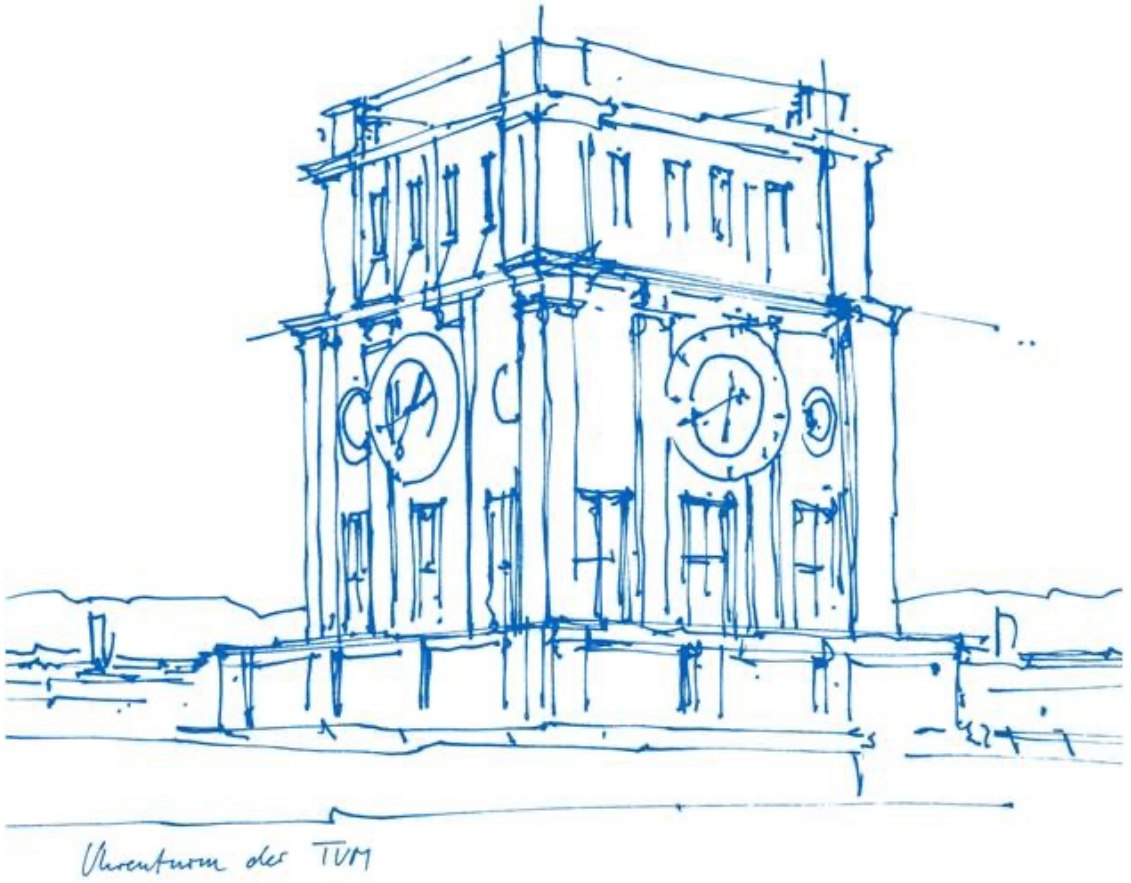
Chair of Connected Mobility & Chair of Network Architectures and Services
Department of Computer Engineering
TUM School of Computation, Information and Technology
Technical University of Munich

Simulation and Practice: A Hybrid Experimentation Platform for TSN

Marcin Bosk, Filip Rezabek, Johannes Abel, Kilian Holzinger,
Max Helm, Georg Carle, and Jörg Ott

Corresponding author:
Marcin Bosk – bosk@in.tum.de



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Academic Salon on High-Performance and Low Latency Networks and Systems

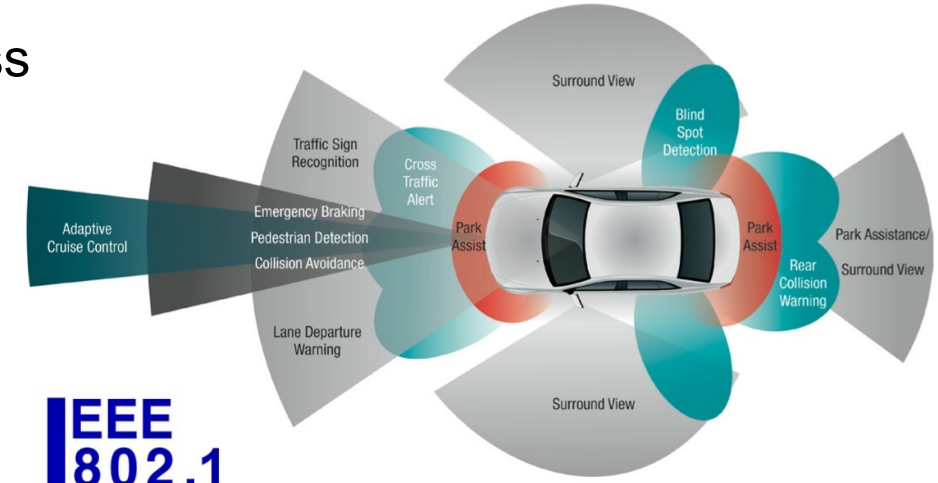
Garching bei München, Deutschland

Motivation
Real-Time and Time-Sensitive Systems

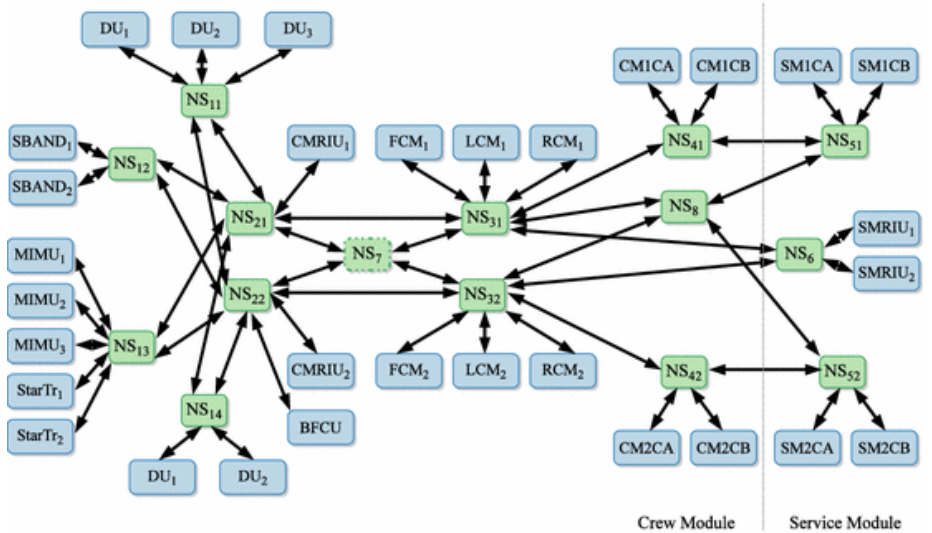
Bounded latency, low packet delay variation, and low packet loss

- Industrial Automation
- In-Vehicle Networks
- Spacecraft Networks

Usually used: CAN, LIN, FlexRay → Low bandwidth availability!



Source: Machine Design



Orion CEV Network; Source: https://doi.org/10.1007/s11241-014-9214-8

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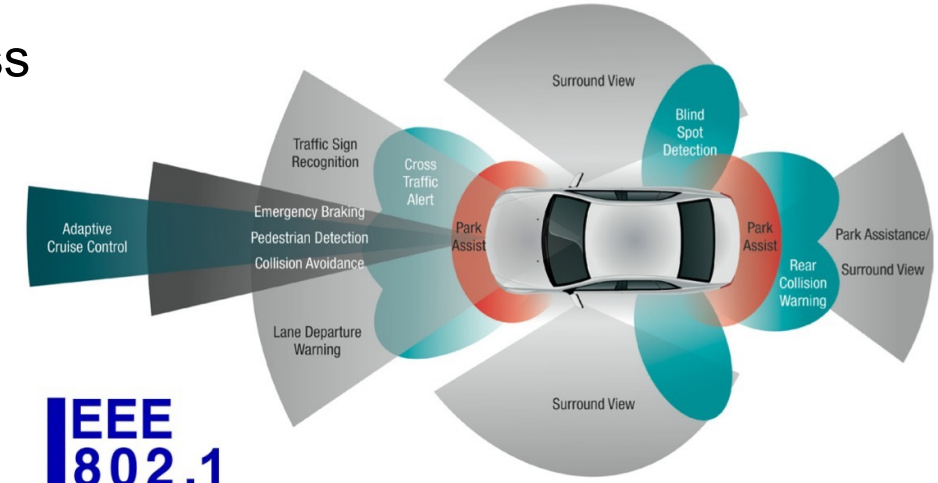
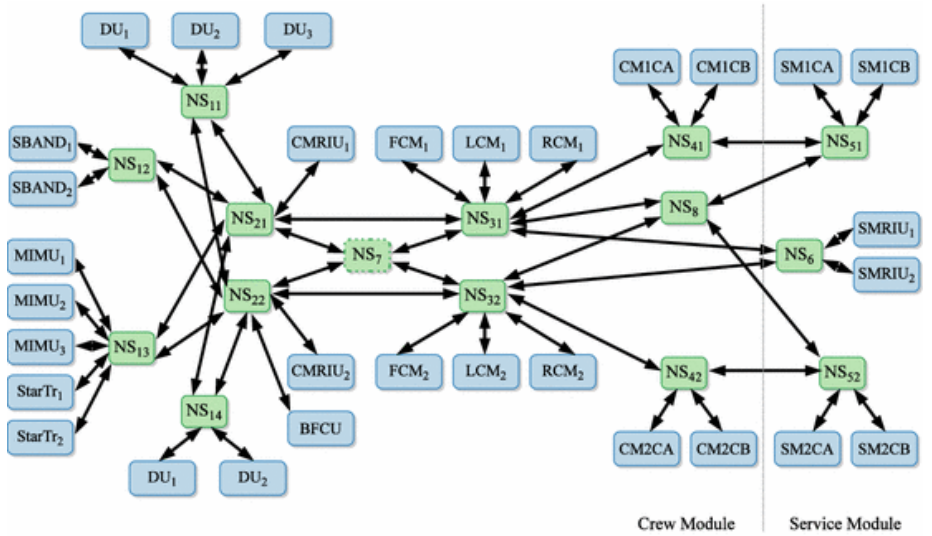


Source: Machine Design

Solution → **Ethernet with IEEE 802.1Q**

IEEE 802.1Q Time-Sensitive Networking (TSN) standards

- deterministic communication
- fulfillment of strict timing constraints
- high redundancy and fault tolerance



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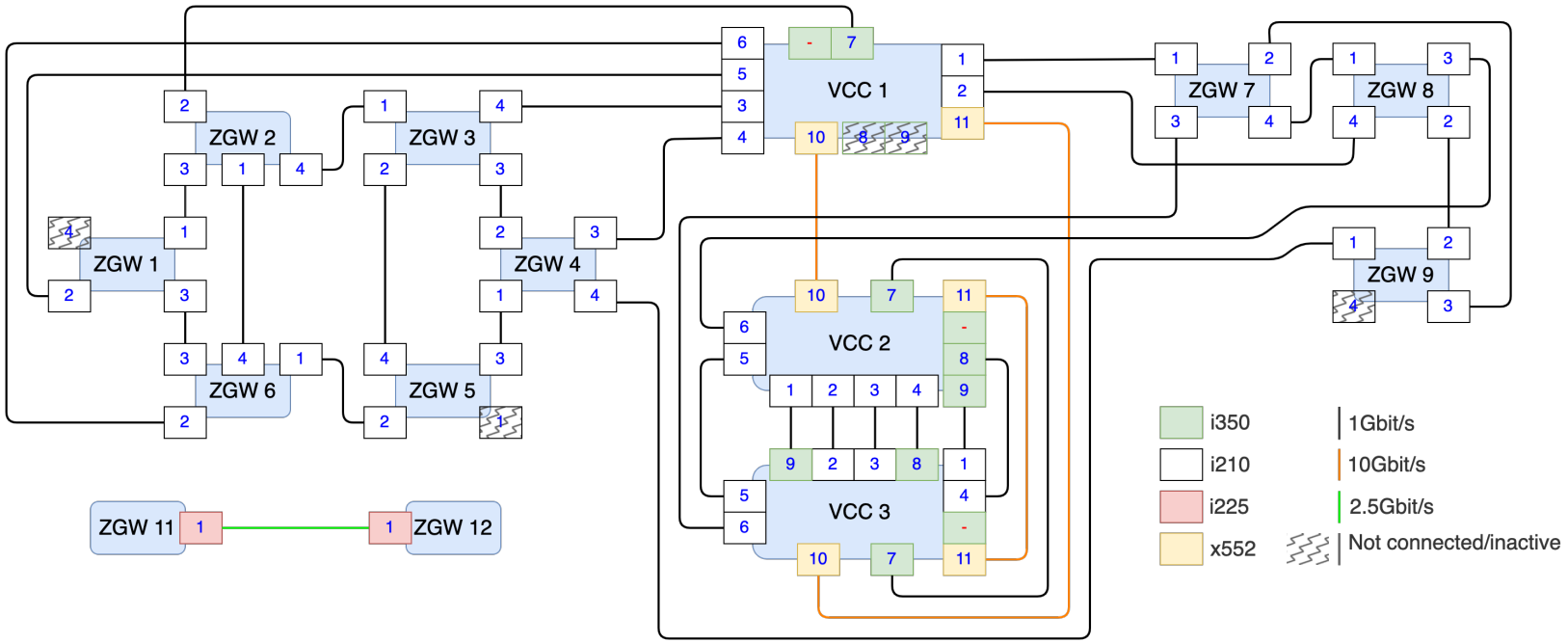
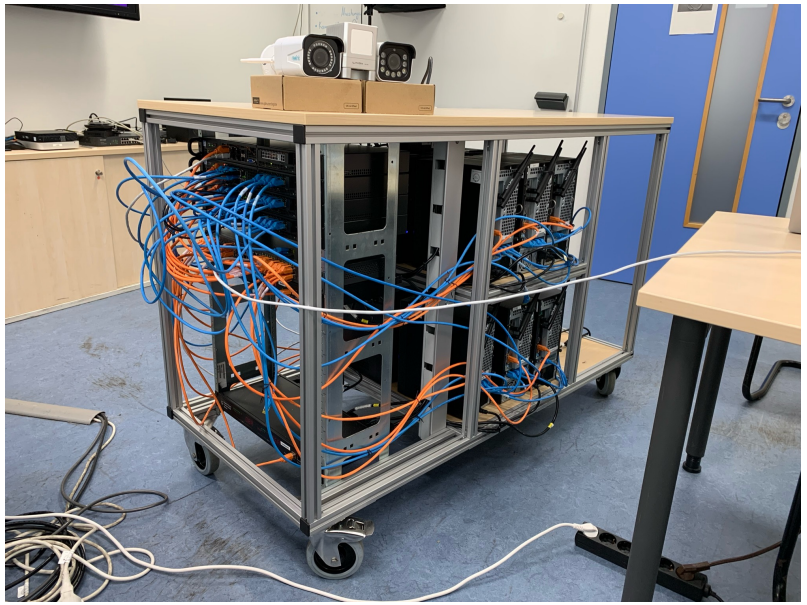
Motivation
The EnGINE Framework





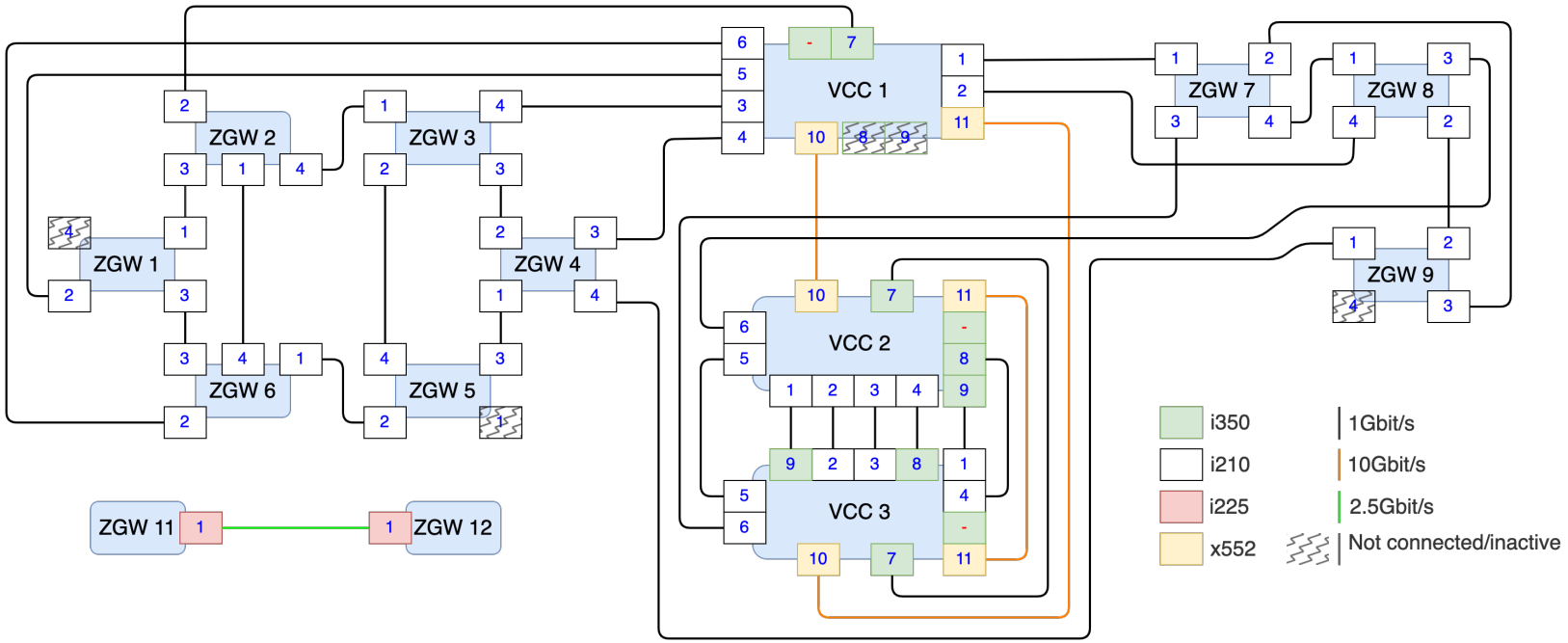
Automated experiment execution using Ansible

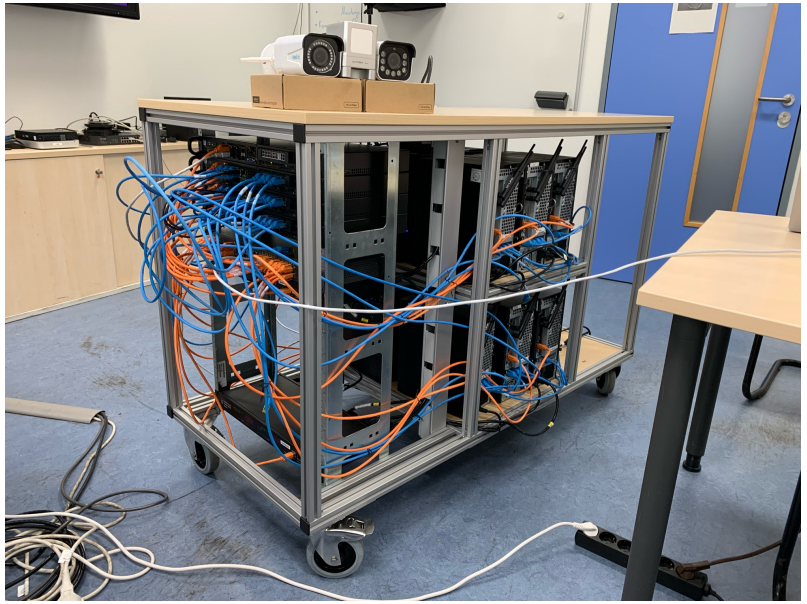
→ Tailored towards TSN experimentation

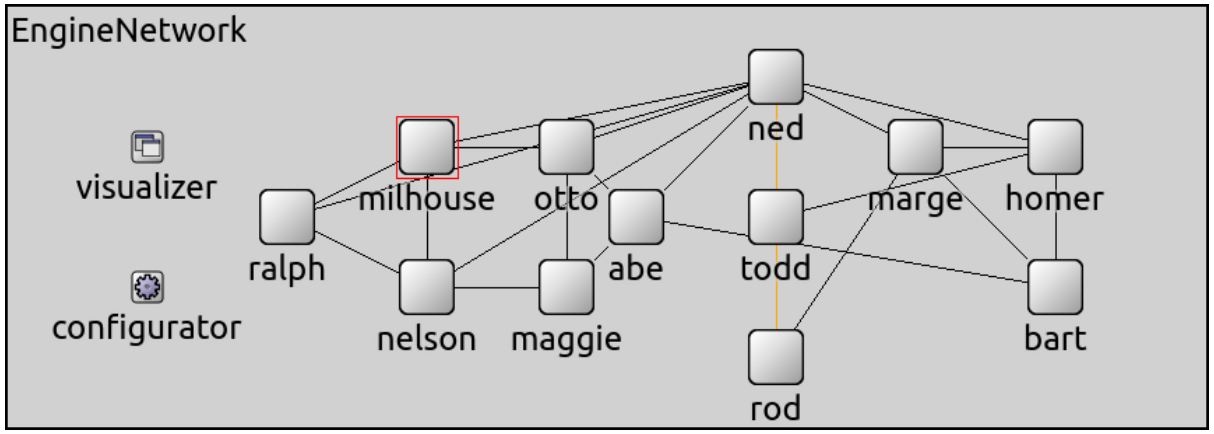
→ Easily extensible for other networking experiments

Rezabek, Filip, et al. **"EnGINE: Flexible research infrastructure for reliable and scalable time sensitive networks."** *Journal of Network and Systems Management* 30.4 (2022): 74.

Motivation
Practice and Simulation







Motivation
Practice and Simulation

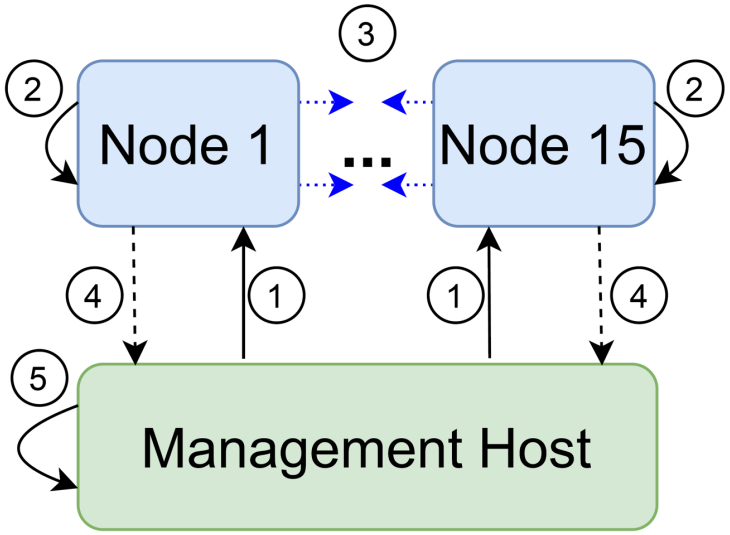
Approach	Availability	Reproducibility	Realism	Interpretability	Visibility	Scalability
Simulation	✓	✓	○	✓	✓	✓
Hardware	○	○	✓	○	○	○
Our Approach	✓	✓	✓	✓	✓	✓

EnGINE
Node Configuration and Management

Experiments orchestrated by a management host

Use pos to manage nodes, OS images, users, experiments, etc.

Reserve nodes using a calendar



1. Management host communicates with nodes
2. Nodes execute the tasks
3. Interact with other nodes
4. Store the collected artifacts
5. Process artifacts

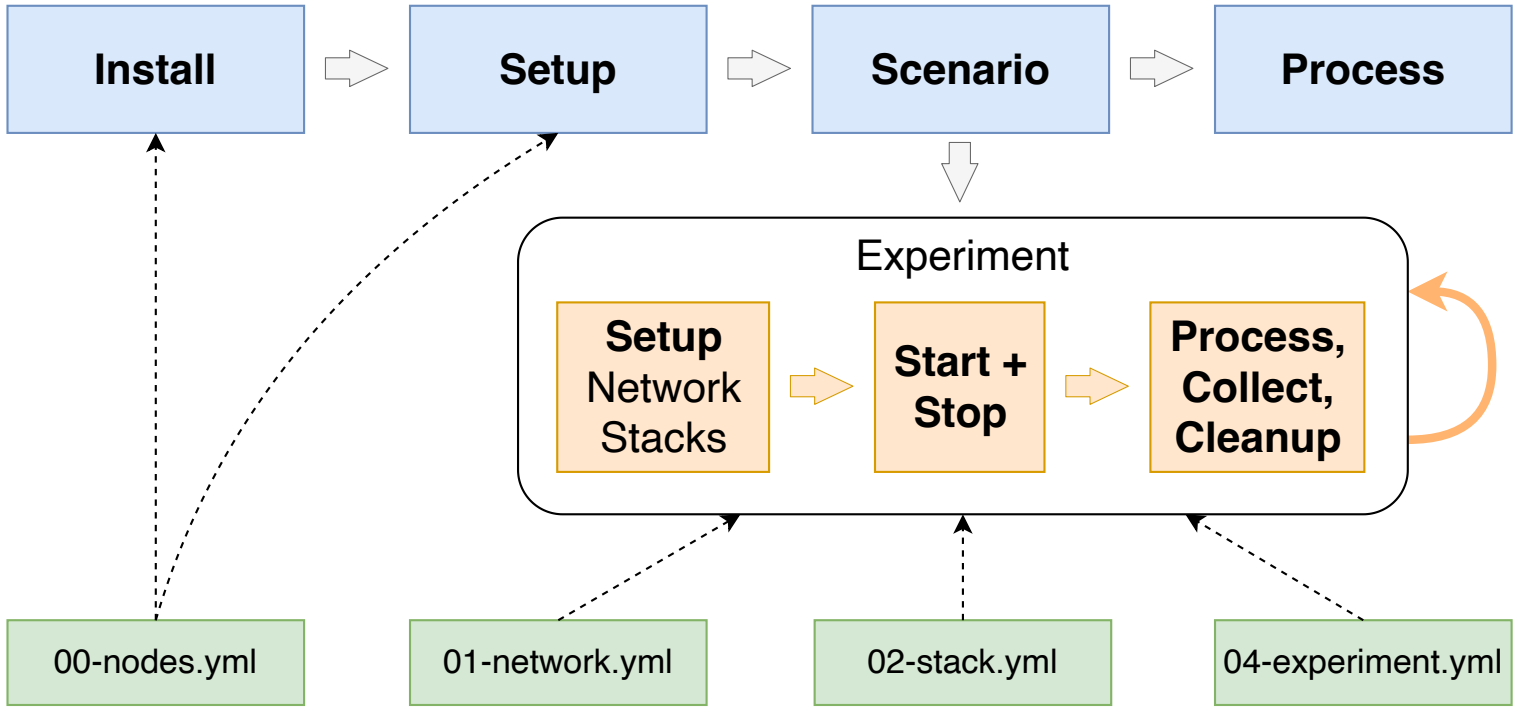
EnGINE
Experiment Orchestration

Based on Linux and open-source solutions, e.g.

- *Ansible* for experiment orchestration
- *Open vSwitch* for layer 2 control
- *Iperf3* for traffic generation
- *tcpdump* for artifact collection

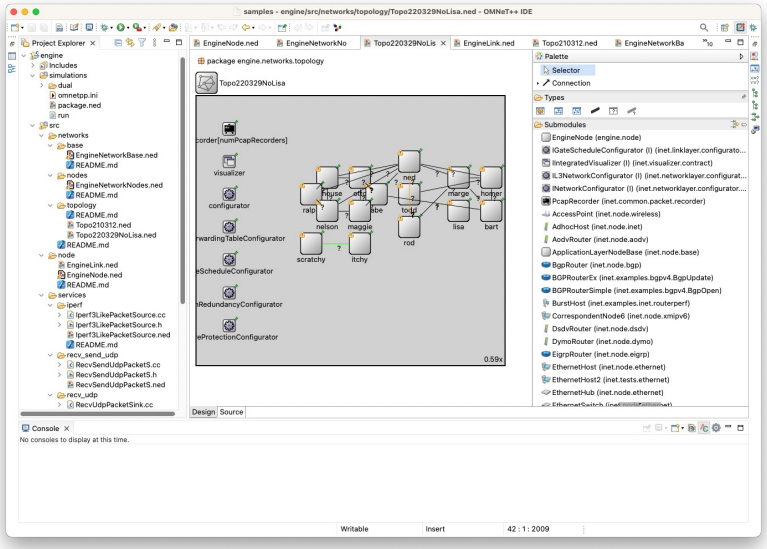
Four phases governing

- experiment preparation
- execution
- processing



Simulation Environment
OMNeT++

Open-source, discrete-event simulator for networks written in C++



Highly modular

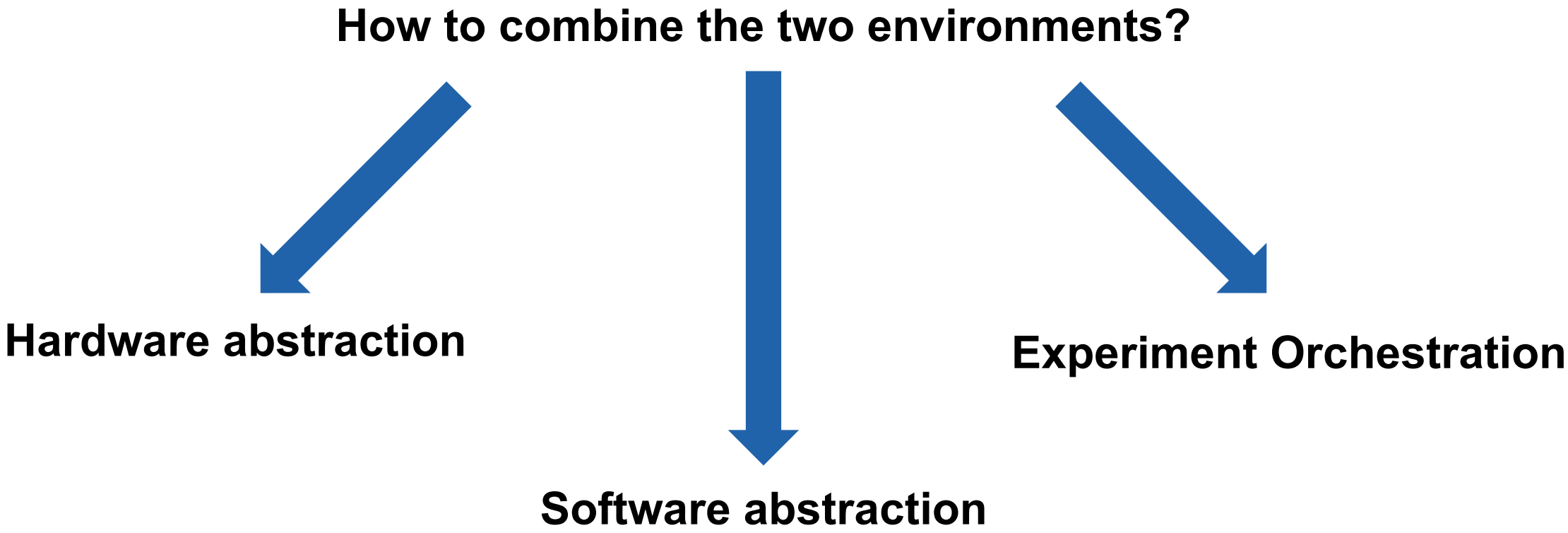
- Functionality implemented via NED modules and C++ classes
- Experiments configured via INI files
- New functionality added via frameworks

Support for computer networks via the INET Framework

- Full IP network stack
- With recent updates, also TSN standards
- Traffic generation and packet trace recording

```
Running simulation...
** Event #0   t=0   Elapsed: 2.8e-05s (0m 00s)  0% completed  (0% total)
     Speed:     ev/sec=0   simsec/sec=0   ev/simsec=0
     Messages:  created: 3460   present: 3460   in FES: 189
** Event #84736   t=0.599482299676   Elapsed: 2.00164s (0m 02s)  0% completed  (0% total)
     Speed:     ev/sec=42334.3   simsec/sec=0.299499   ev/simsec=141350
     Messages:  created: 44657   present: 5032   in FES: 311
** Event #176128   t=0.921412774736   Elapsed: 4.00184s (0m 04s)  0% completed  (0% total)
     Speed:     ev/sec=45691.5   simsec/sec=0.160949   ev/simsec=283887
     Messages:  created: 89293   present: 6032   in FES: 390
** Event #269312   t=1.20079146366   Elapsed: 6.00193s (0m 06s)  0% completed  (0% total)
     Speed:     ev/sec=46589.9   simsec/sec=0.139683   ev/simsec=333540
     Messages:  created: 134431   present: 6834   in FES: 381
** Event #373760   t=1.530669969145   Elapsed: 8.0043s (0m 08s)  0% completed  (0% total)
     Speed:     ev/sec=52162.2   simsec/sec=0.164744   ev/simsec=316626
     Messages:  created: 184819   present: 7000   in FES: 385
** Event #478720   t=1.884305188794   Elapsed: 10.008s (0m 10s)  0% completed  (0% total)
     Speed:     ev/sec=52382.4   simsec/sec=0.176489   ev/simsec=296803
     Messages:  created: 235861   present: 7069   in FES: 361
** Event #574208   t=2.195695648624   Elapsed: 12.0103s (0m 12s)  0% completed  (0% total)
     Speed:     ev/sec=47690   simsec/sec=0.155519   ev/simsec=306650
     Messages:  created: 282376   present: 7578   in FES: 380
```

How to combine the two environments?


How to combine the two environments?
Hardware abstraction
Software abstraction
Experiment Orchestration

Design
Hardware Abstraction in OMNeT++ Simulator

EnGINE Node modules realize the hardware devices

Traffic generation applications on INET's TSN devices

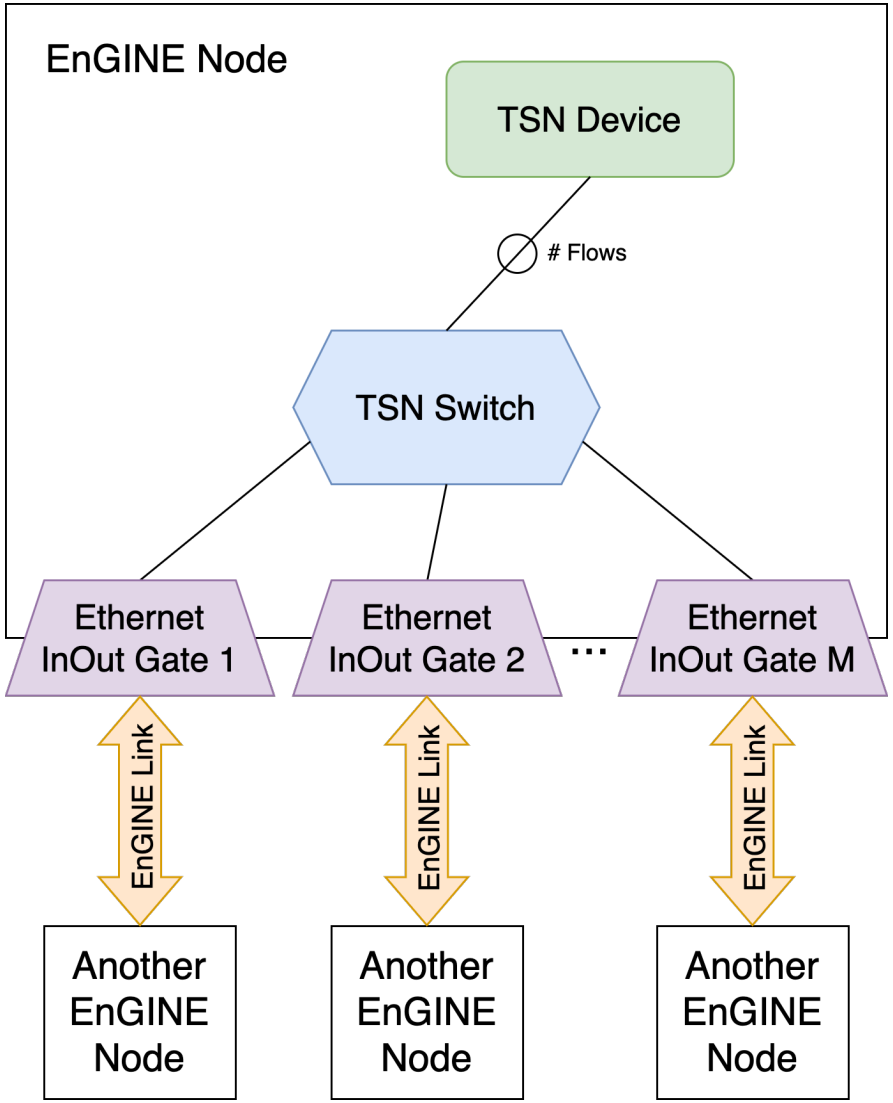
TSN switch abstracts Linux networking and OpenVSwitch

Ethernet InOut gates abstract physical interfaces

- TSN traffic shaping realized with INET shapers
- *Ieee8021qTimeAwareShaper* for IEEE 802.1Qbv
- *Ieee8021qCreditBasedShaper* for IEEE 802.1Qav

EnGINE Links abstract hardware ethernet connections

- Connections within EnGINE node introduce no delay and have unlimited bitrate



Design
Software Abstraction

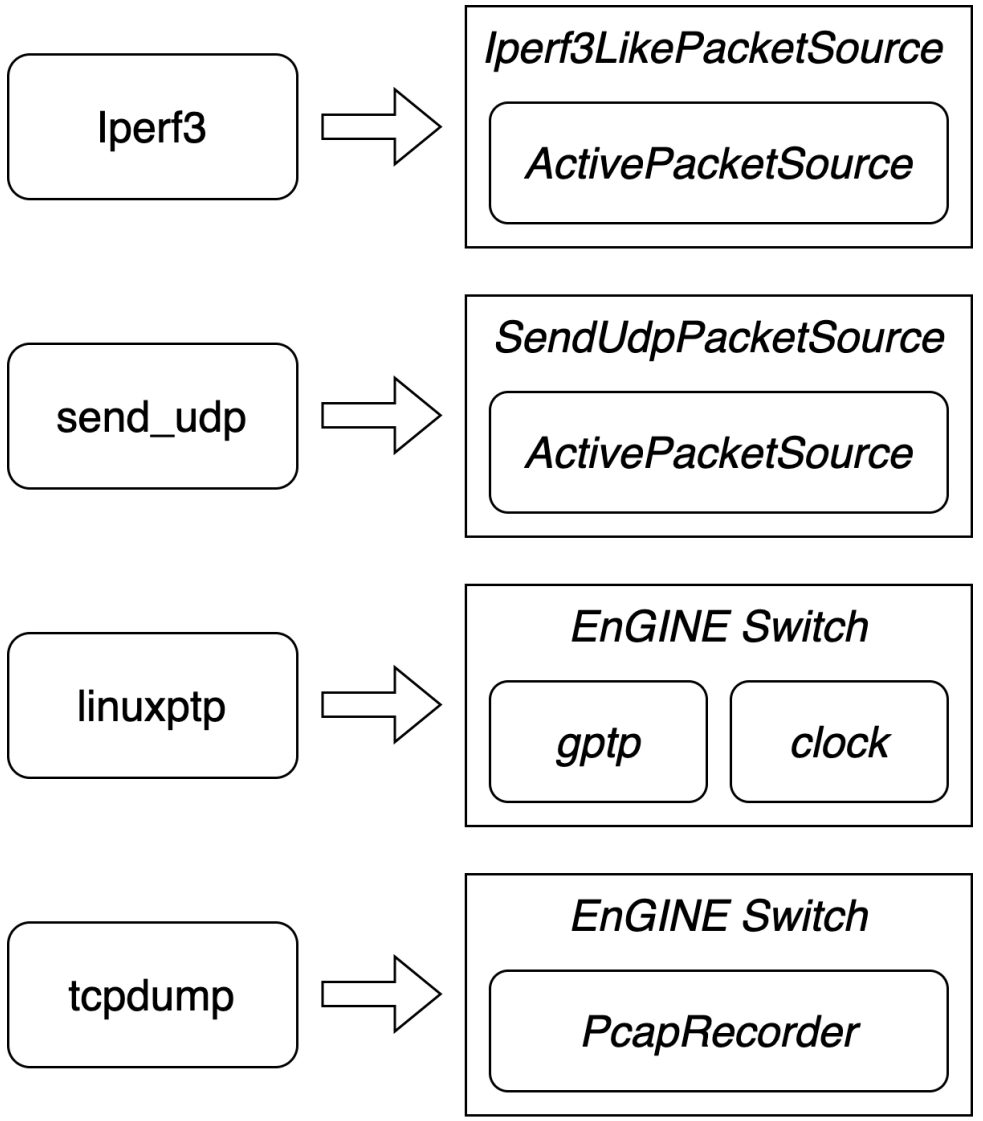
Traffic generation, recording, and time synchronization

Abstraction based on existing OMNeT++ modules

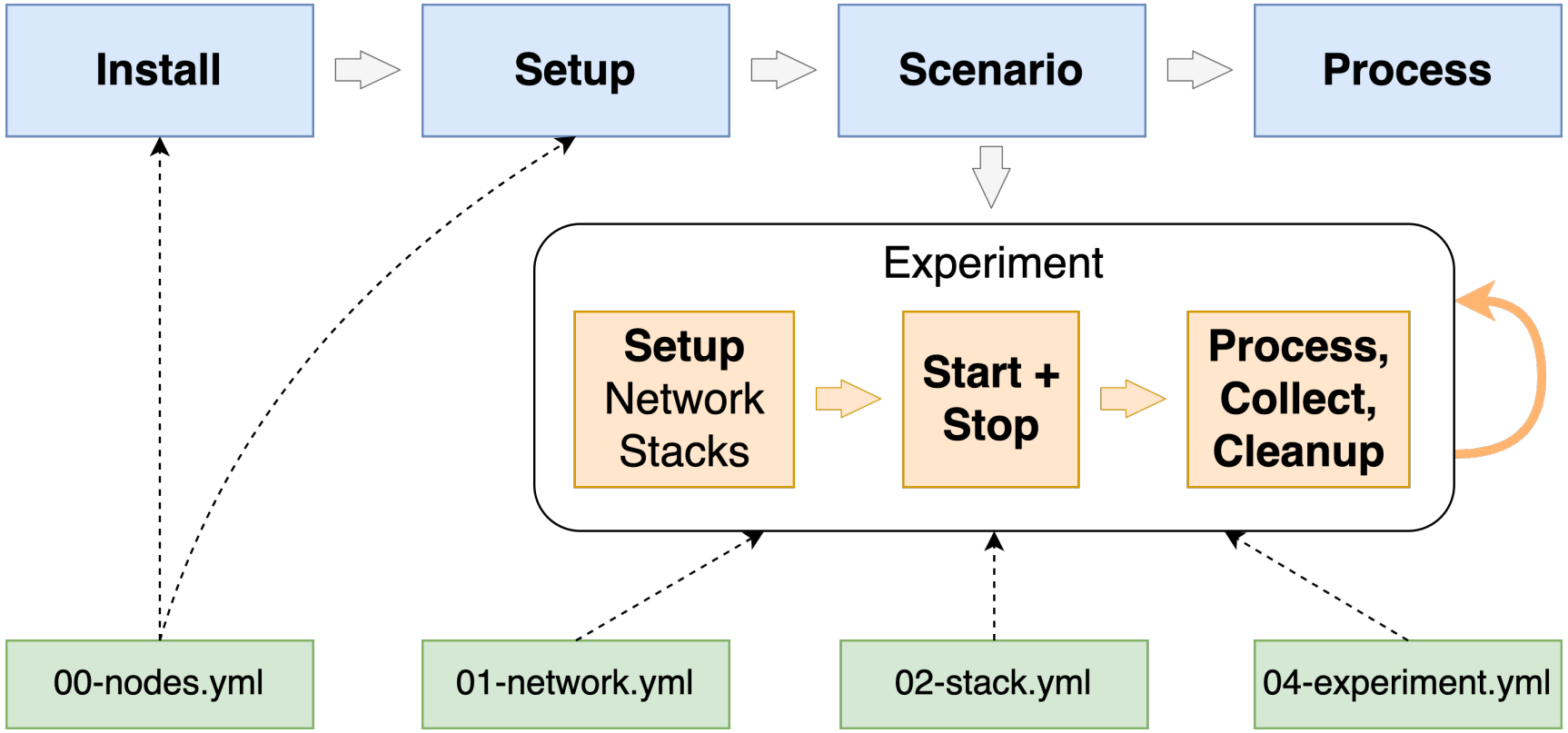
- Customized implementation of traffic sources
- Default INET *UdpSinkApp* used as traffic sinks

Additional insights via OMNeT++ statistics, e.g.

- Queue level
- CBS credit over time



Design
Experiment Configuration and Orchestration



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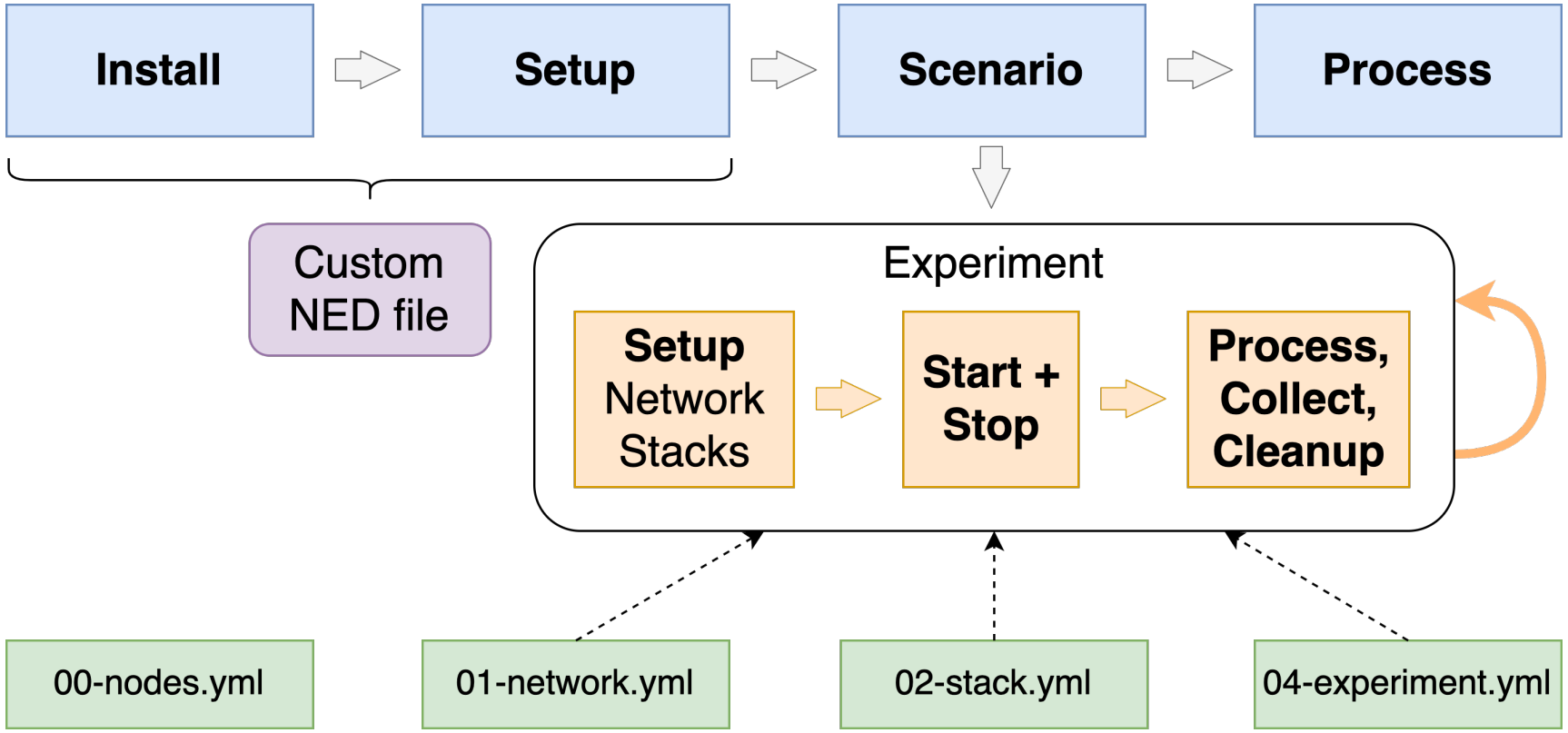

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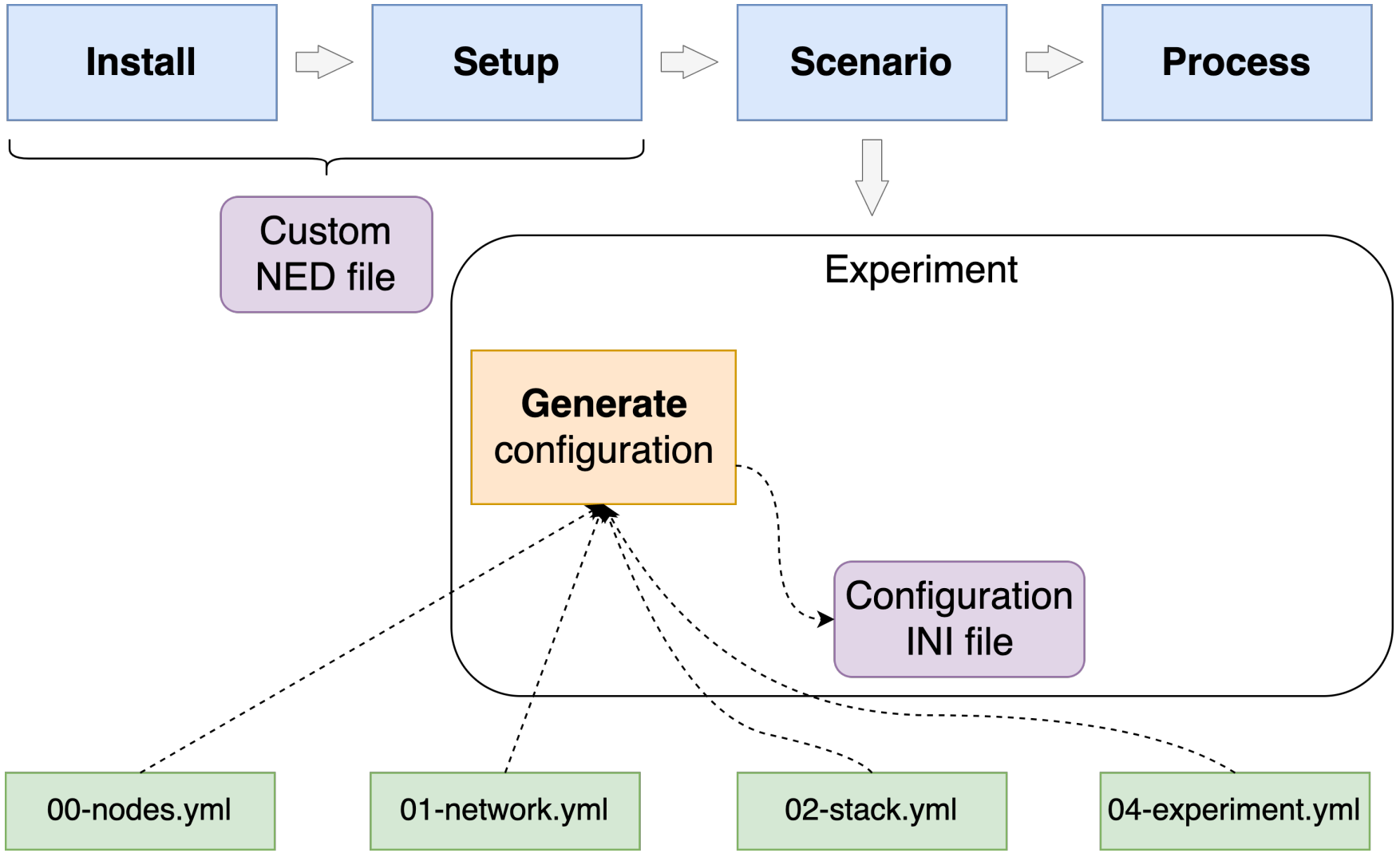

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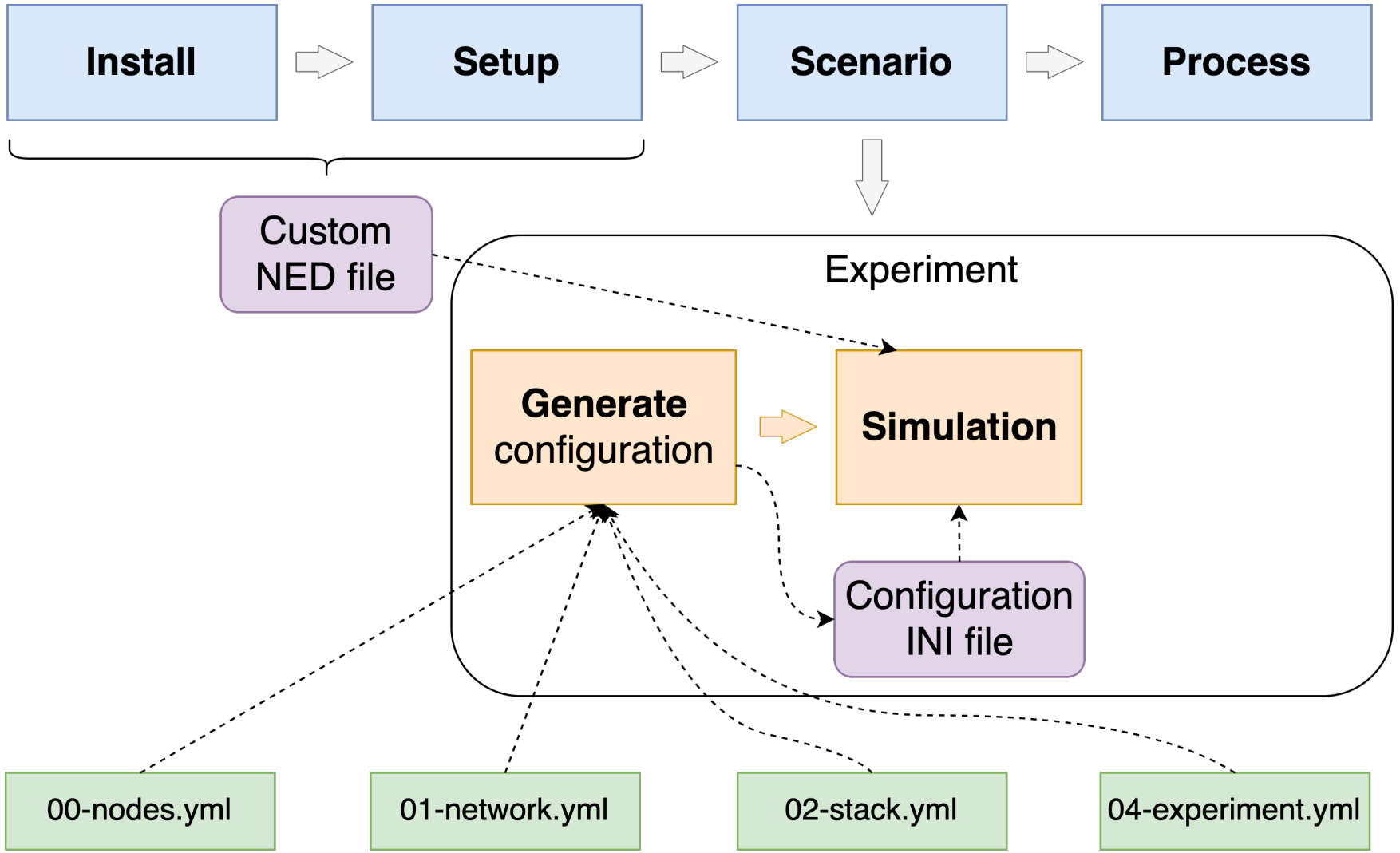

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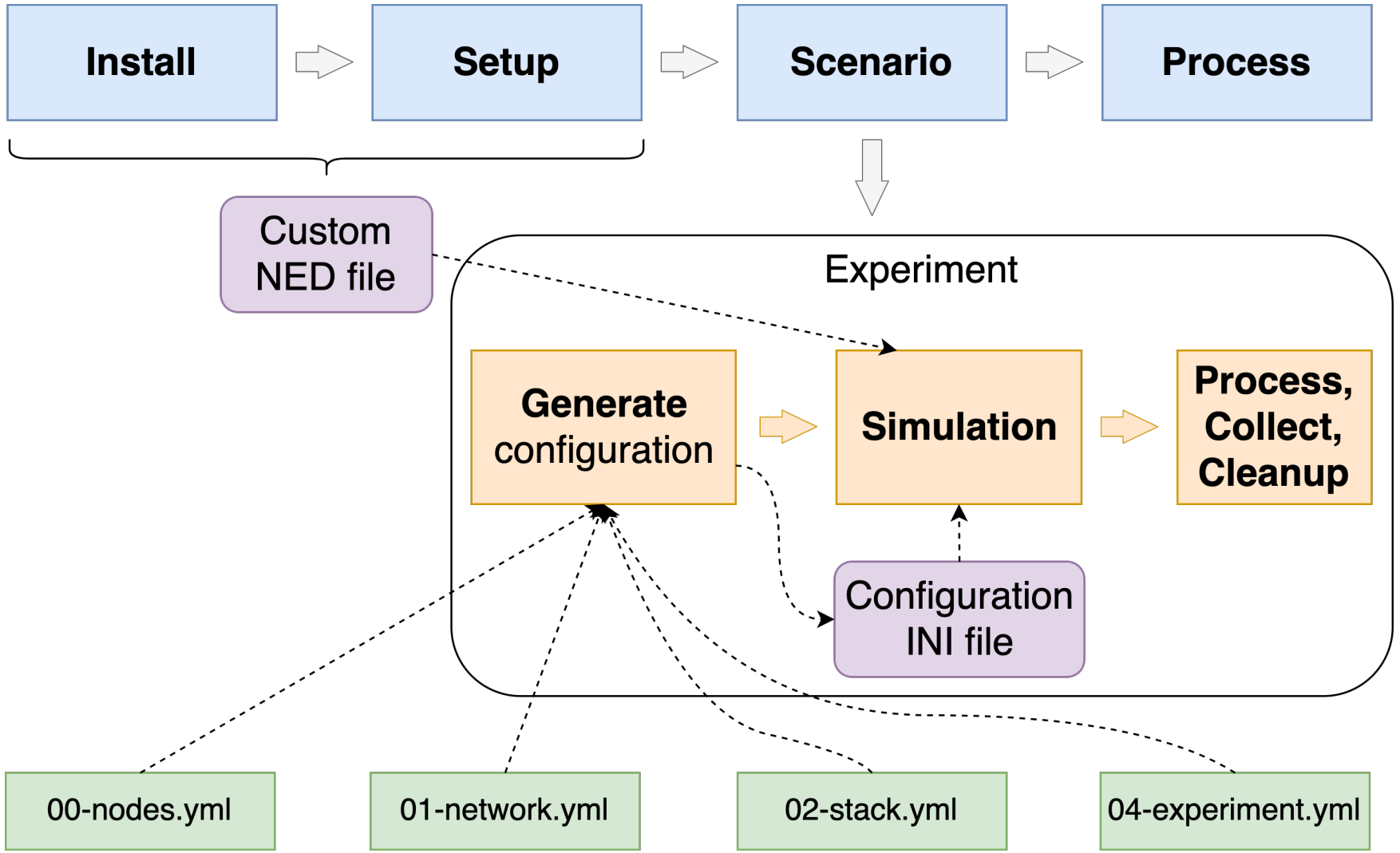
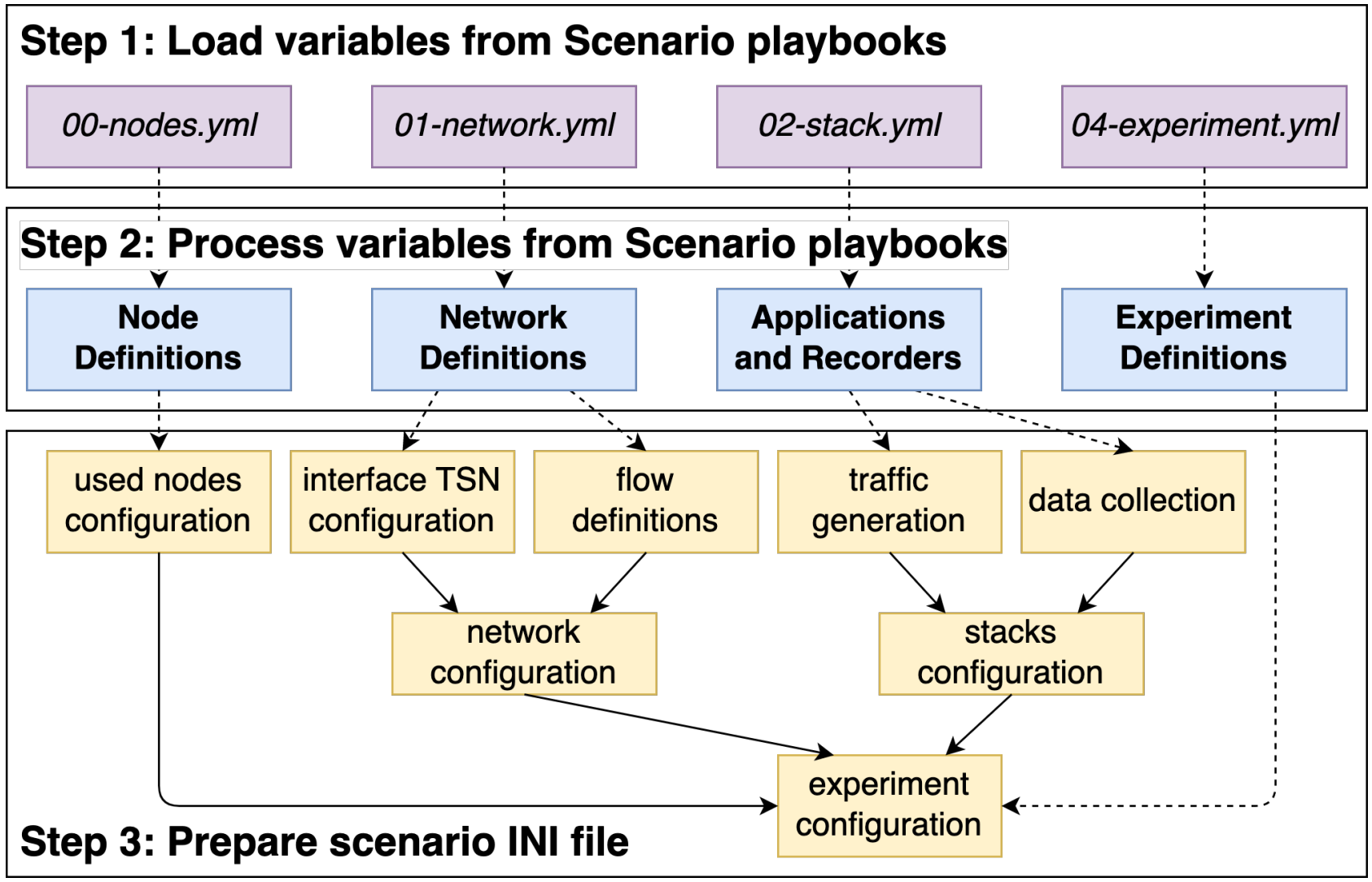


Design
OMNeT++ Configuration Generation



Benefits

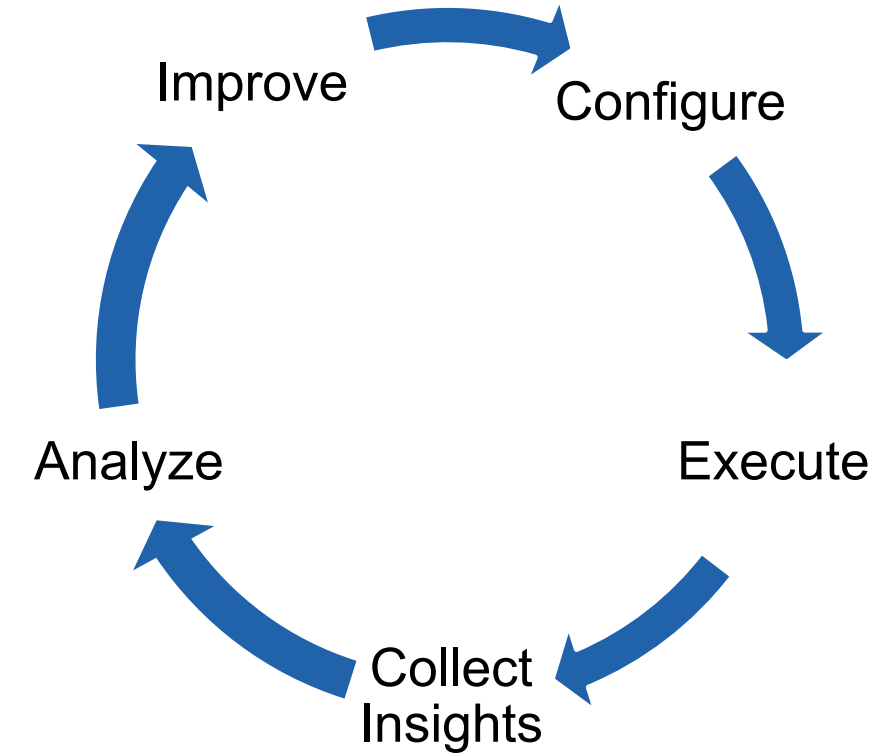
One configuration for HW-based and simulated experiments

Additional insights

Ability to validate simulation implementations

Lower bar of entry to experimentation

Foundation for Digital Twin development



EnGINE
Framework

Evaluation
Experiment Design

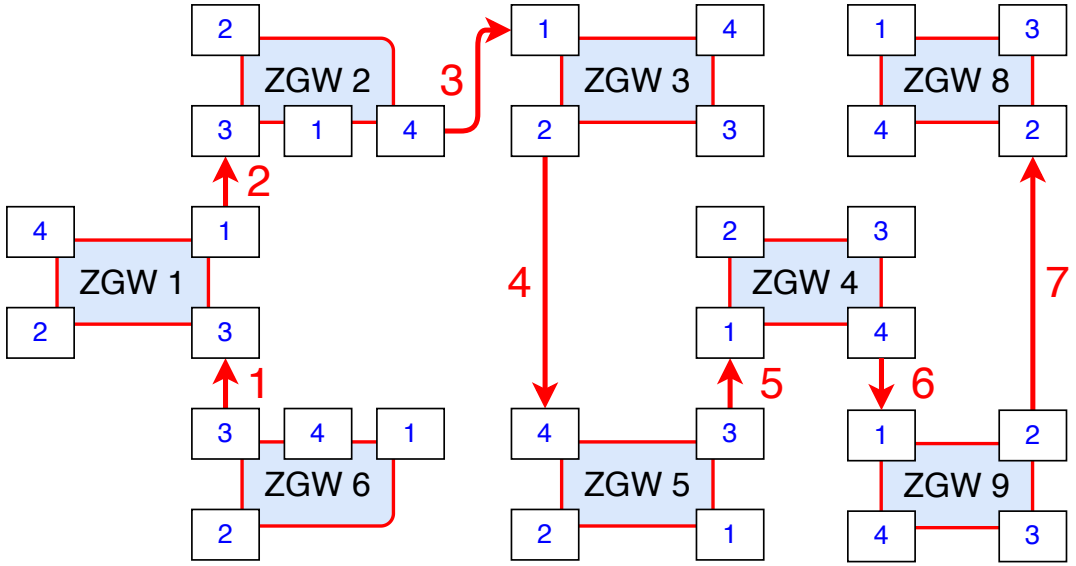
Goal: Compare simulation results with HW-based ones

Use EnGINE methodology for experiment design

- Consider a 7-hop network
- Include cross-traffic

Three experiments testing the functionality of

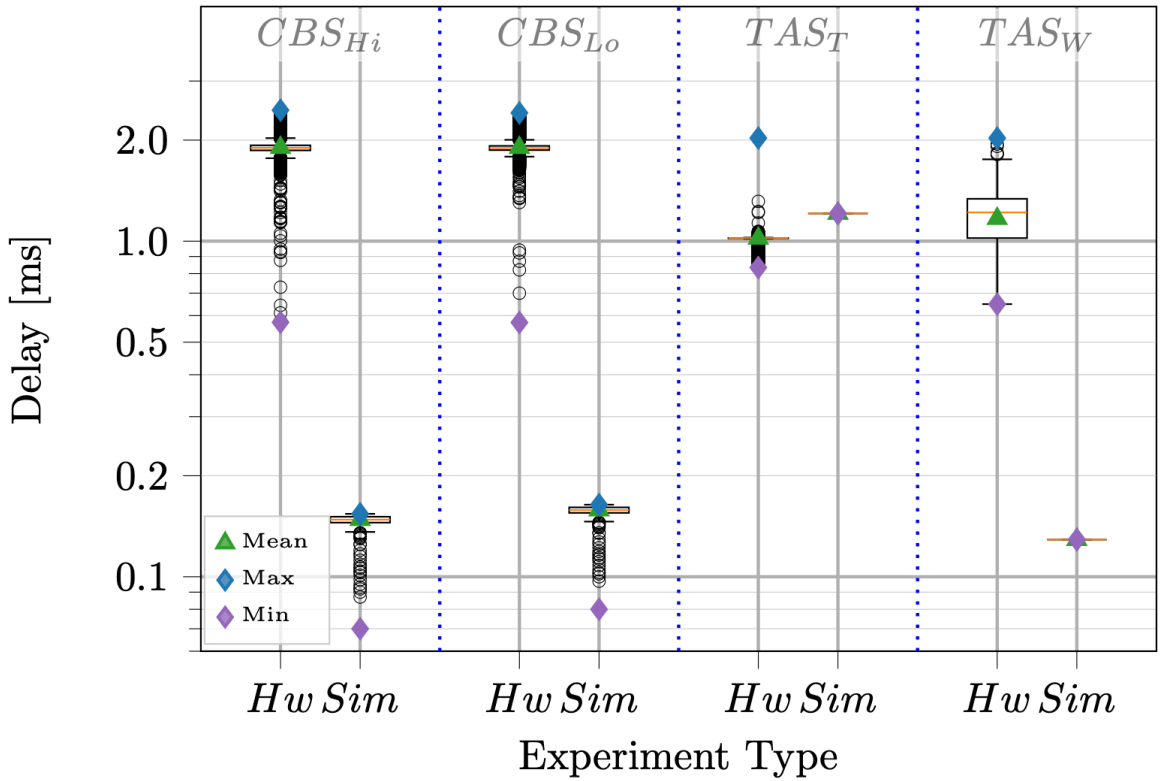
- Credit-Based Shaper (CBS)
- Time-Aware Shaper (TAS)

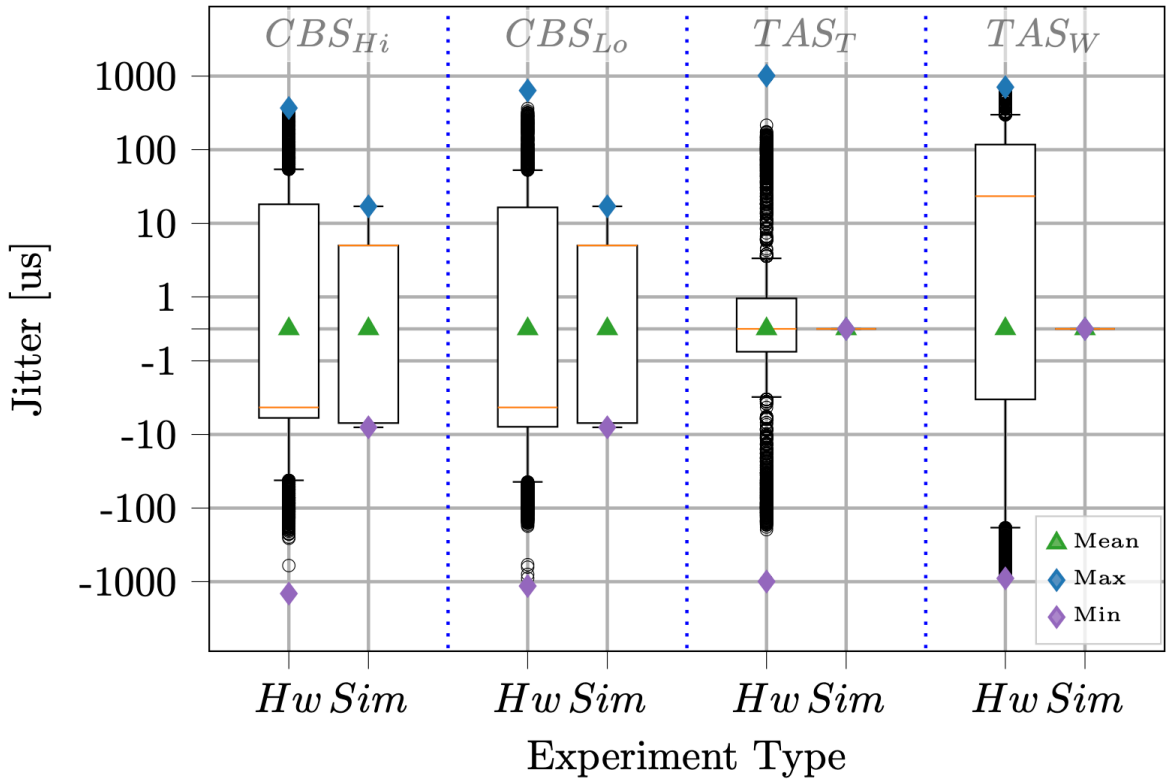


Bosk, Marcin, et al. **"Methodology and Infrastructure for TSN-Based Reproducible Network Experiments."** *IEEE Access* 10 (2022): 109203-109239.

Experiment	CBS	TAS_T	TAS_W
Traffic Bitrate	2x 100Mbps	100Mbps	100Mbps
Priority	3, 2	3	3
Traffic Shaping	2x CBS @ 100Mbps	TAS @ 1ms window	TAS @ 100us window

Evaluation
Results





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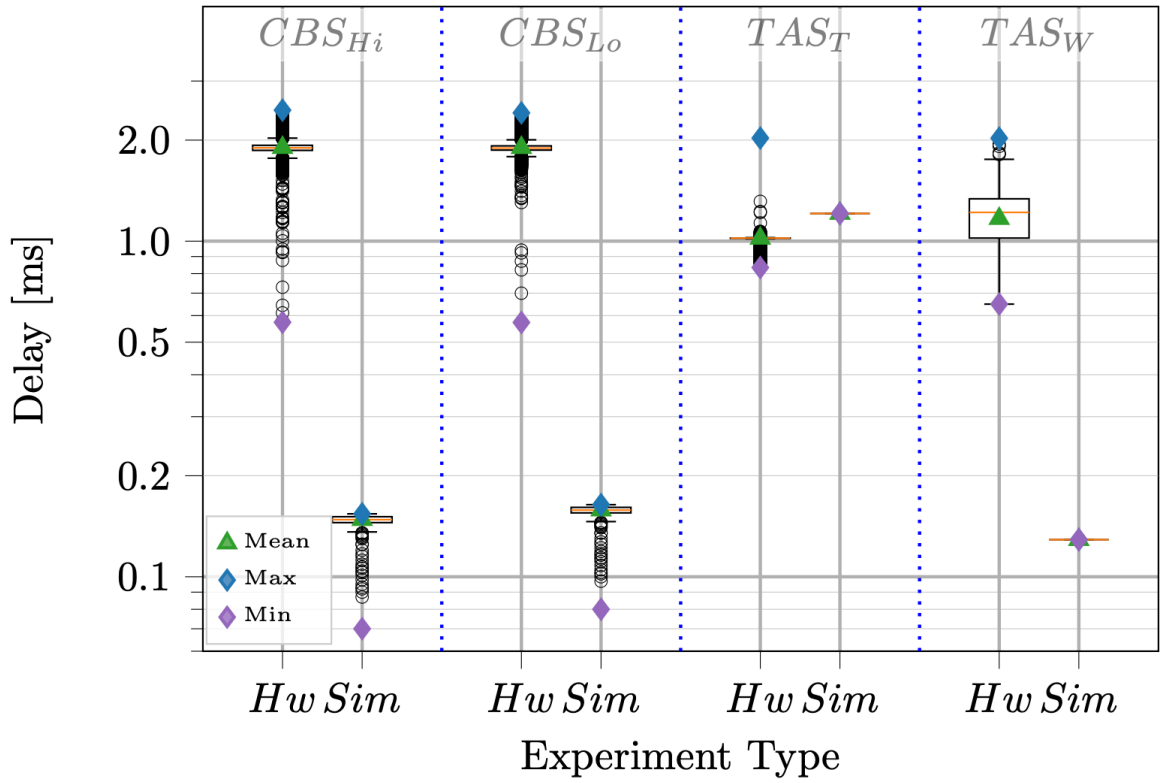
Evaluation
Summary

Discrepancy between simulation and HW

Processing delay not considered in simulation

Clock drift and jitter not modelled

Requires further development and modelling



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Conclusion

An approach combining HW-based experiments and simulation using

- The EnGINE experimental framework for HW-based TSN experiment
- OMNeT++ discrete event simulator

Ability to execute the same experiments in HW and simulation

Availability	Reproducibility	Realism	Interpretability	Visibility	Scalability
✓	✓	✓	✓	✓	✓

Collaboration platform – configure once, let everyone test

Need for further work to address simulation and HW result discrepancy!

Thank You!

EnGINE Framework

Marcin Bosk
@OrBoskey
@bosk-m
bosk@in.tum.de

Bosk, M., Rezabek, F., Abel, J., Holzinger, K., Helm, M., Carle, G., & Ott, J. (2023, June). **Simulation and Practice: A Hybrid Experimentation Platform for TSN.** In *2023 IFIP Networking Conference (IFIP Networking)* (pp. 1-9). IEEE.