexible software packet generator (MoonGen)
- Bandwidth: Up to 100 Gbit/s or 100 Mpkts/s
- High-precision and high-accuracy generation

Device under Test (DuT)

- Device under test processes packets
- Forwards packets back to LoadGen
- LoadGen analyzes traffic (generated vs. received)

Measuring Latency—High-Accuracy and High-Precision Timestamping



Three-node setup

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- LoadGen analyzes traffic (generated vs. received)

Timestamper

- LoadGen cannot timestamp all sent packets in hardware (only approx. 1000 pkts/s)
- Specific Intel NICs (e.g., E810) can timestamp all received packets in hardware
- Use passive optical splitters to convert entire traffic to *received* traffic

Low-latency Measurements

Low-Latency Software Stack Design

Problems & Solutions

Reasons for latency impairment

- Interrupt-based IO
  - Linux NAPI
- CPU features
  - Dynamic scheduling of processes onto CPU cores
  - Virtual cores (SMT/Hyperthreading)
  - Energy-saving mechanisms
  - Dynamic cache allocation
- Expensive VM IO

Low-Latency Software Stack Design

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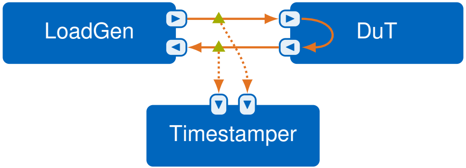
Improving latency performance

- Polling-based IO
  - DPDK
- CPU features
  - Statically allocate CPU cores for processes
  - Disable SMT/Hyperthreading
  - Disable energy-saving mechanisms
  - Static cache allocation (Intel CAT)
- NIC acceleration (SR-IOV)

Setup



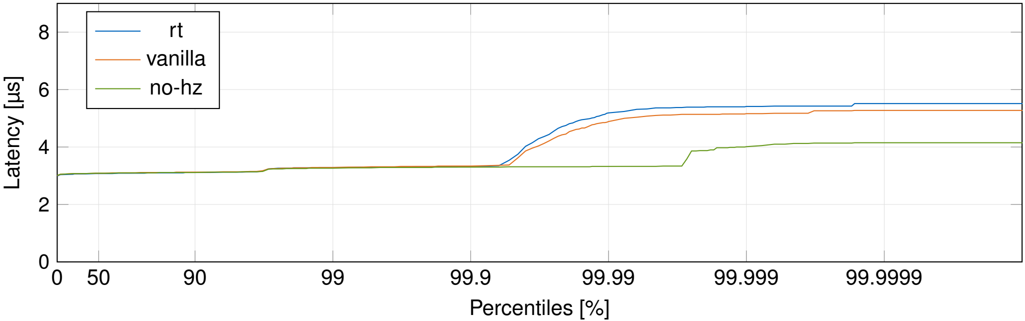
Three-node setup

- Loadgen runs a packet generator (MoonGen) creating UDP packets
- Device under Test (DuT) runs a forwarding application
  - Investigation of different scenarios by modifying the DuT
  - DuT runs a forwarder in different investigated scenarios
- Timestamper records DuT ingress/egress traffic (passive optical TAPs)
  - Hardware-timestamping of entire network traffic (timer resolution 12.5 ns)
- Hardware: Xeon D-1518 (Quad-core, 2.20 GHz), NIC: X557 (10G)
- Traffic: UDP, constant bit rate

Impact of the Linux Kernel

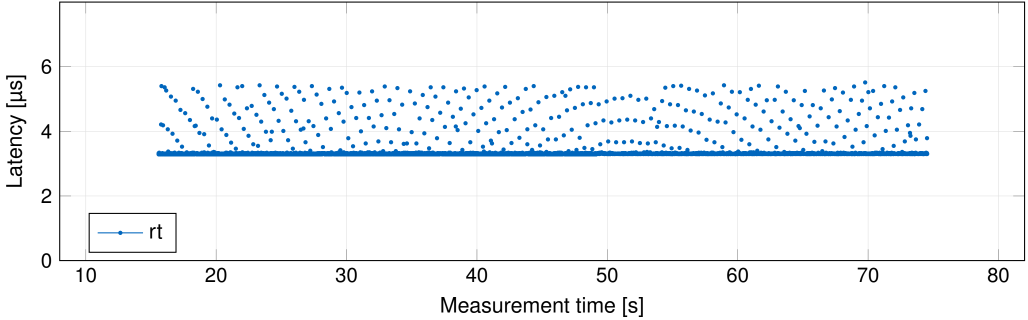
- Linux kernel is offered in different variants
- Two-specific versions of the Linux kernel are optimized to deliver a predictable latency:
  - Realtime kernel
    - Specific kernel patches to deliver consistent latency
  - No-HZ or tickless kernel
    - Disables regular interrupts of the Linux kernel (so-called "tick")
    - Kernel uses the tick to perform housekeeping taks via interrupts (e.g., scheduling)
- The following measurements investigate three different Linux kernels for the DuT
  - rt (realtime) Linux kernel
  - vanilla (unmodified) Linux kernel
  - no-hz (tickless) Linux kernel
- The following measurements use a DPDK-based forwarder

Impact of the Linux Kernel



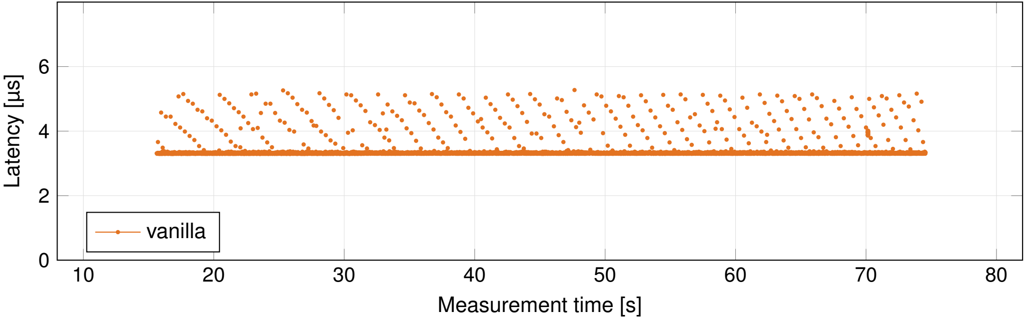
- No measurable differences for percentiles below 99.9
- Stable latency (below 6 µs) is possible for software forwarding even for high percentiles:
  - Similar behavior between realtime and vanilla kernel
  - Lower latency for tickless kernel

Impact of the Linux Kernel



- Two different possibilities for realtime kernel
  - High chance to have stable latency of approx. 3 µs
  - Low chance to be processed during interrupt ("tick") resulting in higher latency of up to 6 µs

Impact of the Linux Kernel



- Two different possibilities for realtime kernel or vanilla kernel:
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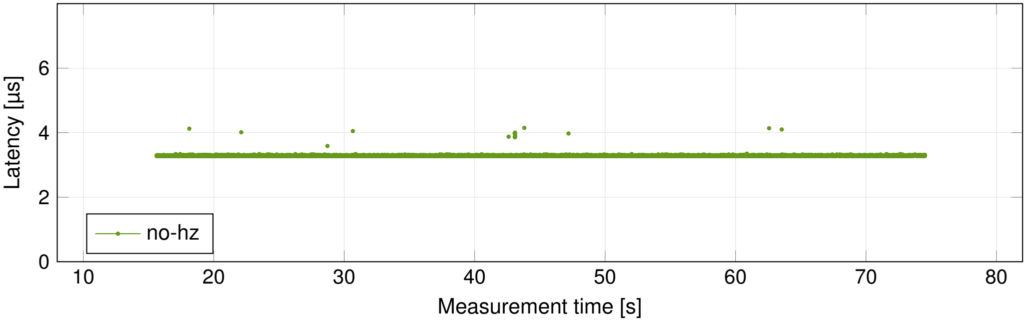
Impact of the Linux Kernel

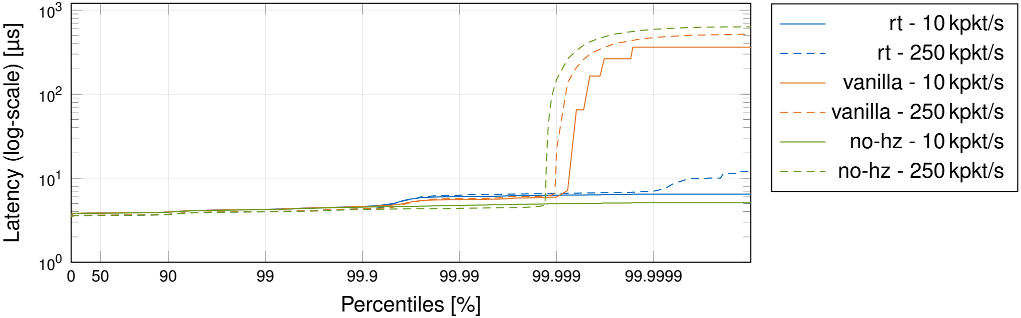


- Two different possibilities for realtime kernel or vanilla kernel:
  - High chance to have stable latency of approx. 3 µs
  - Low chance to be processed during interrupt ("tick") resulting in higher latency of up to 6 µs
- More stable behavior for tickless kernel without interrupts

Impact of the Linux Kernel

- Impact of Linux on other packet processing applications
- The following measurements investigate three different Linux kernels for the DuT
  - vanilla (unmodified) Linux kernel
  - rt (realtime) Linux kernel
  - no-hz (tickless) Linux kernel
- DuT: Suricata an intrusion prevention system using a DPDK-based network stack

Impact of the Linux Kernel

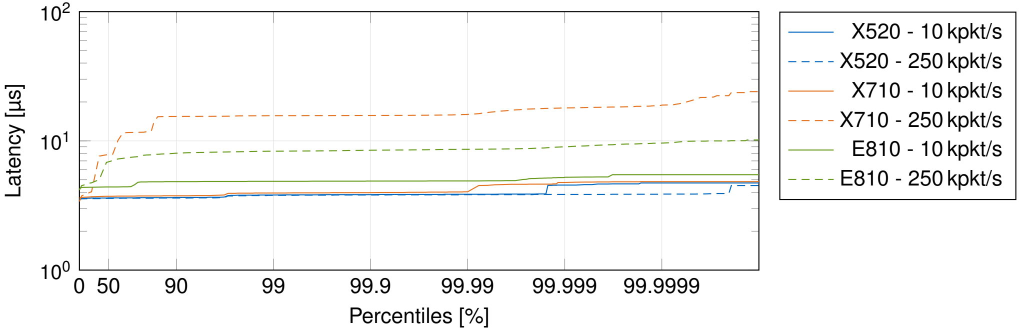


- Significant difference between previous measurement:
  - Vanilla and tickless show similar latency behavior
  - Realtime kernel shows consistently lower performance for high percentiles
- Reason:
  - Tickless kernel only works for single-thread application (otherwise it falls back to vanilla behavior)
  - Realtime kernel offers more consistent performance for multithreaded applications such as Suricata

Impact of the NIC

- Different generations of (Intel) NICs are currently available:
  - X500 generation (up to 10 Gbit/s, released in 2009)
  - X700 generation (up to 40 Gbit/s, released in 2014)
  - E800 generation (up to 100 Gbit/s, released in 2020)
- The following measurements use a DPDK-based forwarder with rates between 10 and 250 kpkt/s

Impact of the NIC

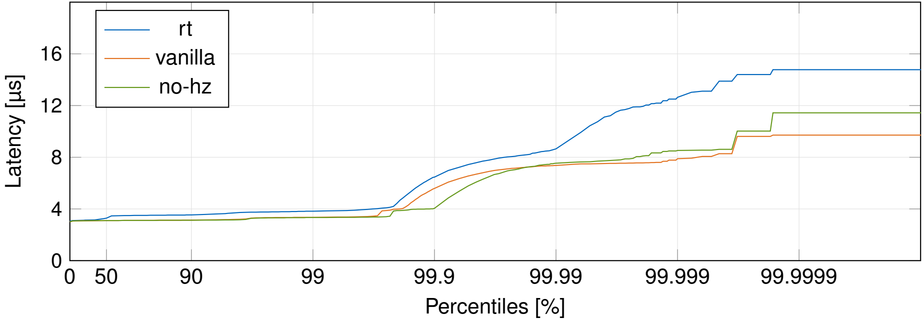


- X500 rather simple architecture, most of the features implemented in hardware, most stable latency
- X700 more complex architecture (more like a switch architecture than NIC), significant latency increase
- E800 complex architecture, more stable latency than previous generation

Impact of Virtualization

- Impact of virtualization on latency
- The following measurements use a DPDK-based forwarder
- SR-IOV is used for a hardware-accelerated network IO of VMs (based on X557 NIC)
- Comparison of vanilla, realtime, and tickless kernel

Impact of Virtualization



- Similar latency performance vanilla and tickless kernel
- Realtime kernel performs slightly worse for high percentiles
- In general, latency in VMs can be close to bare-metal deployments

Conclusion

Measurement methodology

- Measurement methodology is highly relevant to perform effective measurements (especially for latency)
- Hardware support is required for latency measurements

Conclusion

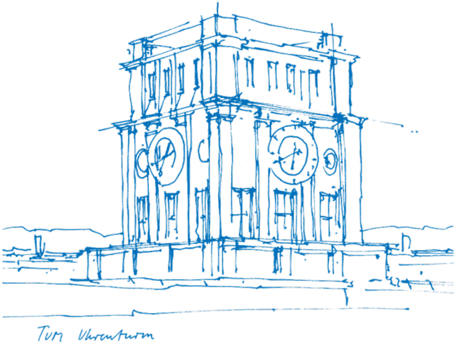
Measurement methodology

- Measurement methodology is highly relevant to perform effective measurements (especially for latency)
- Hardware support is required for latency measurements

Low-latency experiments

- Linux kernel relevant for latency (even if OS stack is not used)
- No clear recommendation which kernel is best, highly depends on the specific scenario:
  - realtime kernel offered the lowest latency for multi-threaded applications
  - tickless kernel offered lowest latency for single-threaded applications
  - vanilla kernel performed best for our VM scenario
- Choice of NIC controller impacts latency
- In our scenario, we observed that older NICs with a simpler architecture offered the best latency

Thank you for listening.



Bibliography

[1] P. Emmerich, S. Gallenmüller, D. Raumer, F. Wohlfart, and G. Carle. “MoonGen: A Scriptable High-Speed Packet Generator”. In: ACM IMC, Tokyo, Japan, 2015.

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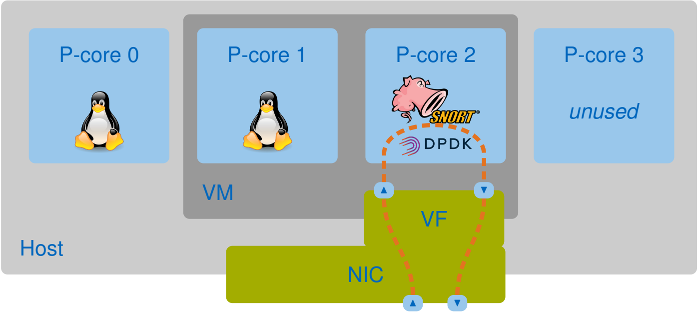
Backup

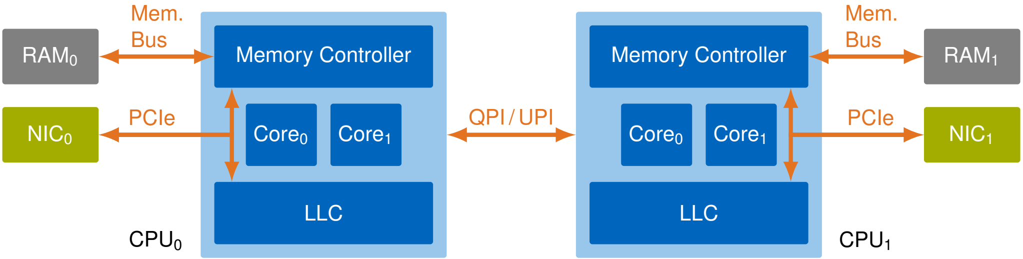
Design



Example setup on a 4-core CPU

- Static pinning: Host OS ➔ p(hysical)-core 0, VM OS ➔ p-core 1, App ➔ p-core 2
- P-core 2 is isolated from scheduling from Host OS & VM OS
- SR-IOV splits NIC into Virtual Functions (VF), one VF exclusively bound to p-core 2

Hardware Architecture



Typical high-level hardware architecture

Typical resources available for packet processing

- Ethernet: 10 Gbit/s to 100 Gbit/s
- PCIe: 32 Gbit/s to 125 Gbit/s (8$\times$ PCIe 2.0 / 4.0)
- Memory bus: 51 Gbit/s to 205 Gbit/s (DDR3-800 / DDR4-3200)
- QPI/UPI: 77 Gbit/s to 166 Gbit/s
- CPU: 2.0 GHz/core to 4.0 GHz/core