Chair of Network Architectures and Services
School of Computation, Information and Technology
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Considerations and Methodologies for Reproducible Network Experiments of Programmable Network Devices

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Ph.D. Defense

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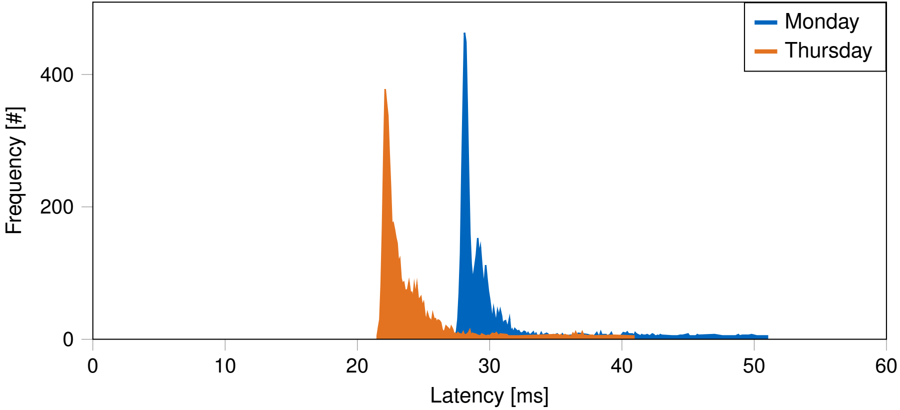
	Prof. Roberto Bruschi, Ph.D.

Garching, Thursday 17th July, 2025

Motivation — Reproducible Experiments



- Experiment results differ between experiments! Why?

→ Reproducibility essential for scientific progress

Structure

Thesis Chapter		Focus Point	Publications
1	Introduction		
2	Portable & Independent Experiments: A Methodology	Testbed Portability	CoNEXT'21, WONS'24, ComComs'25
3	Use Case I: Hardware-based NPU	Hardware Diversity	ITC'21, SIGCOM 5G-MeMU'22
4	Use Case II: Software-based NPU	Software Diversity	ITC'20, EURO P4'20
5	Use Case III: Programmable SDN Switches	Complex Topologies	IFIP Networking'23, ComComs'24
6	Conclusion		

Related Work

Testbeds:

- Crucial experiment-enabling scientific instrument
- Experiments target specific testbeds
- → Restricted view limits result robustness [1]

Testbed Properties:

Complex Topologies — Apt for complex, multi-node setups?
Software Diversity — Fitting for iterative development?
Hardware Diversity — Allows/supports arbitrary hardware?
Testbed Portability — Experiments portable to other testbeds?

	Chameleon Keahey et al. [2]	*CloudLab* Duplyakin et al. [3]	*pos* Gallenmüller et al. [4]	This Work
Complex Topologies	✓	✓	✓	✓
Software Diversity	✓	✓	✓	✓
Hardware Diversity	○	○	✓	✓
Testbed Portability	○	○	×	✓

→ This work extends the pos methodology with experiment portability

[1] N. Zilberman, "An Artifact Evaluation of NDP", ACM SIGCOMM CCR, vol. 50, no. 2, 2020.
[2] K. Keahey et al., "Lessons learned from the Chameleon testbed",, ser. USENIX ATC'20, 2020.
[3] D. Duplyakin et al., "The Design and Operation of CloudLab",, ser. USENIX ATC '19, 2019.
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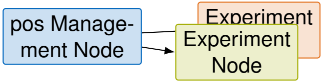
Thesis Chapter 2: pos — Reproducibility-by-Design

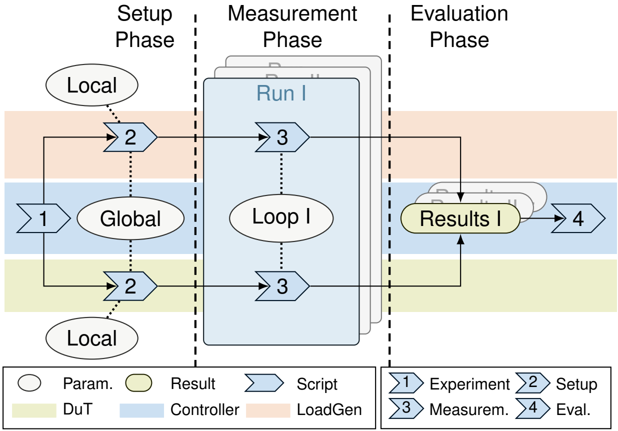
Research Question (RQ 2a): *Can we design a reproducibility-centric testbed?*

Answer / Approach:

- Structure testbed resources: Management and experiment nodes, e.g., Device under Test (DuT) and Load Generator (LoadGen)



- Promote multi-phase experiment workflow
  1. Setup phase
  2. Measurement phase
  3. Evaluation phase
- Fixed initial state ensures well-defined instructions and parameters



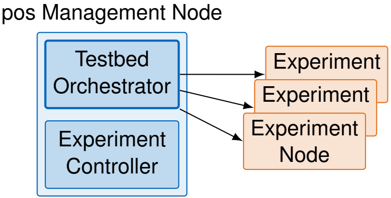
→ How can the pos methodology be *ported* to arbitrary testbeds?

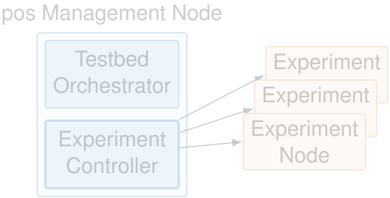
Research Question (RQ 2b): *Is a reproducibility-centric methodology portable to other testbeds?*

pos Management Node:

- Central point to organize and run experiments
- Observation: Two roles of pos management node
- Testbed Orchestrator: Configuration of experiment nodes
  - Define and provision OS for experiment nodes
  - Power on/off experiment nodes
- Experiment Controller: Execution of experiment steps
  - Execute experiment scripts on experiment hosts
  - Receive and record experiment artifacts

→ Build portable pos by separation of these roles





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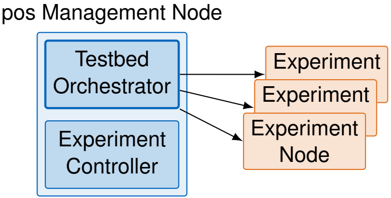
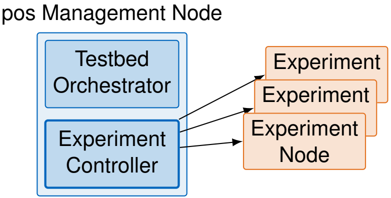




Thesis Chapter 2: pos — Implementing Portability

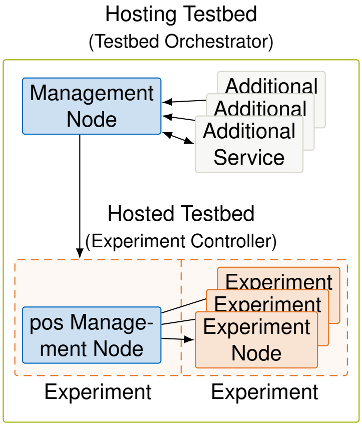
Approach:

- Portability by embedding pos in target testbed
- Distinction of hosting and hosted testbed:
  - Hosting Testbed → Testbed Orchestrator
  - Hosted Testbed → Experiment Controller
- pos and its workflow: Inside experiments of the hosting testbed

Advantages:

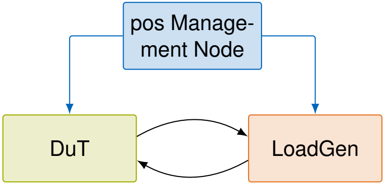
- Testbed-agnostic pos workflow
- Enables low-barrier experiment reproduction regardless of testbed
- Adaptable coupling: Hosted testbed could access additional services

→ Demonstrate portable-pos-enabled reproducible research



Setup:

- Select existing experiment and compare outcomes on different hosting testbeds
- Revisit experiment described by Gallenmüller et al. [4]:
  - MoonGen-based throughput measurement of Linux forwarder
  - Parameters: Packet size and packet rate
- Experiment repeated on:
  - Dedicated pos
  - Portable pos on CloudLab
  - In thesis: Portable pos on Chameleon
  - In thesis: Virtualized pos



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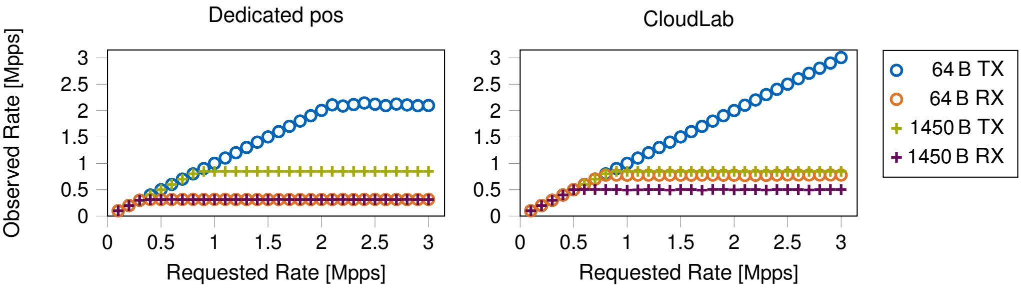
Thesis Chapter 2: pos — Validation of Portability: Results



Experiment Results:

- Hardware of DuT:
  - Dedicated pos: Intel Xeon E5-2640 v2 (2.0 GHz)
  - CloudLab: Intel Xeon E5-2660 v3 (2.2 GHz)

➔ Different max. forwarding rates (CPU frequency)

Portability of pos:

- Experiment scripts independent of hosting testbed
- Portability highlights possible replicability caveats

➔ Porting shows robustness of results

➔ Successful validation of portable pos approach

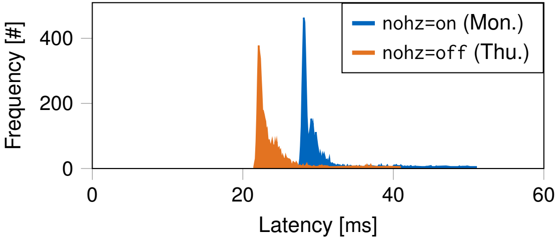
Motivation — Understanding Unreproducible Experiments

Recap Setup:

- Repeated black-box-based latency measurement of forwarding DuT via LoadGen
- Intermediate visualization of measurement output showed unexplained differences

Solution:

→ Different boot parameter toggled real-time-support state (nohz) of Linux kernel



Summary:

- Minor configuration change can imply significant DuT behavior change
- Preventable with portable pos — also ensures consistent boot parameters of experiment nodes

→ Experiment reflects behavior of programmable SDN switch

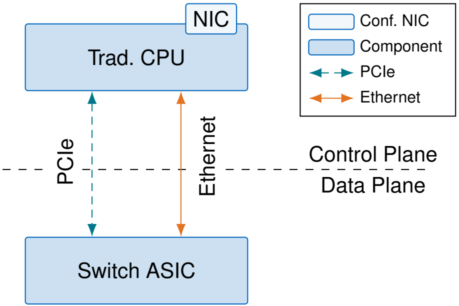
Programmable SDN Switch:

- Recently: P4-programmable SDN device
- Deployment target: High-throughput low-latency networks, e.g., data center

→ New switching architecture emerges

New Switching Architecture:

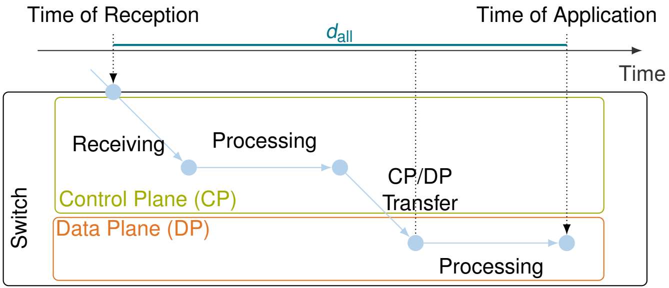
- Data plane: Dedicated ASIC for fast-paced traffic
- Control plane: Configuration changes with custom software via configuration NIC
- Communication via PCIe and Ethernet



→ How does information propagate from control to data plane?

Configuration Changes:

- Difference between time of reception and time of application
- Information propagation with different in-switch stages
  - within control plane
  - within data plane
- → Old configuration state may remain for some time



→ What are typical values and distributions of the control plane delay d_{all}?

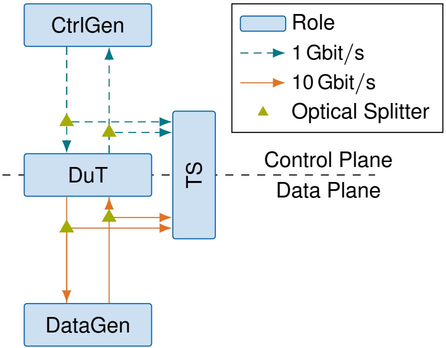
Research Question (RQ 5b): *Considering the control plane: to which extent does the implementation impact the overall system performance?*

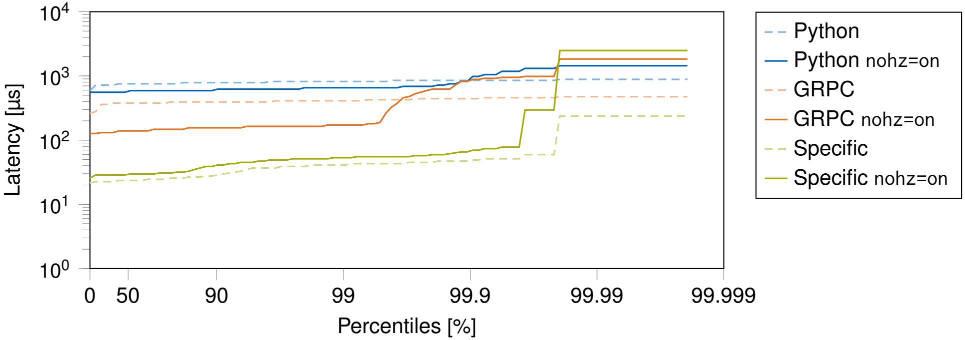
Investigated Parameters:

- Three control plane implementation variants: Python, GRPC, and Vendor-/Device-Specific
- System configuration: Default or performance-tuned (nohz=on)

Experiment Setup:

DuT	a programmable SDN switch
CtrlGen	issues configuration updates (rate: 100 Hz)
DataGen	transmits load traffic (rate: 6 Gbit/s)
TS	passively records traffic (duration: 50 s)





Experiment Results:

- Control plane update latency can reach ms range
- Generally, performance tuning improves impact

Research Question:

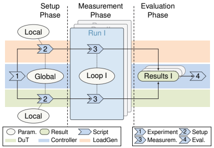
- Distinct performance difference between implementation

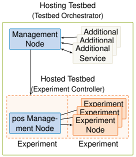
→ Informed choice and through tuning required

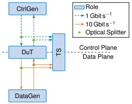
Conclusion

Motivation:

- Reproducibility as hard-to-attain goal
- Reproducibility as necessity
- Testbeds as means to reach reproducibility
- Previous works do not support reproducibility-by-design or are limited to specific testbed







Contributions:

- Methodology with reproducibility-by-design *(RQ 2b)*
- Methodology with portability-by-design *(RQ 2a)*
- Highlight on challenges and respective approaches for reproducible experiments, e.g., *(RQ 5b)*

Further Contributions:

- Identifying and addressing key challenges towards reproducibility (RQ 1a)
- Addresses approaches for reproducibility with complex or non-deterministic systems (RQ 3a)
- Discusses benefits of and concepts for reproducible software development (RQ 4a)