Chair of Network Architectures and Services
School of Computation, Information and Technology
Technical University of Munich

A High-Fidelity Virtualized Digital Twin System for ISP Core Networks

Johannes Späth, Georg Carle

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University of Augsburg, Germany

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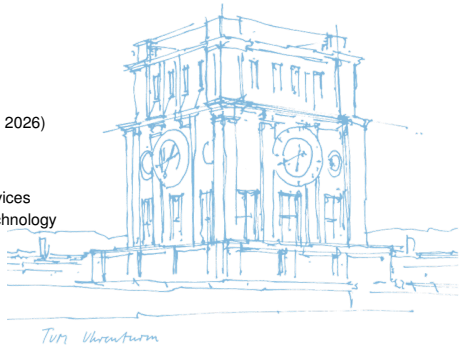

Why use digital twins for ISP core networks?

- ISP core networks are **critical infrastructure**
- Failures lead to service disruptions and can have economic impact
  → Fault management is a central concern

[1] Source: https://www.degrouptest.com/actualite/sabotage-des-reseaux-fibre-de-plusieurs-operateurs-huit-departements-touches

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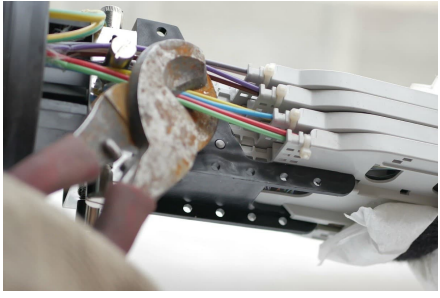

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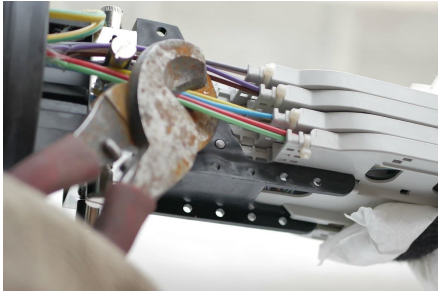

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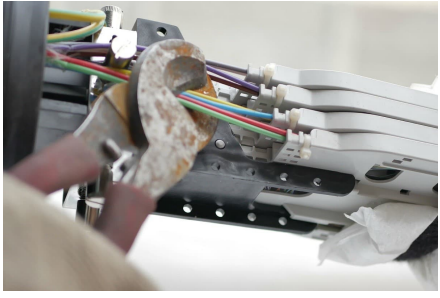
- Digital twins are a "copy" of the production network
  → Offer a **safe environment** for what-if analysis and incident dataset generation



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Requirements

- Realistic network environment
- High fidelity (different types of incidents across different ISO/OSI layers, control plane/data plane, . . .)
- Standardized data model
- Extensibility/flexibility

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$\Rightarrow$ An extensible, high-fidelity digital twin system capable of accurately reproducing ISP core network behavior

Related Work

Network Digital Twins

- *Simulation*: **OMNeT++** [1], **ns-3** [2]
- *Emulation*: **Mininet** [3]
- *Virtualization*: **HVNet** [4]
- *Graph Neural Networks*: **RouteNet** [5], **TwinNet** [6]

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[1] A. Varga and R. Hornig. "An Overview of the OMNeT++ Simulation Environment". 2010.

[2] G. F. Riley and T. R. Henderson, "The ns-3 Network Simulator". 2010.

[3] B. Lantz, B. Heller, and N. McKeown, "A Network in a Laptop: Rapid Prototyping for Software-Defined Networks". 2010.

[4] F. Wiedner, M. Helm, S. Gallenmüller, and G. Carle, "HVNet: Hardware-Assisted Virtual Networking on a Single Physical Host". 2022.

[5] K. Rusek, J. Suárez-Varela, P. Almasan, P. Barlet-Ros, and A. Cabellos-Aparicio. "RouteNet: Leveraging Graph Neural Networks for Network Modeling and Optimization in SDN". 2020.

[6] M. Ferriol-Galmés, J. Suárez-Varela, J. Paillissé, X. Shi, S. Xiao, X. Cheng, P. Barlet-Ros, A. Cabellos-Aparicio. "Building a Digital Twin for Network Optimization Using Graph Neural Networks". 2022.

YANG Modeling/Models

How to collect data? What formats to use?

YANG modeling language (RFC 7950)

- Features
  - **Hierarchy modeling** (containers, lists, leaf nodes)
  - **Extensibility** (modules, submodules, augmentations)
  - **Strong typing** (keys, references, identifiers)

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  - **Hierarchy modeling** (containers, lists, leaf nodes)
  - **Extensibility** (modules, submodules, augmentations)
  - **Strong typing** (keys, references, identifiers)
- IETF-standardized models exist for large parts of the ISO/OSI stack
- Standardization also pushed by ISPs
- Protocols exist to retrieve and manipulate device data defined by YANG models (NETCONF/RESTCONF)

```
module: ietf-l3-unicast-topology
  augment /nw:networks/nw:network/nw:network-types:
  +--rw l3-unicast-topology!
  augment /nw:networks/nw:network:
  +--rw l3-topology-attributes
     +--rw name?   string
     +--rw flag*   l3-flag-type
  augment /nw:networks/nw:network/nw:node:
  +--rw l3-node-attributes
     <...>
  augment /nw:networks/nw:network/nt:link:
  +--rw l3-link-attributes
     <...>
  augment /nw:networks/nw:network/nw:node/nt:termination-point:
  +--rw l3-termination-point-attributes
     +--rw (termination-point-type)?
        +--:(ip)
        |  +--rw ip-address*       inet:ip-address
        +--:(unnumbered)
        |  +--rw unnumbered-id?    uint32
        +--:(interface-name)
        +--rw interface-name?   string
```

L3 Topology YANG Model (RFC 8346)

YANG Modeling/Models

Number of Dimensions in YANG Models for a Simple Topology

Given a simple **six-router topology**

L2 Topology (RFC 8944)

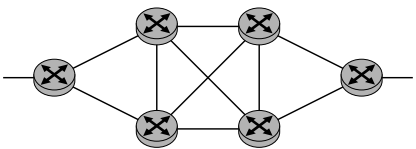
	`int`	`bool`	`custom`	`identifier`
Per router	0	0	0	1
Per interface	0	0	1	1
Per link	0	0	0	5
In total	0	0	22	88

L3 Topology (RFC 8346)

	`int`	`bool`	`custom`	`identifier`
Per router	0	0	0	1
Per interface	0	0	2	1
Per link	0	0	0	5
In total	0	0	44	88

Interface Parameters (RFC 8343)

	`int`	`bool`	`custom`	`identifier`
Per interface	16	11	20	0
In total	352	242	440	0



In total: **1276 parameters** for three YANG models

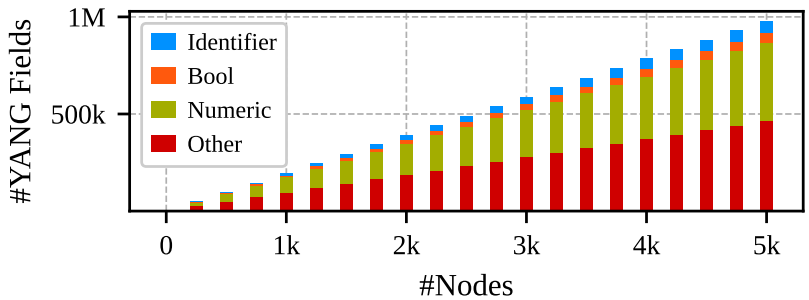
- 352 `int`
- 242 `bool`
- 506 `custom`
- 176 `identifier`

⇒ Typically larger networks and more YANG models!

YANG Modeling/Models

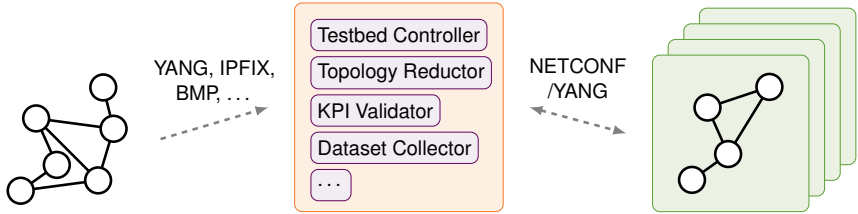
Number of YANG Fields for Large Topologies

- RFC 8944 + RFC 8346 + RFC 8343
- Random Barabási-Albert graphs with increasing number of nodes
- Fields grouped by data type



Approach

Overview



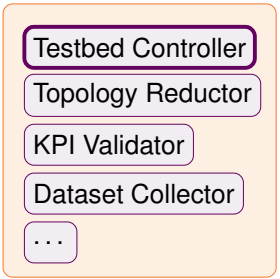
- State of real network is exported using standardized mechanisms like YANG-modeled data, IPFIX, and BMP
- Interaction with DT networks is done via NETCONF/YANG
- DT Manager is central component that gathers data from real network and interacts with the DT networks
  → Extensible on demand

Approach

Digital Twin Manager Components

Testbed Controller

- Orchestration of the virtualized router replicas
- Network topology control
- Configuration management



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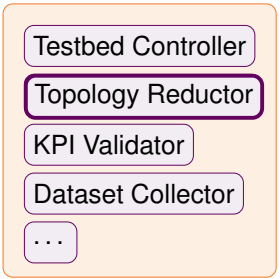
Topology Reductor

- Sampling and/or aggregation of the original network topology
- Flow- and link-rate reduction
- Based on pre-defined goals and available resources



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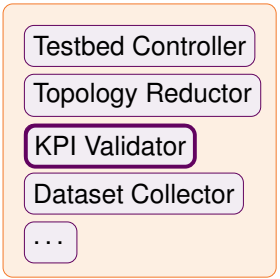
KPI Validator

- Evaluates the current state of the networks (both production and DTs)
- Checks that Key Performance Indicators (KPIs) are met



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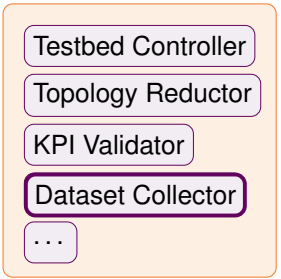
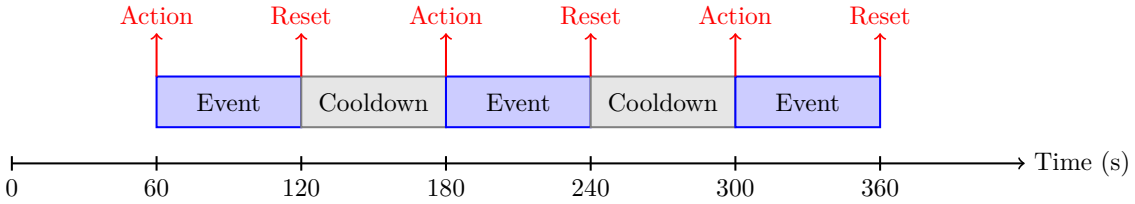
Dataset Collector

- Allows creation of ML training datasets
- Timeline-based injection of multiple fault instances into the same DT



Approach

Dataset Collector – Timeline-Based Dataset Generation



Action

```
{
    "time": 60,
    "nodes": ["r1"],
    "action": "action.sh",
    "params": []
}
```

Reset

```
{
    "time": 120,
    "nodes": ["r1"],
    "action": "reset.sh",
    "params": []
}
```

Conclusions and Outlook

Goals of Our System

- High-fidelity digital twin system
- Standardized data models
- Dataset generation

Approach

- Virtualization-based digital twin networks
- Data export using YANG
- Timeline-based dataset generation

Outlook

System serves as a basis for…

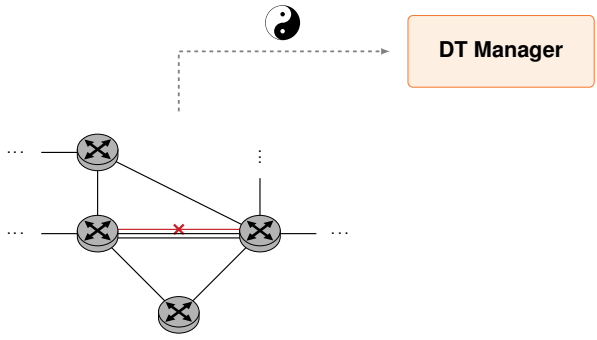
- …fault management in ISP core networks
- …automated incident dataset generation
- …closed-loop systems and self-driving networks

Preprint PDF

Questions? – spaethj@net.in.tum.de

Backup Slides

Example Fault Scenario: Link Aggregation Group (LAG) Overload



- One link of the LAG should be set down

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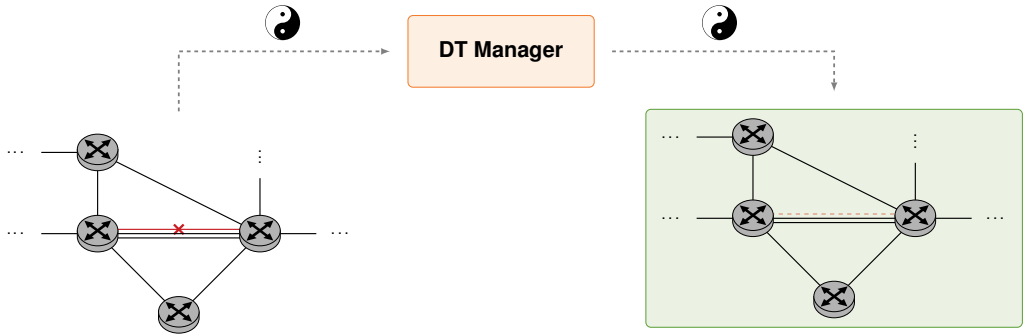

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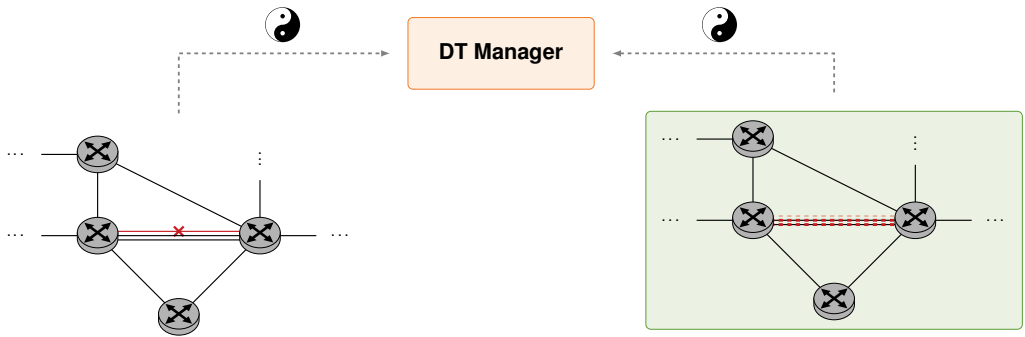

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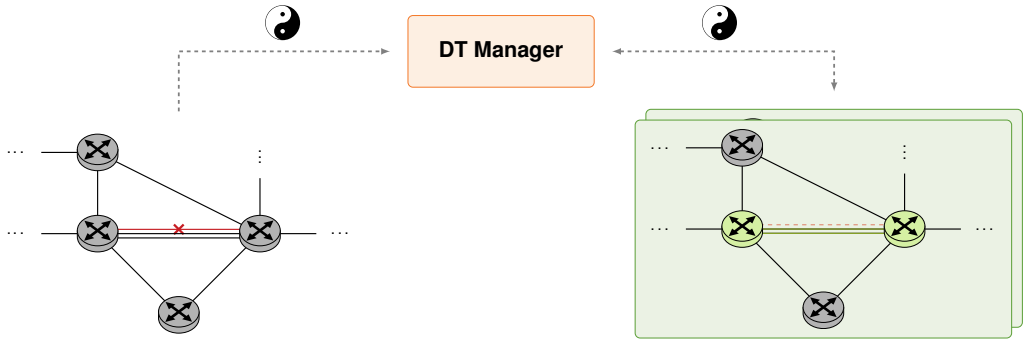

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- Change is replicated in a digital twin (DT)
- Problem is detected in DT (overload situation)
- DT with new config is tested

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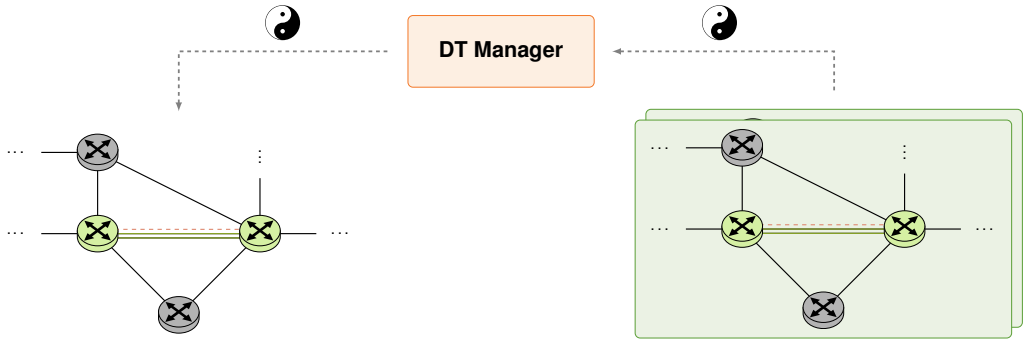

- One link of the LAG should be set down
- **Working config is propagated back to the original network**

- Change is replicated in a digital twin (DT)
- Problem is detected in DT (overload situation)
- DT with new config is tested