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CISTER - Research Centre in Real-Time & Embedded Computing Systems

# On the adequacy of SDN and TSN for Industry 4.0

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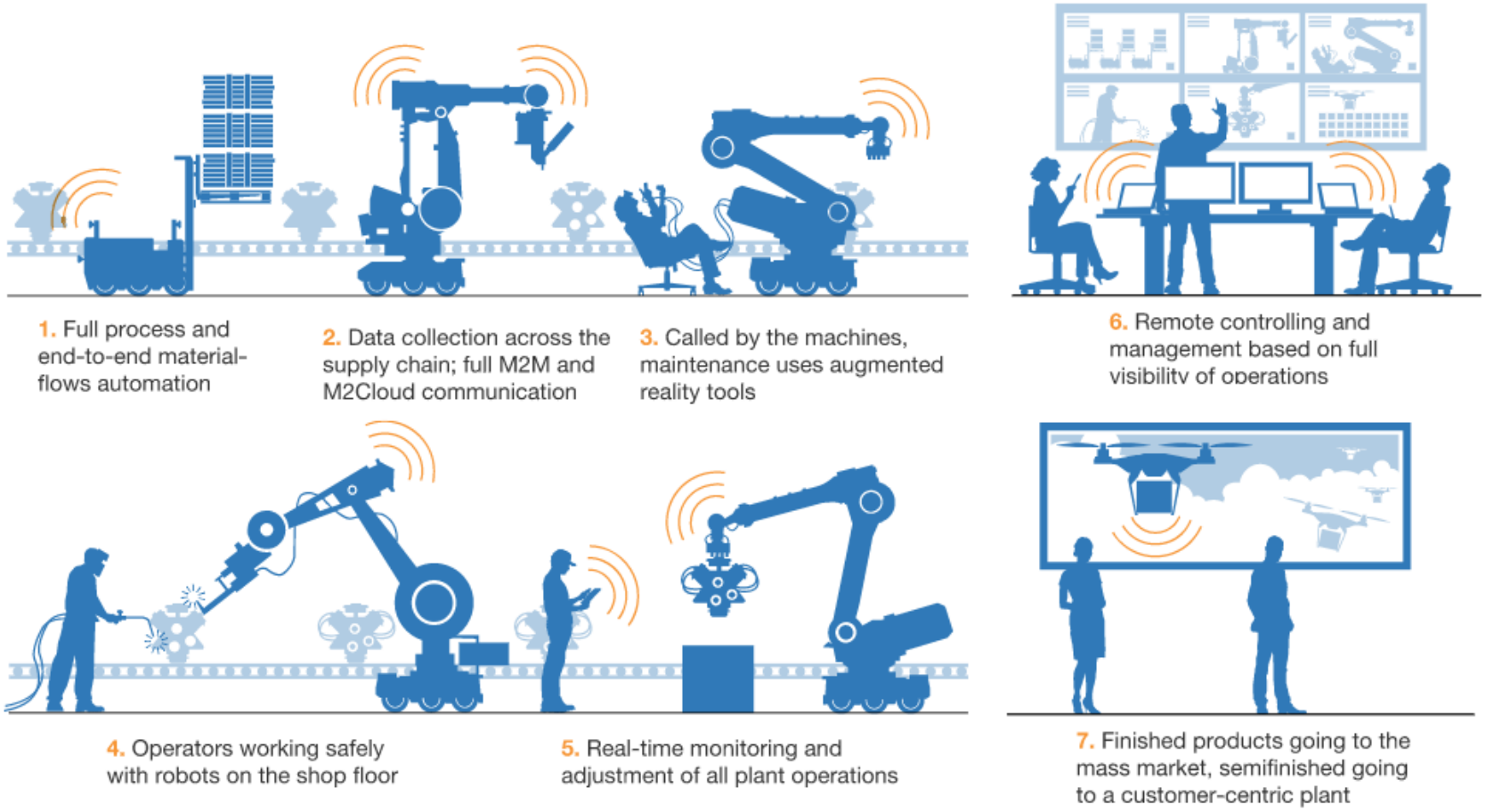
# Outlook

- Industry 4.0 and Smart Factories
  - Concepts and requirements
  - Focus on communications
- Background on SDN
- Background on TSN
- Qualitative comparison
- Conclusions

# Towards Industry 4.0

## Smart Factory Plant Example



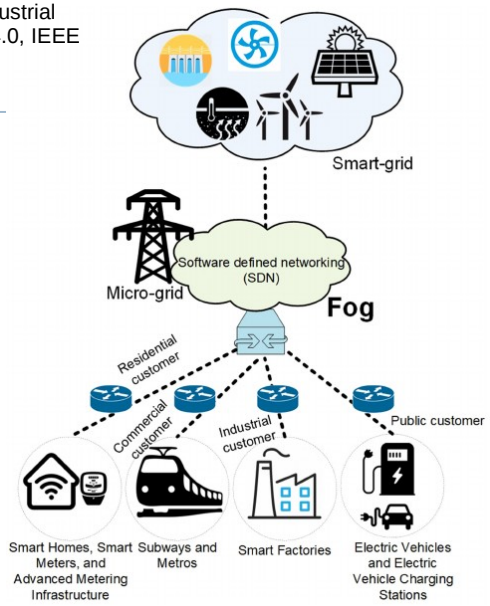

*Source: "Industry 4.0 How to navigate digitization of the manufacturing sector", McKinsey Digital, 2015

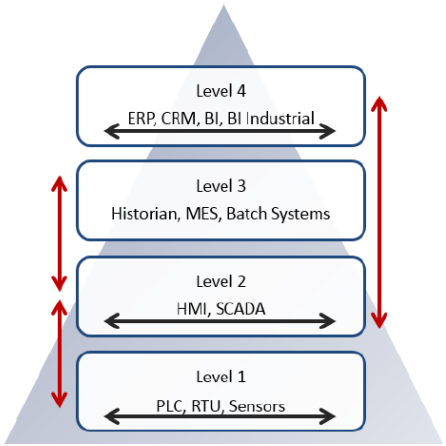
# Industry 4.0

## Network perspective

- Heterogeneous technologies
  - Conventional sensors/actuators, Machine vision, ERP, ...
- Heterogeneous requirements
  - Bandwidth from bps to Mbps; Hard/Soft/ and Non Real-Time traffic
  - Mixed criticality
- Heterogeneous computing architectures
  - Distributed, Centralized, Fog, Edge, ...
- Dynamic requirements
  - Variable number of nodes, variable configurations, ...
- Integration
  - Full visibility of operations, global management tools

Fog-enabled smart grid. M. Aazam et al, Deploying Fog Computing in Industrial Internet of Things and Industry 4.0, IEEE TIII, Vol. 14, N. 10, Oct 2018



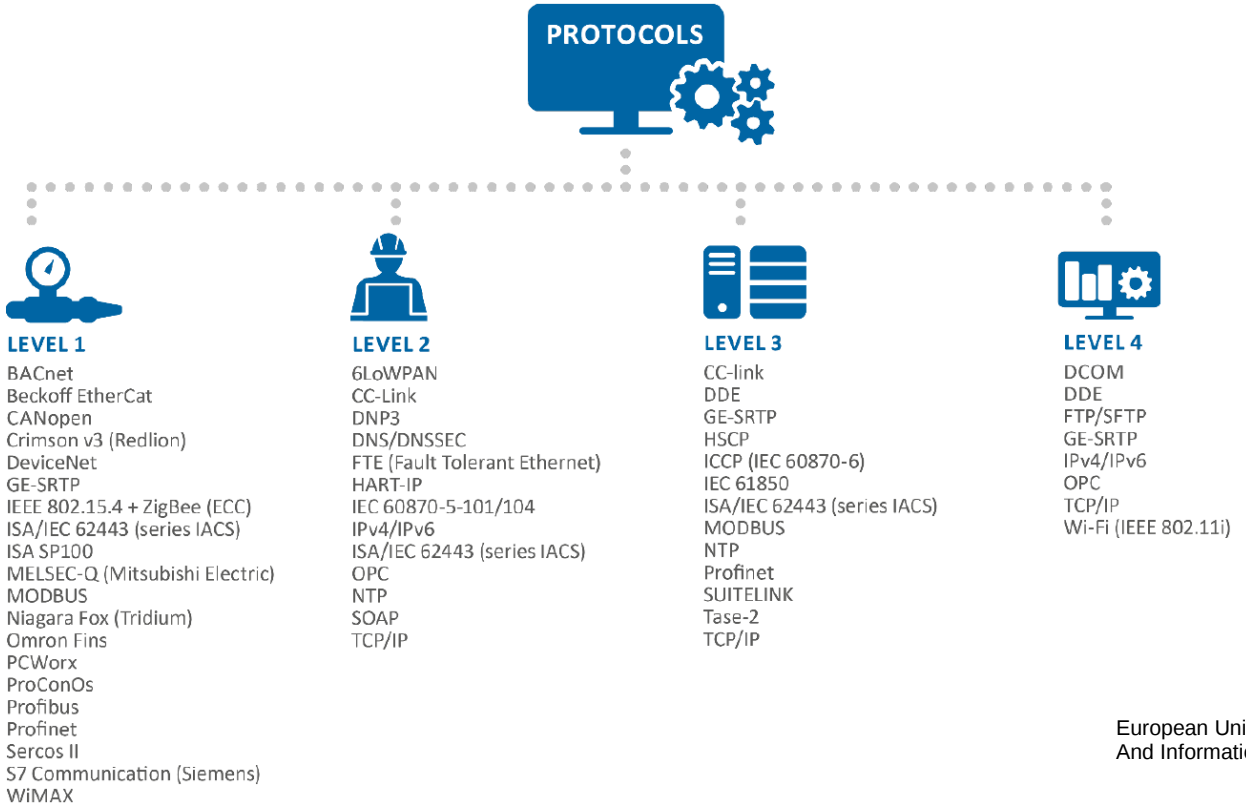

European Union Agency For Network And Information Security, 2016

# Networking technologies

- Industrial technologies/protocols for the lower layers

PROFINET TSN Industrial Ethernet ETHERNET POWERLINK EtherCAT

- Combined with IP based protocols at the higher layers



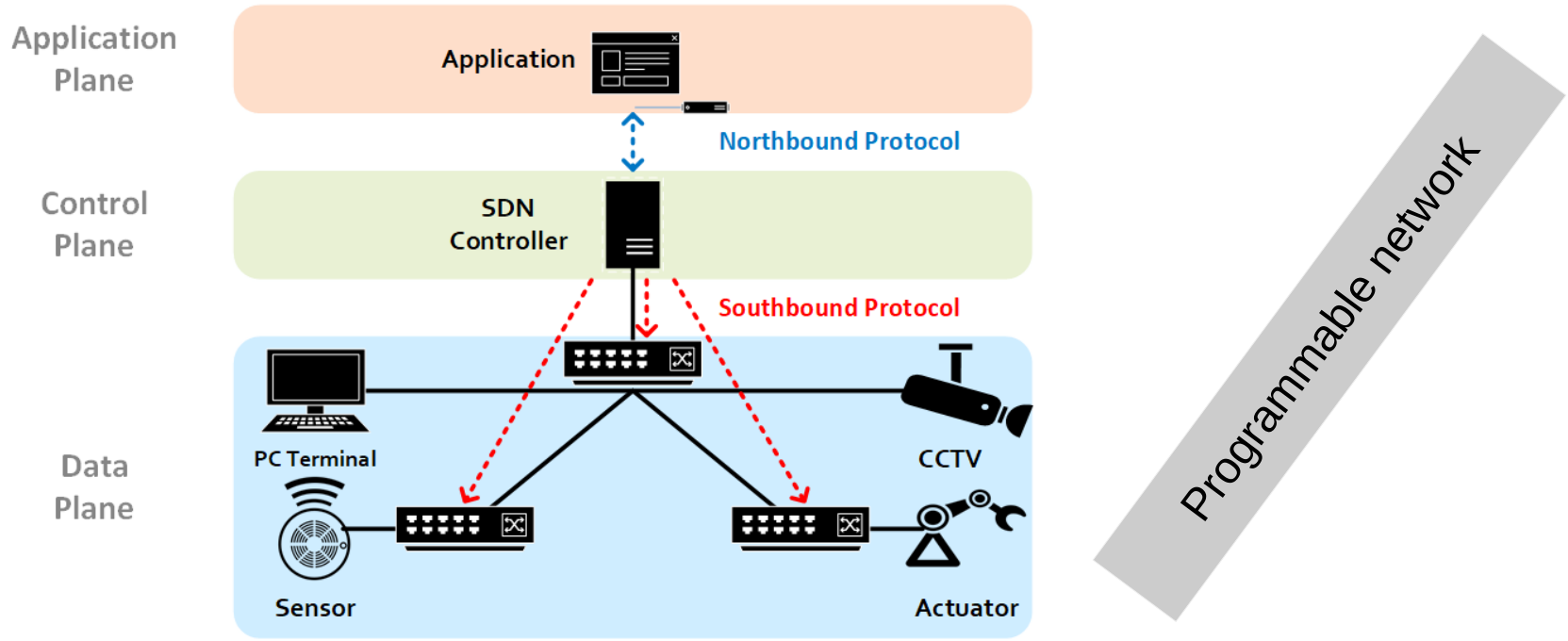

European Union Agency For Network And Information Security, 2016

# Networking for I4.0

- Two candidates for Industry 4.0 communications infrastructure
  - **Software Defined Networking (SDN)**
    - Origins on datacenters
    - Disruptive paradigm
      - Network programmability
  - **IEEE Time Sensitive Networking (TSN)**
    - Evolutionary approach (roots on AVB)
    - Extends existing IEEE standards
      - Support to automation-class traffic

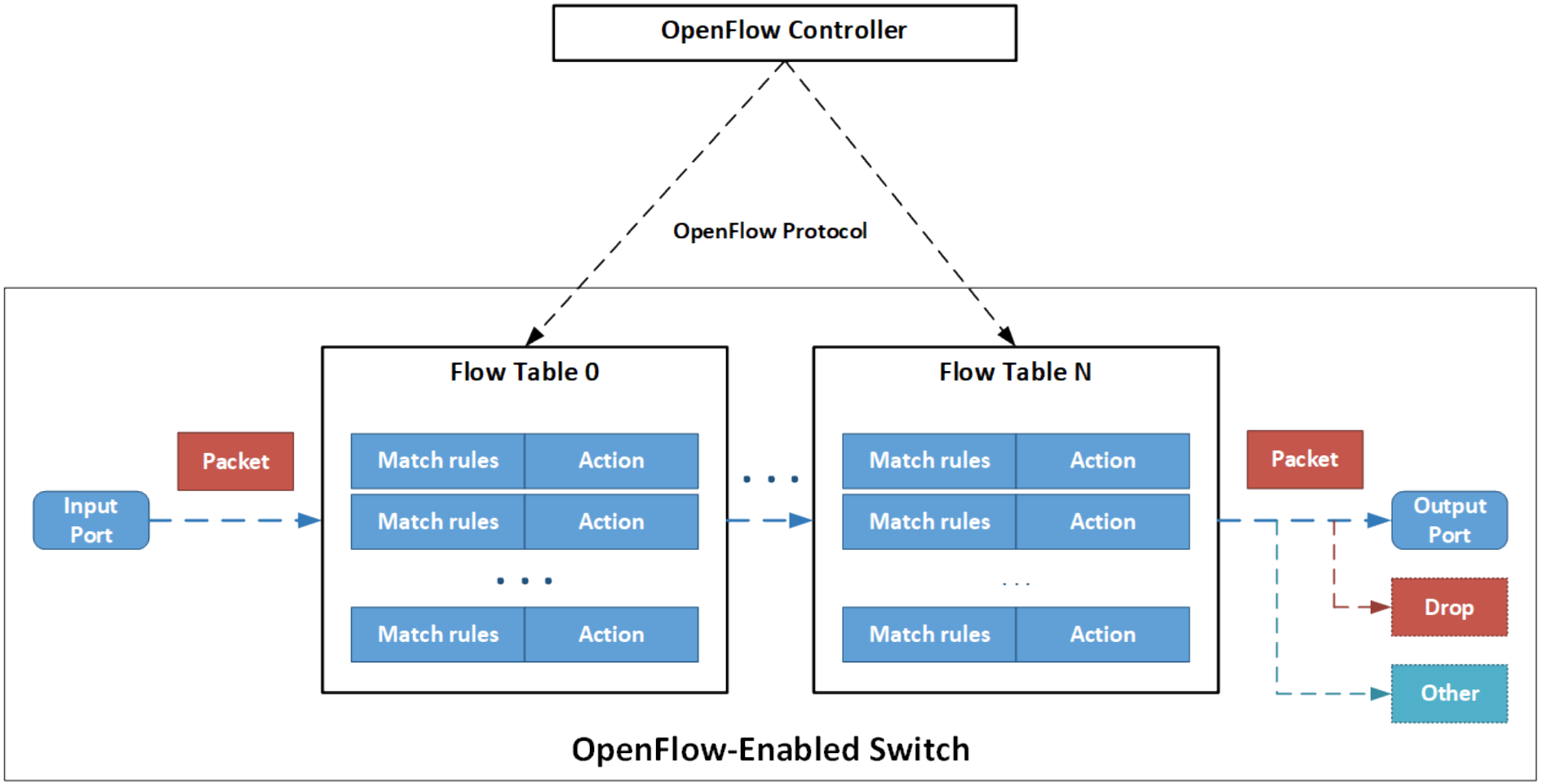
# Software Defined Networking

- OpenFlow Protocol
  - *De facto* SDN standard
  - Southbound interface
  - Deployed in campus networks, datacenter networks, …



# Software Defined Networking

## How does OpenFlow work?



# Software Defined Networking

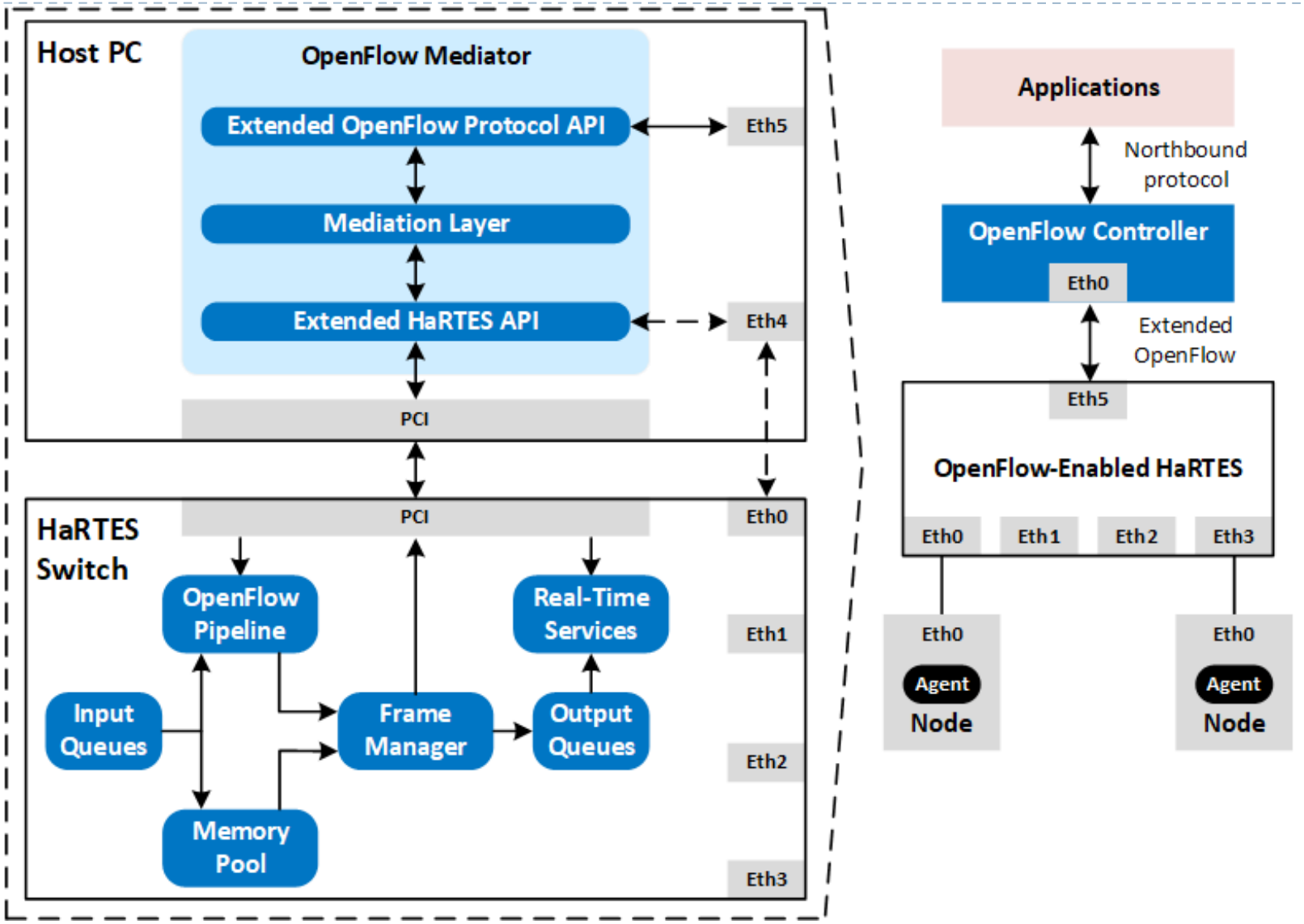
- Suitable for management of complex environments
  - Large networks, heterogeneous requirements
  - Programmability allows an unprecedented level of flexibility

- However:
  - **Real time communications severely limited**
    - Time-triggered traffic not supported,
    - Quality-of-Service (QoS) mechanisms/metrics unsuitable for strict timeliness guarantees

# Software Defined Networking

- Real time on SDN/OpenFlow
  - **Performance evaluations**
    - Highlight the benefits of the flexibility (arbitrary topologies, custom protocols, reconfigurations)
    - Highlight the real-time performance limitations
  - **Extensions**
    - Enhancements to the queues management
    - Overlay protocols (TDMA, FTT)
    - Integration with deterministic layer 2 protocols (PROFINET, HaRTES)
      - **Bring real-time services to OpenFlow**

# Example: Integration with HaRTES



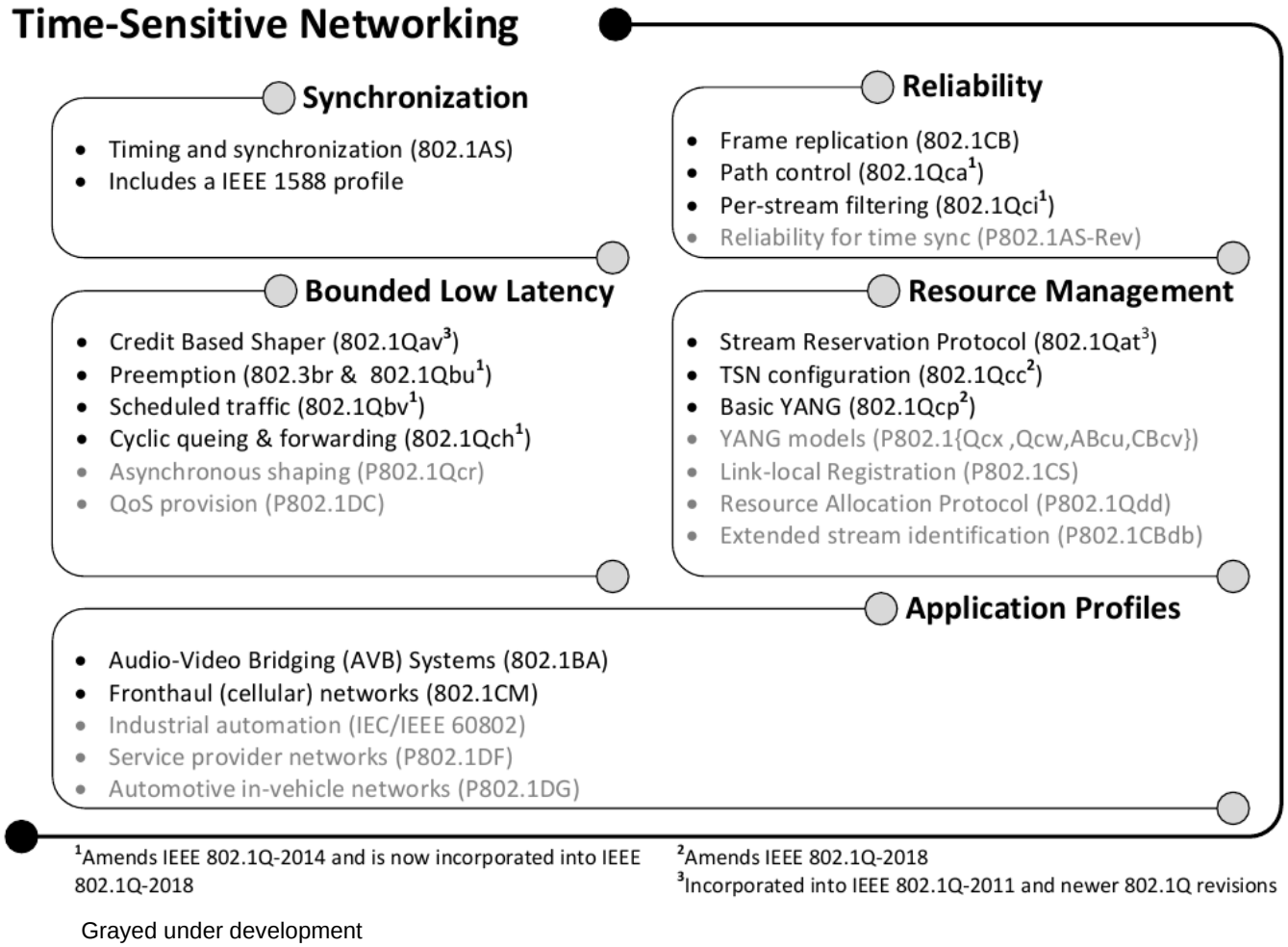
# IEEE Time-Sensitive Networking

- Set of standards developed by the IEEE 802.1 time-sensitive networking task group


- Successor of Audio-Video Bridging task group (AVB)
- Focus on improving the real-time behavior of IEEE 802 network technologies.
- TSN focuses on four main aspects:
  - Temporal synchronization among devices
  - End-to-end bounded latency
  - High reliability for real-time traffic streams
  - Management of network resources.

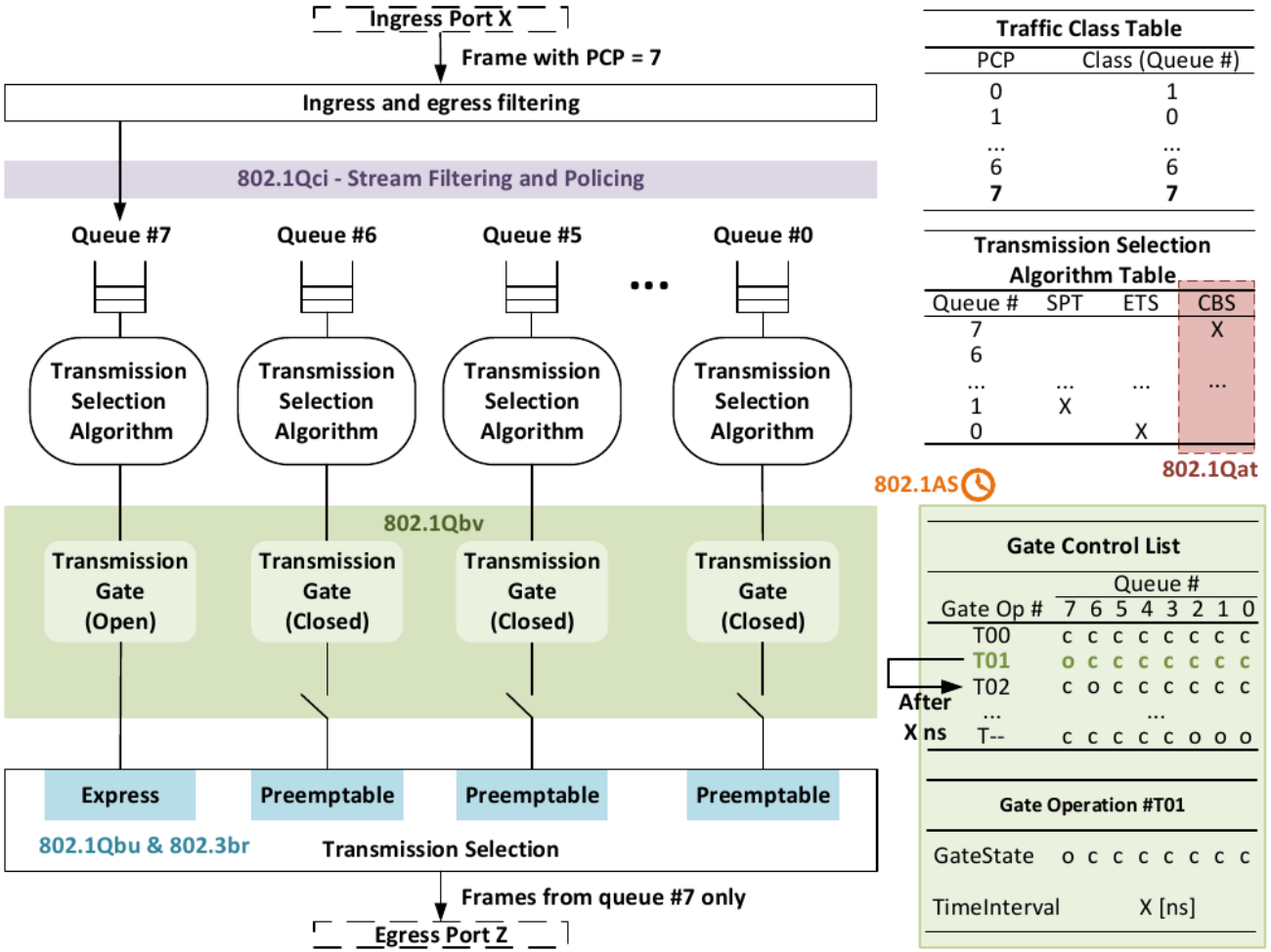
# IEEE Time-Sensitive Networking

- TSN Standards Overview



# IEEE Time-Sensitive Networking

- TSN forwarding enhancements



# Qualitative comparison

- Adopted criteria
  - **Real-time performance**
    - Latency and jitter figures of real-time traffic
  - **Overhead**
    - Consumed/wasted bandwidth
  - **Mutual isolation**
    - Support to heterogeneous traffic types without mutual interference
  - **Granularity of QoS control**
    - Diversity and parametrization of allowed QoS policies;
  - **Traffic management architecture**
    - Logical management architectures
  - **Flexibility**
    - Ability to create/modify reservations promptly/dynamically

# Qualitative comparison

- Real-time performance
  - **TSN**
    - [+] Supports TT and ET traffic (transmission gates, CBS, …) with low latency
    - [-] Limited number of classes (6 in practice), flat servers limit RT performance of ET traffic
  - **OpenFlow**
    - [-] No notion of real-time and time-triggered traffic. Poor performance.
  - **OpenFlow with extensions**
    - [++] FTT-OF, OF-RT support low latency TT and ET traffic (FTT arch)
    - [+] SDPROFINET: support for TT, but lacks support for ET
    - [+] TSSDN: supports TT with few limitations (node-level TX control)
    - [-] SDN-HSF: no support for TT. Enhance queuing provides isolation and BW control for ET traffic

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| RT Performance | TT | 5 | 1 | 5 | 4 | 5 | 1 | 5 |
| | ET | 3 | 1 | 5 | 1 | 3 | 3 | 5 |

# Qualitative comparison

- Overhead
  - **TSN**
    - [-] Reserved TT slots and frame preemption consume bandwidth
  - **OpenFlow**
    - [+] No relevant overheads
  - **OpenFlow with extensions**
    - [--] FTT-OF/OF RT: periodic trigger messages + idle time in TT windows
    - [-] SDPROFINET/TSSDN: only window idle time
    - [+] SDN-HSF: No relevant overheads

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| Overhead | | 4 | 5 | 3 | 4 | 4 | 5 | 3 |

# Qualitative comparison

- Mutual isolation
  - **TSN**
    - [+] Segregation of TT and ET traffic, filtering and policing
    - [-] Limited number of traffic classes
  - **OpenFlow**
    - [--] No intrinsic notion/distinction of traffic types
  - **OpenFlow with extensions**
    - [++] FTT-OF/OF RT: strict segregation of TT/ET/NRT traffic
    - [+] SDPROFINET/TSSDN: TT traffic segregation.
    - [--] SDN-HSF: No intrinsic notion/support to traffic types

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| Mut. Isolation | | 4 | 1 | 5 | 2 | 3 | 1 | 5 |

# Qualitative comparison

- QoS Granularity
  - **TSN**
    - [-] Overall modest
      - QoS specified per class, not per stream
      - Lacks explicit deadlines, precedence constraints, ...
      - CBS parameters specified as frames per interval and maximum latency
  - **OpenFlow**
    - [--] Only bandwidth and priorities
  - **OpenFlow with extensions**
    - [++] FTT-OF/OF-RT: full set of common QoS attributes
    - [+] SDPROFINET: allows capturing common QoS attributes (from formal spec)
    - [-] TSSDN: only periodicity of TT traffic (constrained to integer multiples of cycle)
    - [-] SDN-HSF: Only bandwidth and queuing discipline

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| QoS Granularity | | 3 | 1 | 5 | 2 | 4 | 2 | 5 |

# Qualitative comparison

- Traffic Management Architecture
  - **TSN**
    - [++] Distributed and centralized architectures
      - Scalability and efficiency, remote configuration
  - **OpenFlow**
    - [-] Restricted to (logically) centralized management
  - **OpenFlow with extensions**
    - [-] FTT-OF/OF RT: only centralized (master node)
    - [+] SDNPROFINET: multiple controllers on a remote control center
    - [-] TSSDN/SDN-HSF: same as OF

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| Management Arch. | | 5 | 3 | 3 | 3 | 4 | 3 | 3 |

# Qualitative comparison

- Flexibility
  - **TSN**
    - [-] Allows configuration but with restrictions (e.g. modifications imply tear down + creation, implying multiple messages, timeouts, …)
    - [-] No application support for QoS management
  - **OpenFlow**
    - [+] Highly flexible, but no application support for QoS management
  - **OpenFlow with extensions**
    - [++] FTT-OF/OF-RT: online creation/modification/elimination + admission control + QoS management support
    - [+] SDPROFINET/TSSDN/SDN-HSF: share properties of OF

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| Flexibility | | 3 | 4 | 5 | 4 | 4 | 4 | 5 |

# Qualitative comparison

- Overview

| Criteria | | TSN | OpenFlow | FTT-OpenFlow | TSSDN | SDPROFINET | SDN-HSF | OpenFlow RT |
|---|---|---|---|---|---|---|---|---|
| RT Performance | TT | 5 | 1 | 5 | 4 | 5 | 1 | 5 |
| | ET | 3 | 1 | 5 | 1 | 3 | 3 | 5 |
| Overhead | | 4 | 5 | 3 | 4 | 4 | 5 | 3 |
| Mut. Isolation | | 4 | 1 | 5 | 2 | 3 | 1 | 5 |
| QoS Granularity | | 3 | 1 | 5 | 2 | 4 | 2 | 5 |
| Management Arch. | | 5 | 3 | 3 | 3 | 4 | 3 | 3 |
| Flexibility | | 3 | 4 | 5 | 4 | 4 | 4 | 5 |

From 1 (Worse) to 5 (Better)

- Remarks
  - Overall TSN performs well.
    - Limitations on performance and flexibility arise from backward compatibility.
    - Configurable but without inbuilt mechanisms for online QoS management
  - Plain OF performs poorly in all aspects related with QoS and real-time
  - Extensions show that the SDN concept can be augmented to support real-time and can outperform TSN in term of performance and mostly flexibility

# Conclusions

- Industry 4.0 poses new requirements on the communication infrastructure
  - Heterogeneity, flexibility, adaptability, …
  - Existing industrial communication protocols cannot cope with those requirements
- Two innovative approaches: TSN and SDN
  - TSN
    - Overall good performance
    - Evolutionary approach bring inherent limitations and high complexity
    - Supported by IEEE and many players
  - SDN
    - Disruptive/clean slate, concept of network programmability
    - Highly flexible and effective, but lacks real-time performance
      - Extensions show that SDN can be augmented to allow RT services
    - Further R&D needed to ascertain its full potential

# Thank you!