Universität Rostock
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Institute of Applied Microelectronics and Computer Engineering

Realtime Publish/Subscribe for the Industrial Internet of Things

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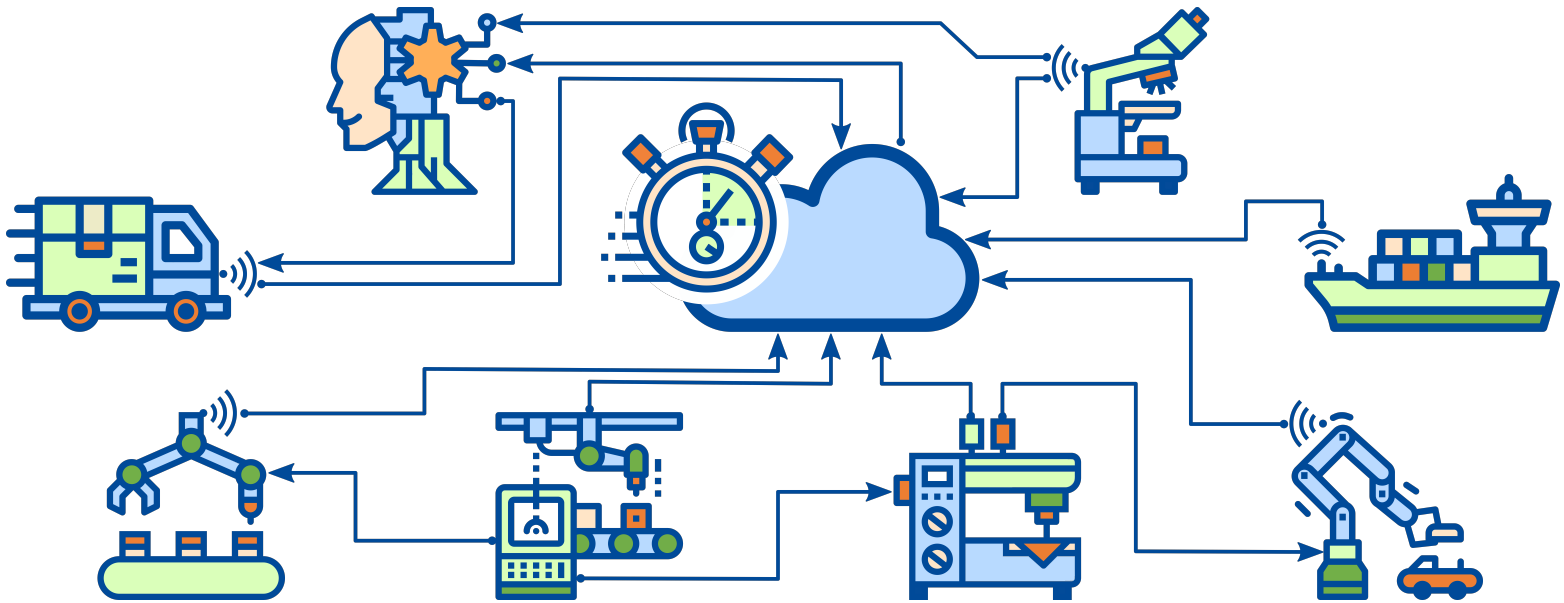
Realtime Communication in the Smart Factory

Machine-to-Machine communication has hard realtime requirements:

- Guaranteed and timely message delivery
- Deadline miss → catastrophic event



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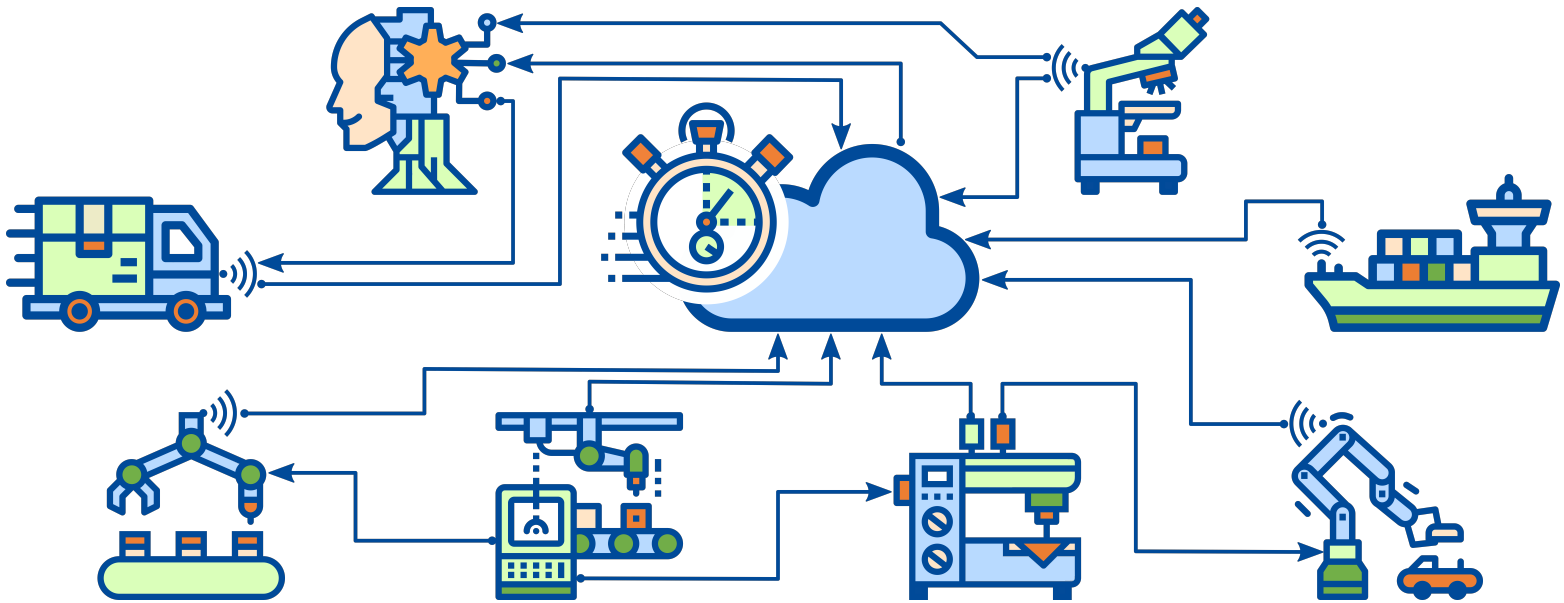


- Typical IT protocols not sufficient (high QoS, but no guarantees)
- Industrial Ethernet: Profinet, EtherCAT, TTEthernet…

Industrial Ethernet Capabilities

Industrial Ethernet provides:

- Communication latencies < 100 µs
- Guarantees
- Converged IT and OT networks

- **IEEE 802.1 Time-Sensitive Networking (TSN)** emerged as vendor-independent solution

IEEE 802.1 Time-Sensitive Networking (TSN)

Traffic Shapers

TSN supports realtime communication by means of different traffic shapers:

- Time-Aware Shaper (IEEE 802.1Qbv) for time-triggered (scheduled) traffic
- Credit-Based Shaper (IEEE 802.1Qav) for bandwidth reservations
- Asynchronous Shaper (IEEE 802.1Qcr), Cyclic Queuing and Forwarding (IEEE 802.1Qch)…
- (Best Effort)

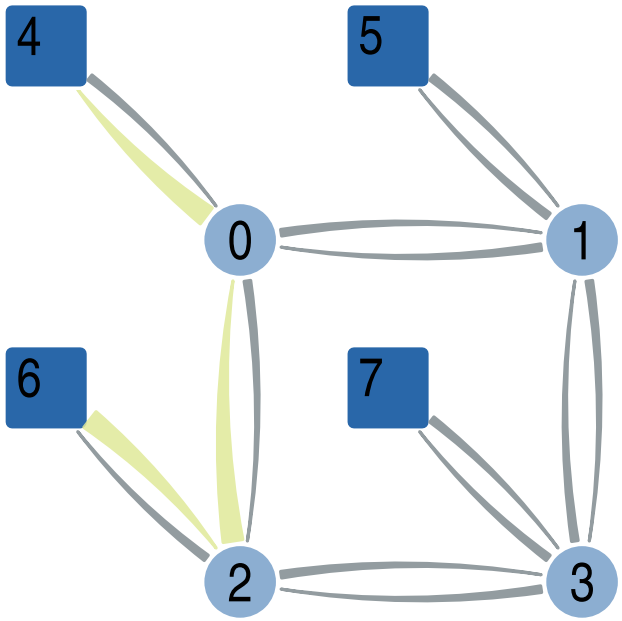
Switch Capabilities

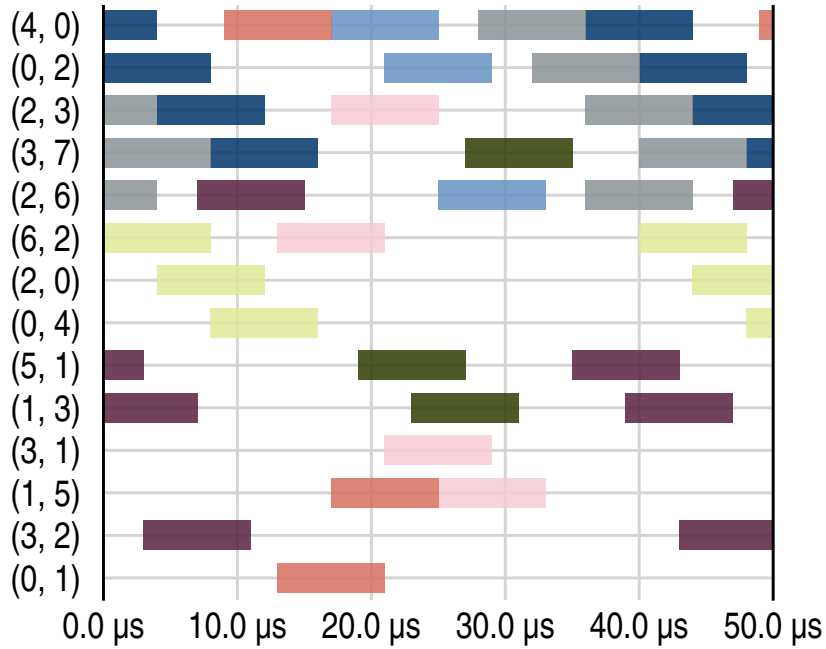
TSN defines switch capabilities that enable and improve realtime communication:

- Synchronization
- Frame preemption
- Seamless redundancy
- …

Configuration of Realtime Communication

- Guarantees demand offline planning and resource reservations
- Example: Traffic schedule for time-triggered communication





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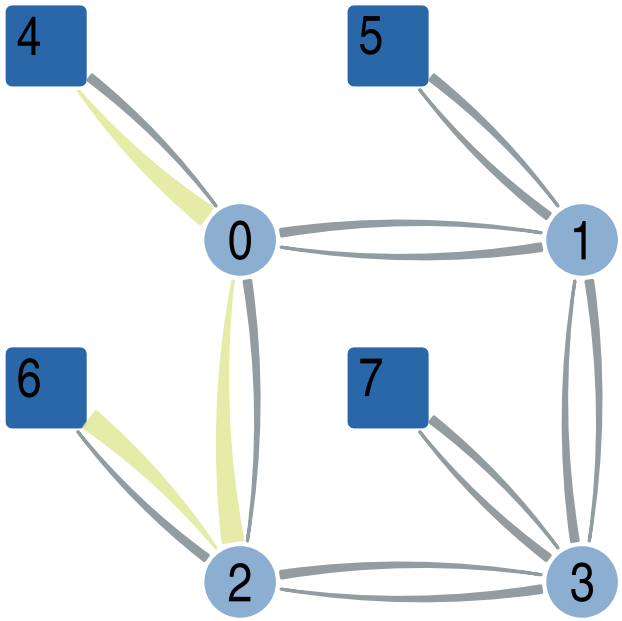
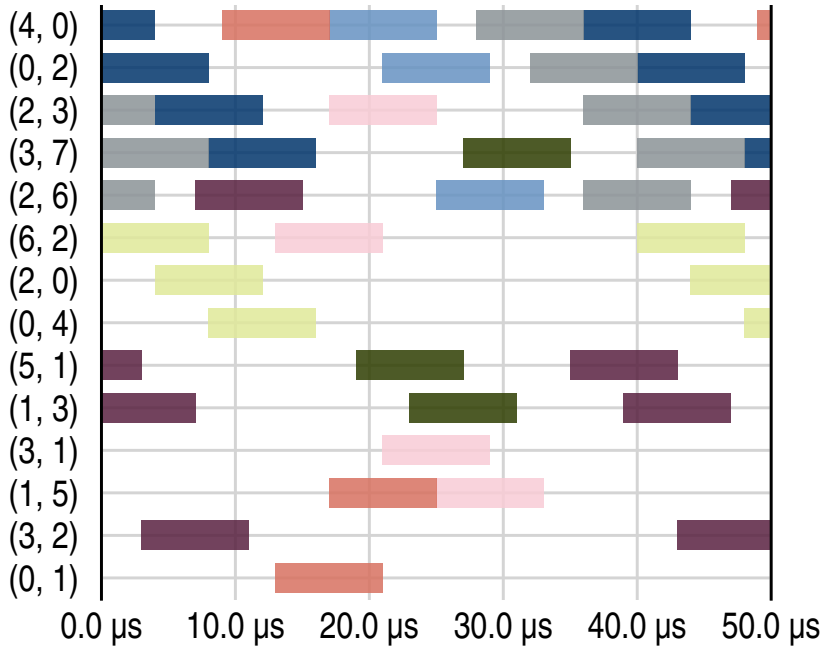
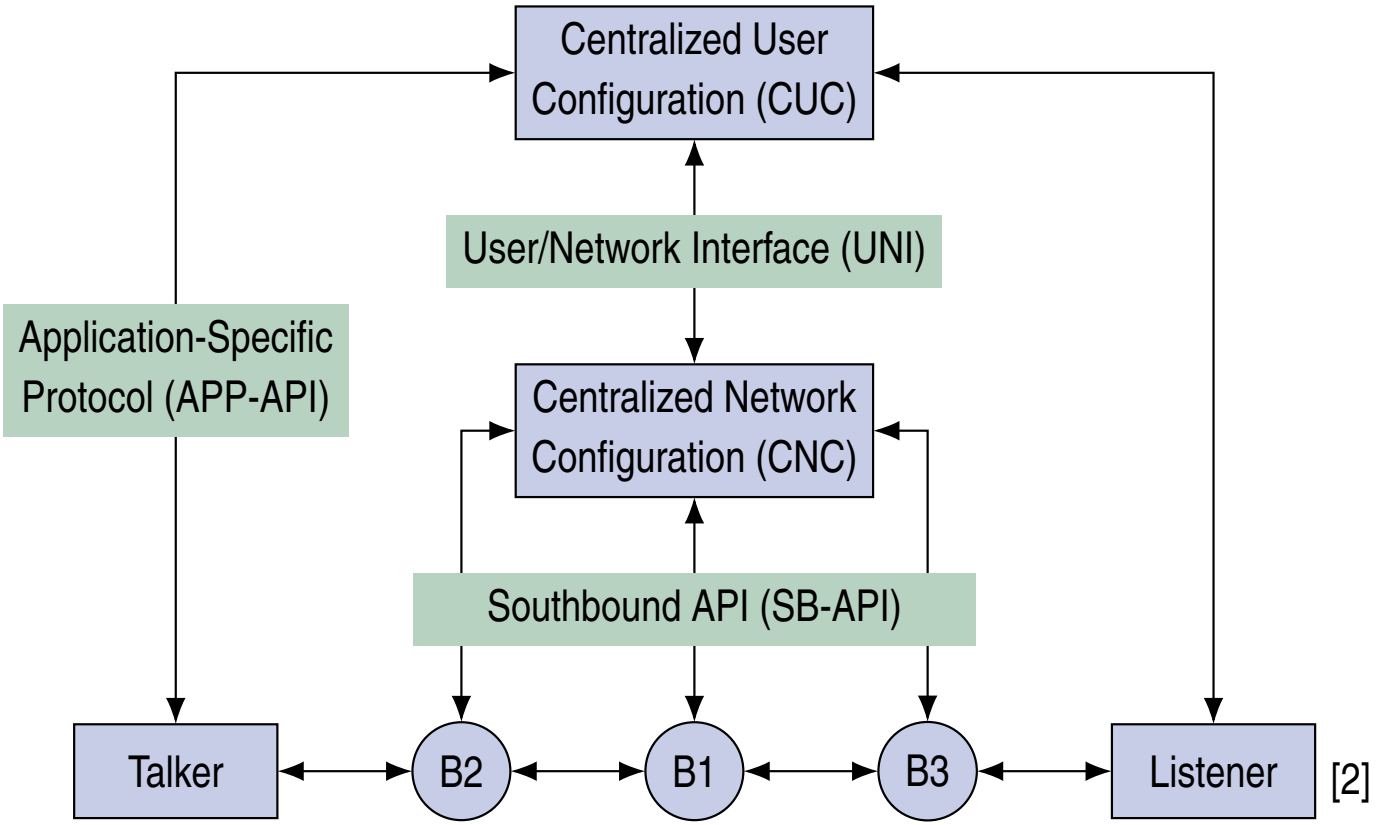




- TSN suggests management architectures in IEEE 802.1Qcc

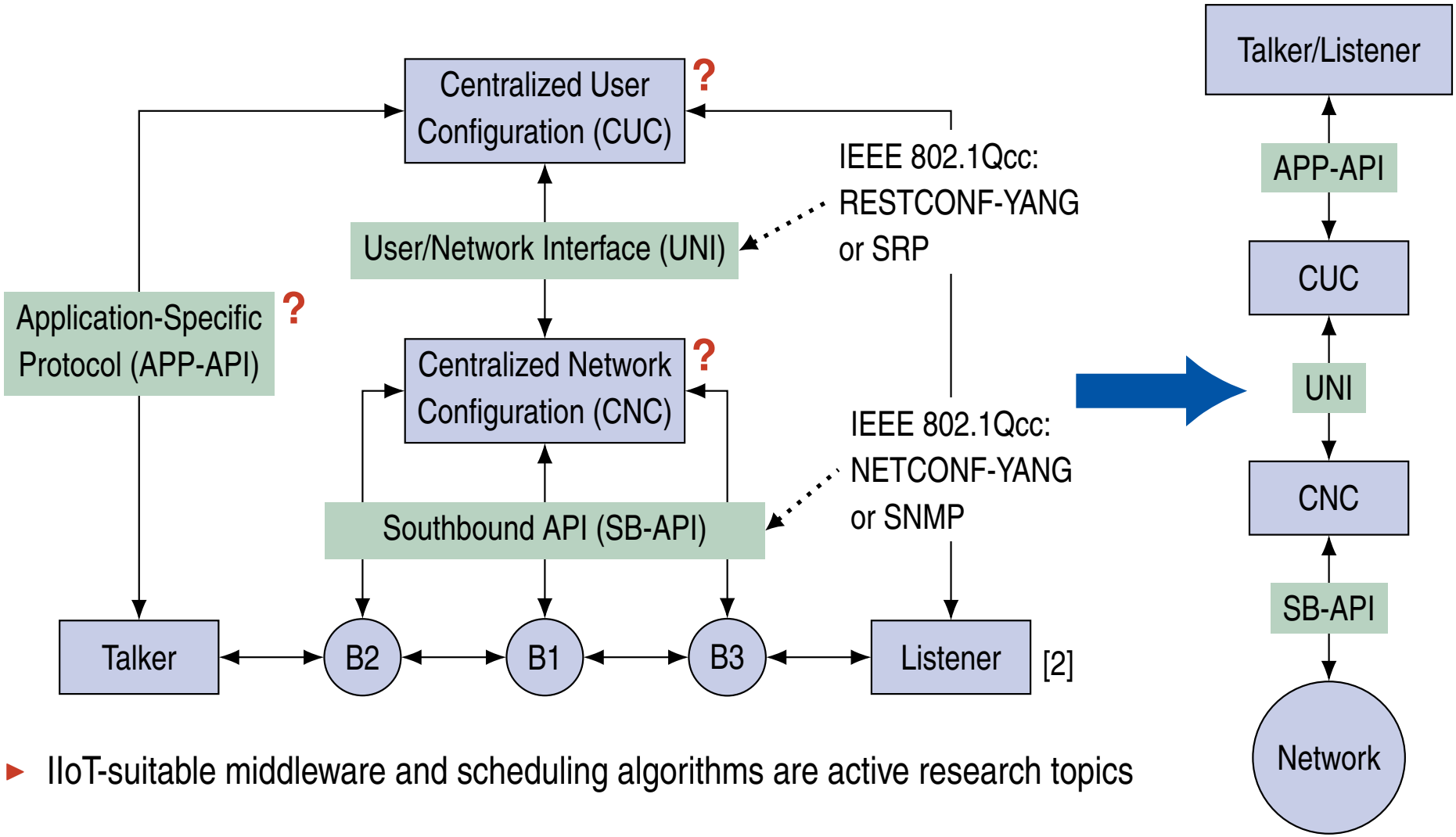
TSN Centralized Architecture



[2]

1. Discovery
2. Collect Requirements
3. Create Streams
4. Scheduling
5. Configuration
6. Realtime Communication

TSN Centralized Architecture



- IIoT-suitable middleware and scheduling algorithms are active research topics

Middleware for the Industrial Internet of Things

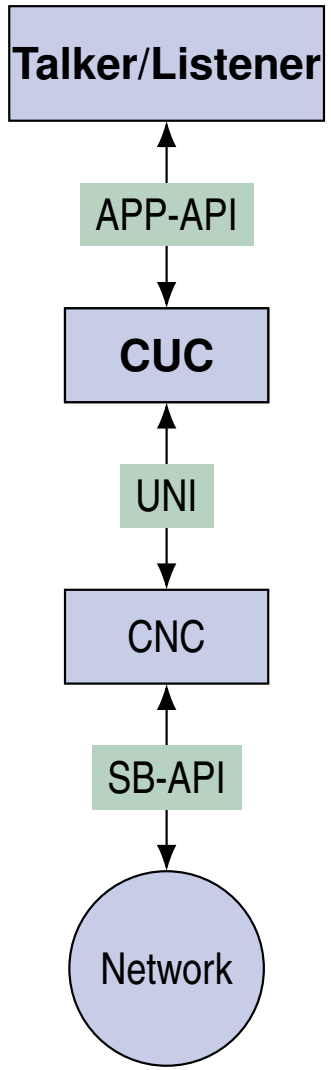
Requirements

- Automatic discovery and stream creation
- Multicast notification services
- Dynamics

- **Publish/Subscribe**

Candidates

- **DDS**: Data Distribution Service [14]
- **OPC UA**: Open Platform Communications Unified Architecture (IEC 62541) [15]
- **SDC**: Service-Oriented Device Connectivity (IEEE 11073) [1] [3] [10]



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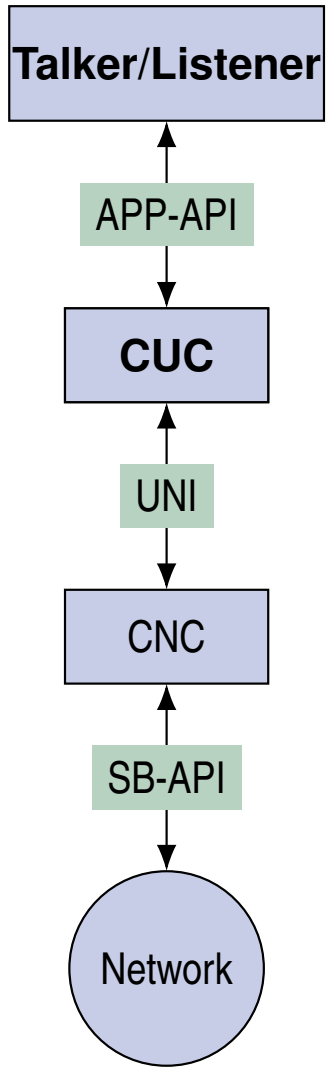
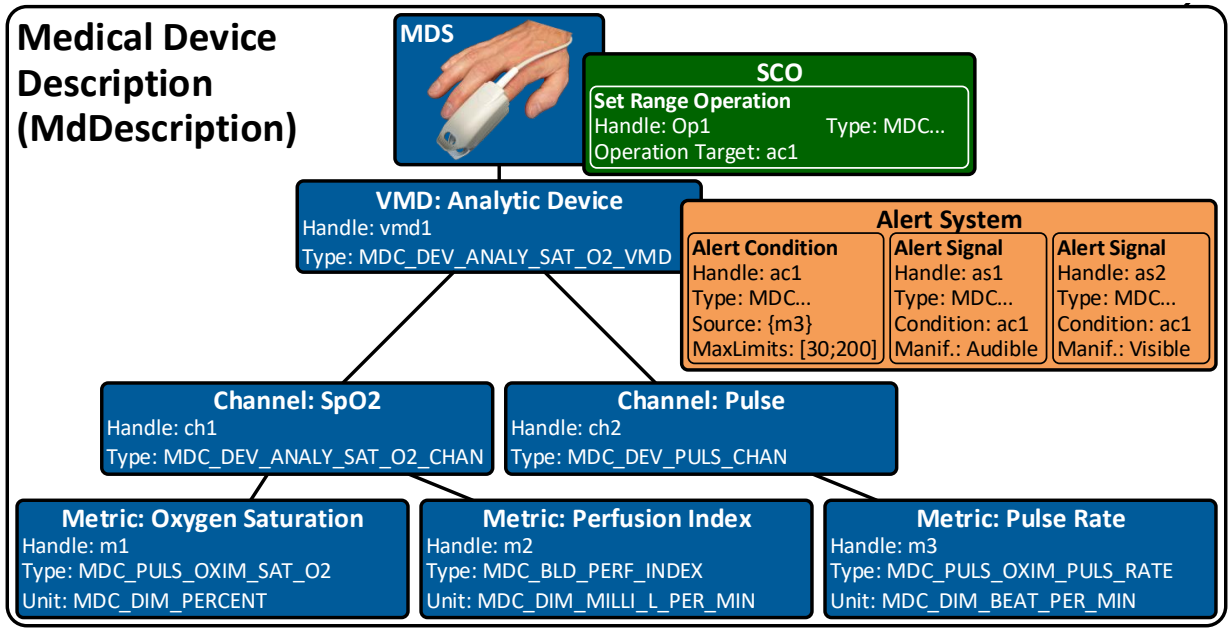
- Existing systems need to improve TSN support
  - Realtime protocol (e.g., prefer UDP)
  - Realtime stream and data modeling
  - UNI: RESTCONF-YANG or SRP



Modeling of Realtime Publish Subscribe (1)



[11]

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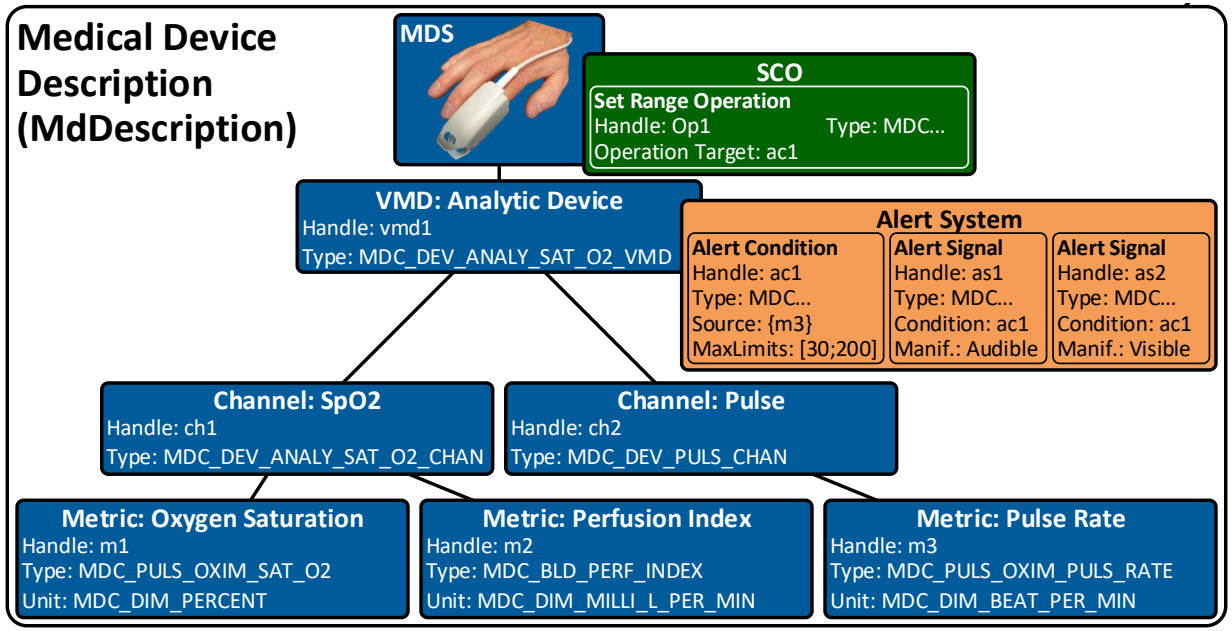


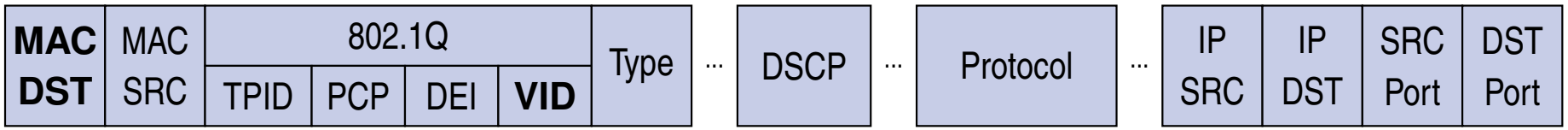
[11]

Device & Data Model

Necessary extensions for the communication requirements:

- Interval/packet size or bandwidth
- Maximum delay
- Inter-stream dependencies (e.g., modeled as data flow graph)

Modeling of Realtime Publish Subscribe (2)



Stream Identification (IEEE 802.1CB)

- Middleware reports realtime streams and requirements via UNI
- CNC allocates resources, chooses the **stream identifier** and informs applications via UNI
  - **Null Stream Identification**
  - Source MAC and VLAN Stream Identification
  - IP Stream Identification
- Middleware uses given stream identifier or stream transformation

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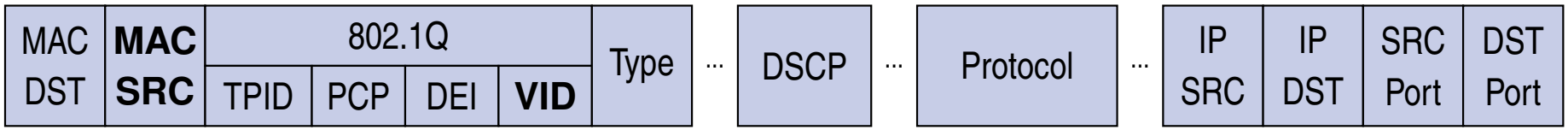

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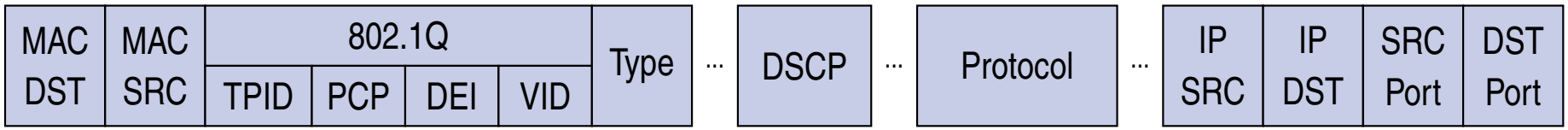

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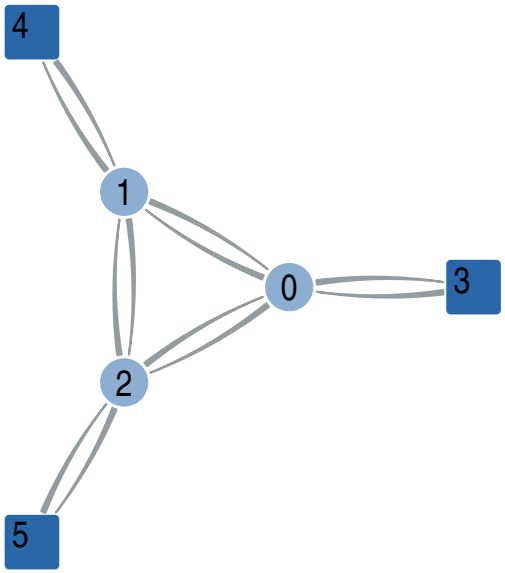
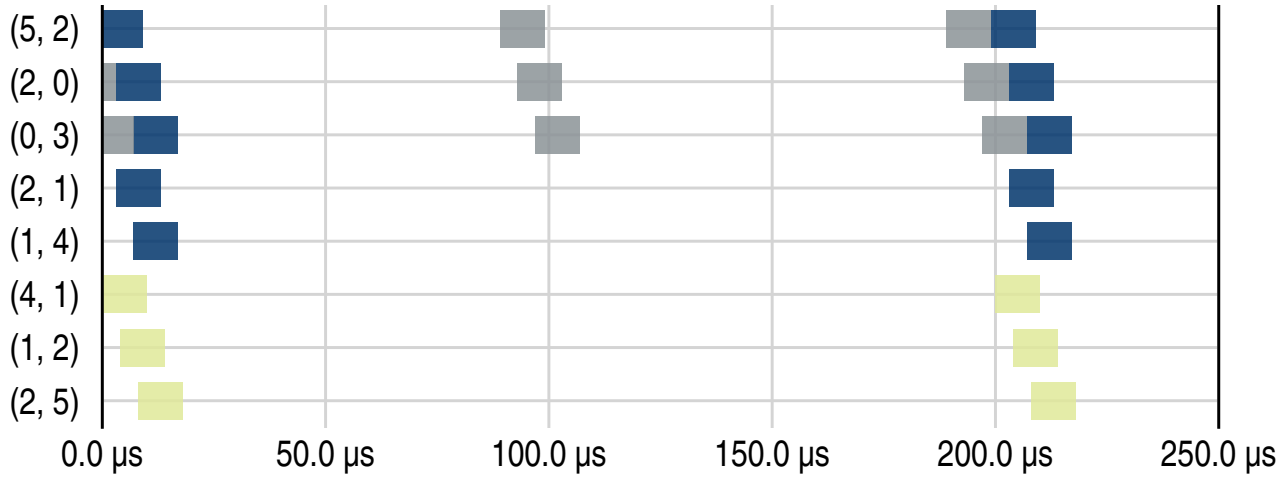
- No existing middleware satisfies all requirements
  - There is ongoing work [5] [17] [9] [4]
- Research directions for increased effiency
  - Content-based header creation
  - Time slot sharing

Network Planning: Routing and Scheduling

```
"s0" : {"src": 5, "dsts": [4, 3], "ct": 200, "rsl": 10, "ml": 800}
"s1" : {"src": 5, "dsts": [3],    "ct": 100, "rsl": 10, "ml": 400}
"s2" : {"src": 4, "dsts": [5],    "ct": 200, "rsl": 10, "ml": 800}
```

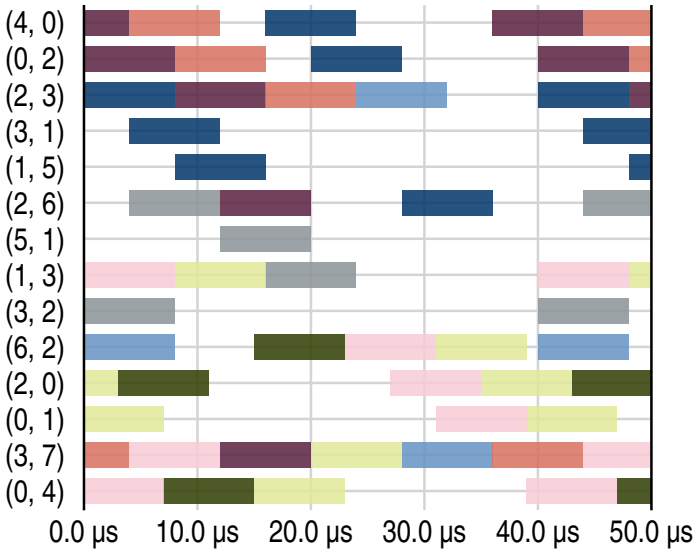




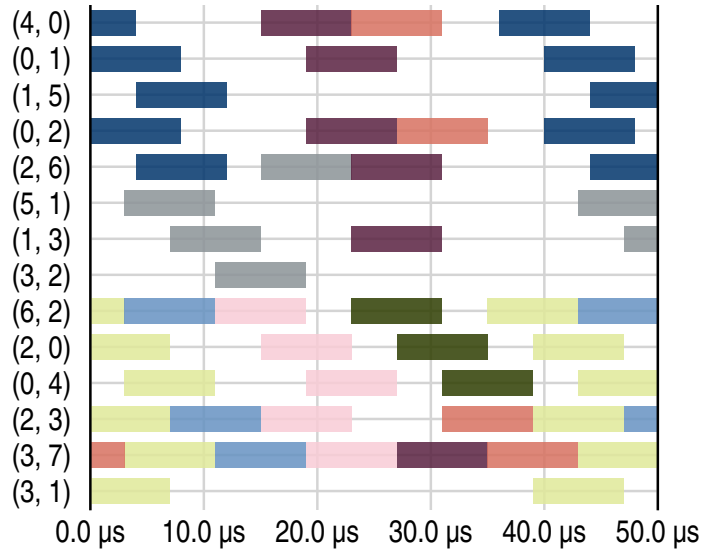
- CNC computes schedule and bandwidth reservations
- Scheduling algorithms are not defined in TSN standards

- Active research community [18] [13] [6] [8] [16] [19]

Network Planning: Open Research Questions



ILP runtime: 0.106 s **Latency: 290 µs**



ILP runtime: 0.345 s **Latency: 108 µs**

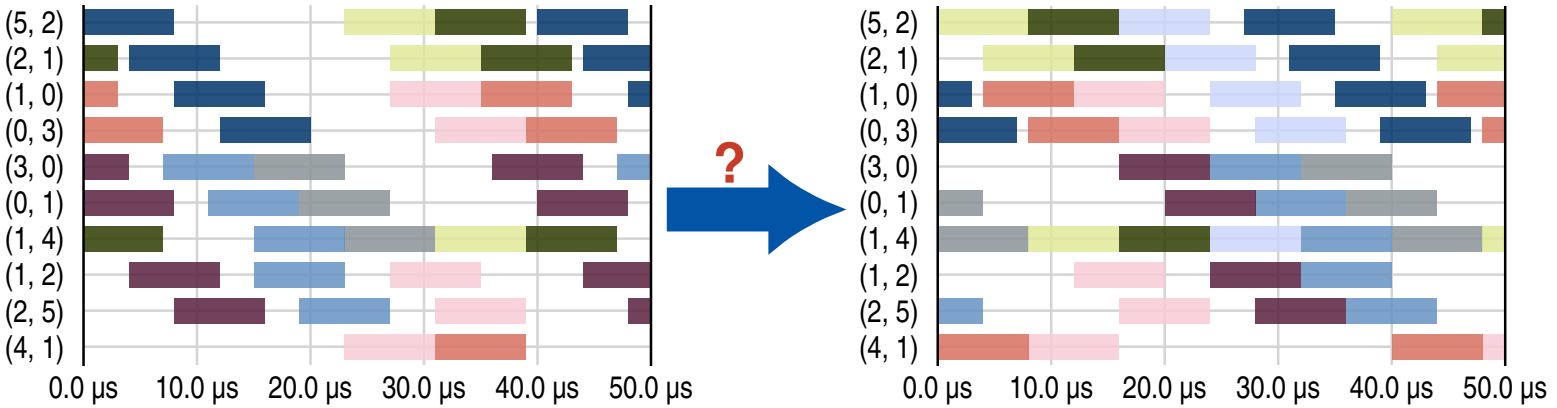
Trade-off: Runtime vs. schedule quality

- Application requirements
- Offline scheduling vs. reconfiguration
- Optimization objectives: Cost, energy

Holistic planning

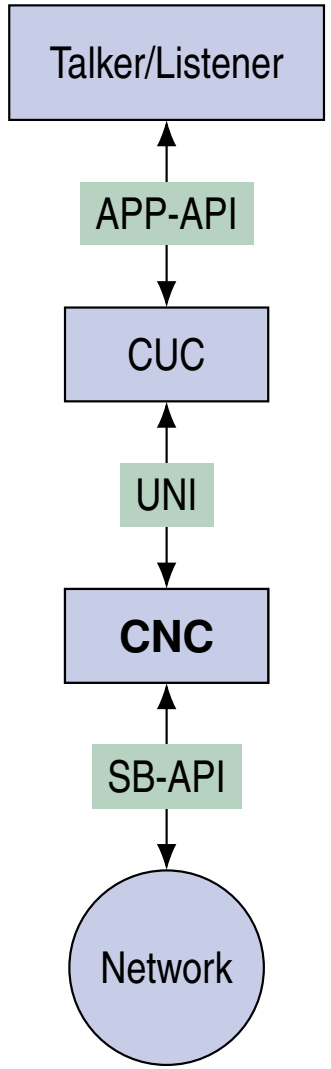
- Topology synthesis [7]
- Computational tasks [12]
- Multi-class planning

Seamless Dynamic Reconfiguration

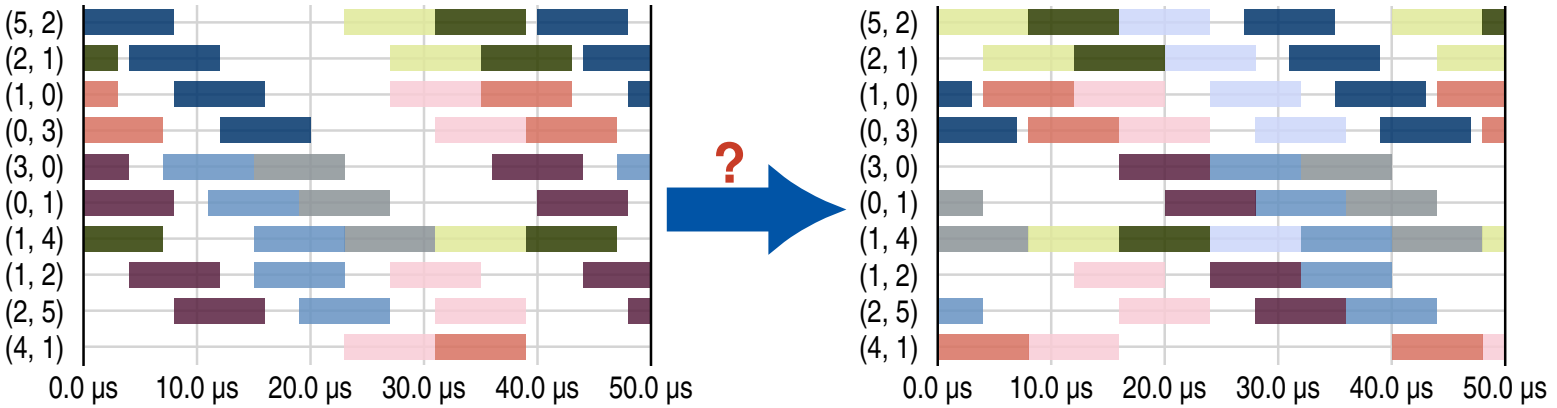


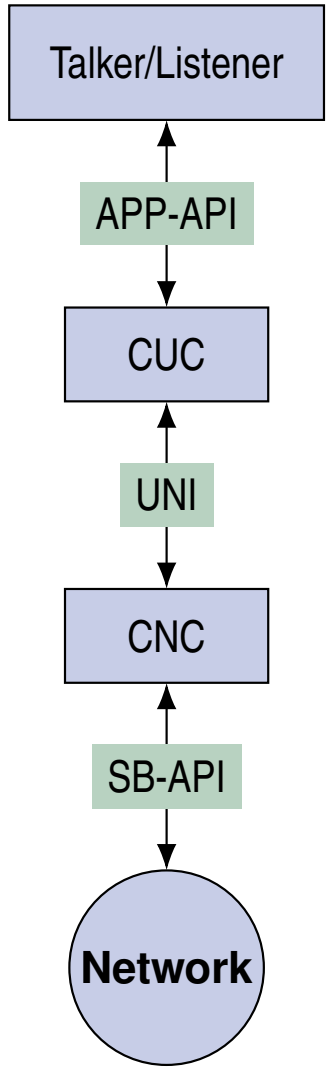
Algorithms for Reconfiguration

- Migration strategies
  - Elementary: One stream at a time
  - Complex: Sequence of elementary migrations
  - Simultaneous: Difficult due to in-flight packets
- Consider jitter tolerance of applications
- Efficient algorithms for complex migrations not available yet



Seamless Dynamic Reconfiguration (2)





Reconfiguration Facilities in TSN Switches

- Configuration per-switch, per-port
- Two sets of configuration variables (see IEEE802.1Q-2018, clause 8.6):
  - Operational: OperCycleTime, OperControlList, OperGateStates…
  - Administration: AdminCycleTime, AdminControlList, AdminGateStates…
  - Timed reconfiguration Oper* ← Admin*
- Offers maximum flexibility
- Algorithms not part of the standard

Scaling

Divide and Conquer

- Architecture
  - Distributed CUC and CNC
  - Hybrid and decentralized architectures
  - Leverage research of distributed SDN controllers
- Algorithms
  - Network decomposition (static and dynamic)
  - Create and merge partial plans
  - Domain-crossing streams

Summary

- Time-Sensitive Networking (TSN) provides well-defined switch capabilities and interfaces
- Ready for practical application with:
  - Static communication patterns
  - Limited network size

- Full potential of the flexible TSN interfaces will become available by ongoing research…

Modeling Realtime Publish/Subscribe

- Data model
- UNI

Seamless Dynamic Reconfiguration

- From elementary to simultaneous migrations
- Keep jitter minimal

Planning: Routing and Scheduling

- Trade-off: Runtime vs. quality
- Holistic planning

Scaling

- Distributed architecture
- Partial plans

References I

[1] Ieee health informatics–point-of-care medical device communication part 10207: Domain information and service model for service-oriented point-of-care medical device communication. *IEEE Std 11073-10207-2017* (Feb 2018), 1–437.

[2] Ieee standard for local and metropolitan area networks–bridges and bridged networks – amendment 31: Stream reservation protocol (srp) enhancements and performance improvements. *IEEE Std 802.1Qcc-2018 (Amendment to IEEE Std 802.1Q-2018 as amended by IEEE Std 802.1Qcp-2018)* (2018), 1–208.

[3] Iso/ieee international standard for health informatics – point-of-care medical device communication – part 20702: Medical devices communication profile for web services. *ISO/IEEE 11073-20702:2018(E)* (Sep. 2018), 1–52.

References II

[4] Bruckner, D., Blair, R., Stanica, M.-P., Ademaj, A., Skeffington, W., Kutscher, D., Schriegel, S., Wilmes, R., Wachswender, K., Leurs, L., Seewald, M., Hummen, R., Liu, E.-C., and Ravikumar, S.
Opc ua tsn a new solution for industrial communication.
Tech. rep.

[5] Eckhardt, A., Müller, S., and Leurs, L.
An evaluation of the applicability of opc ua publish subscribe on factory automation use cases.
In *IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)* (2018).

[6] Falk, J., Dürr, F., and Rothermel, K.
Exploring practical limitations of joint routing and scheduling for tsn with ilp.
In *2018 IEEE 24th RTCSA* (2018), IEEE, pp. 136–146.

References III

[7] Gavrilut, V., Zarrin, B., Pop, P., and Samii, S.
Fault-tolerant topology and routing synthesis for ieee time-sensitive networking.
In *Proceedings of the 25th International Conference on Real-Time Networks and Systems* (New York, NY, USA, 2017), RTNS '17, Association for Computing Machinery, p. 267–276.

[8] Gavriluţ, V., Zhao, L., Raagaard, M. L., and Pop, P.
Avb-aware routing and scheduling of time-triggered traffic for tsn.
Ieee Access 6 (2018), 75229–75243.

[9] Gutiérrez, M., Ademaj, A., Steiner, W., Dobrin, R., and Punnekkat, S.
Self-configuration of ieee 802.1 tsn networks.
In *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (2017), pp. 1–8.

References IV

[10] IEEE Standards Association.
11073-20701-2018 - Health informatics–Point-of-care medical device communication - Part 20701: Service-Oriented Medical Device Exchange Architecture and Protocol Binding.

[11] Kasparick, M., Schmitz, M., Andersen, B., Rockstroh, M., Franke, S., Schlichting, S., Golatowski, F., and Timmermann, D.
Or.net: a service-oriented architecture for safe and dynamic medical device interoperability.
Biomedizinische Technik. Biomedical engineering 63 1 (2018), 11–30.

[12] Lukasiewycz, M., Schneider, R., Goswami, D., and Chakraborty, S.
Modular scheduling of distributed heterogeneous time-triggered automotive systems.
In *17th Asia and South Pacific Design Automation Conference* (2012), IEEE, pp. 665–670.

References V

[13] Nayak, N. G., Dürr, F., and Rothermel, K.
Incremental flow scheduling and routing in time-sensitive software-defined networks.
IEEE Transactions on Industrial Informatics 14, 5 (2017), 2066–2075.

[14] Object Management Group, Inc.
Data distribution service for real-time systems (DDS), version 1.2.
Needham, MA, USA, Jan. 2007.

[15] OPC Foundation.
OPC unified architecture part 14: PubSub.
Scottsdale, AZ, USA, Feb. 2018.

[16] Pahlevan, M., Tabassam, N., and Obermaisser, R.
Heuristic list scheduler for time triggered traffic in time sensitive networks.
ACM Sigbed Review 16, 1 (2019), 15–20.

References VI

[17] Pop, P., Raagaard, M. L., Gutierrez, M., and Steiner, W.
Enabling fog computing for industrial automation through time-sensitive networking (tsn).
IEEE Communications Standards Magazine 2, 2 (2018), 55–61.

[18] Schweissguth, E., Danielis, P., Timmermann, D., Parzyjegla, H., and Mühl, G.
Ilp-based joint routing and scheduling for time-triggered networks.
In *Proceedings of the 25th International Conference on Real-Time Networks and Systems* (2017), pp. 8–17.

[19] Tămaş-Selicean, D., Pop, P., and Steiner, W.
Design optimization of ttethernet-based distributed real-time systems.
Real-Time Systems 51, 1 (2015), 1–35.