Investigation on a Distributed SDN Control Plane Architecture for Heterogeneous Time Sensitive Networks

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***Abstract*—Data-driven services (optimization or condition monitoring) are often deployed using cloud architectures. The shop floor itself becomes more and more flexible and reconfigurable using modular machine design and Plug and Play services. These industrial use cases induce additional requirements to communication systems: scalable real-time communication from sensor to cloud as well as seamless and automatic network configuration on the shop floor. A promising data plane technology for the Industrial Internet of Things (IIoT) is IEEE 802.1 Ethernet TSN that allows convergent and time sensitive communication. The configuration of the IIoT is complex because the IIoT is often large, growing and changing over time and often consists of heterogeneous network domains because of the brownfield and manifold requirements from the applications. Software-defined Networking (SDN) has the potential to reduce the engineering effort and to increase the operation efficiency (monitoring, diagnosis, reconfiguration) of heterogeneous IIoT. SDN Control Planes can be implemented as physical-central, logic-central, distributed or hybrid architecture. The different architectures have specific advantages and disadvantages regarding QoS, throughput and engineering efforts. A key role takes the East-West interface that handles the communication between distributed SDN Controllers. SDN Data Plane agents can help to manage legacy Data Planes with SDN. A TSN Nano Profile with inverse and cooperative operating Time Aware Shaper is a migration solution to upgrade legacy communication controllers with TSN functions. The disadvantages are less throughput and increased latency for acyclic traffic.**

I. Introduction

Industrie 3.0 applies still the automation pyramid architecture (Fig. 1). There are five functional layers: shop floor (physical assets, sensor and actuators), PLC, SCADA, MES and ERP. The lower layers are called OT - Operational Technology and Industrial Communication systems like PROFINET or EtherCAT are used to fulfill the special QoS requirements (low latency and low jitter, synchronization). Often a central network configuration (CNC) is used. The upper layers apply IT - Information Technology and IP (Internet Protocol) communication. The layers are connected using gateways that have to be configured manually with often high engineering efforts. For a mass production system this is sufficient.

Industrie 4.0 defines additional requirements to industrial production systems. Mass customization, efficient automated production of small lot sizes and data-driven cloud-based services [1] that help to increase the overall efficient (energy optimization, condition monitoring and predictive maintenance) are important ones. These technologies require more flexible automation architecture [2].

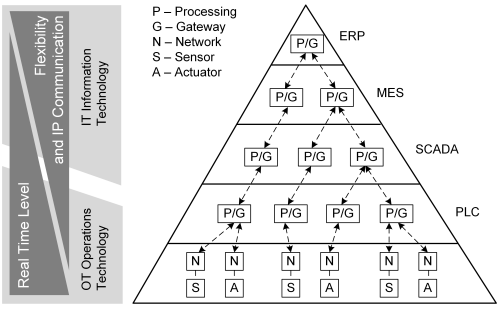

Fig. 1. Industrie 3.0 architecture: Automation Pyramid

A promising architecture is the Industrial Internet of Things (IIoT) [2]. Fig. 2 shows that the IIoT uses less gateways than the automation pyramid architecture and a more uniform communication with IP in the lower layers (shop floor) and also real-time capability in the upper layers (including cloud). The IT and OT are coalescing to the IIoT.

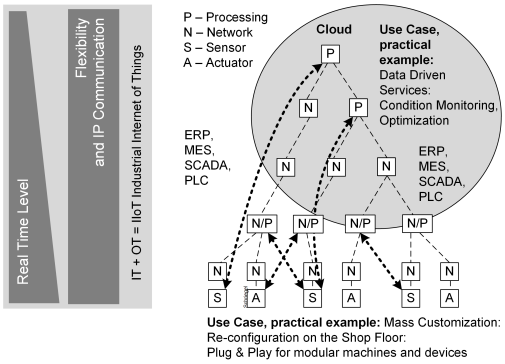

Fig. 2. Industrie 4.0 architecture: Industrial Internet of Things

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Fig. 3 summarizes and structures the requirements. There are Industrie 3.0 (OT) requirements regarding QoS, amount of data and devices as well as the requirements from Industrie 4.0 (IIoT): seamless reconfiguration (Hot Plug), Plug and Play, sensor to cloud communication and convergence.

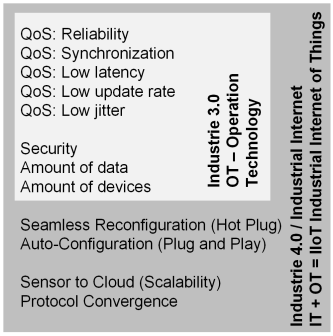

Fig. 3. Industrie 3.0 and Industrie 4.0 Requirements for Communication Systems

The brownfield in Industrial Automation is large and due to special heterogeneous requirements of the applications the solutions today are heterogeneous and often not interoperable. For the automation pyramid architecture this is not a serious problem because gateways are part of the architecture. For the IIoT this is completely different: A more holistic and common communication architecture is needed [2].

A promising technology at the communication MAC layer is Ethernet TSN that allows implementing convergent communication that is independent of protocols and that applies IEEE standards [3]. A promising technology at the communication PHY layer is APL (advanced physical layer) that allows Standard Ethernet and IP communication to low cost sensors on a low cost two wire cable (IEEE 802.3cg). A promising technology at the communication IP layer is DetNet that allows deterministic communication in a routed network (https://datatracker.ietf.org/wg/detnet/).

The configuration of this IIoT is a complex task because the IIoT is large, growing over time and it consists of heterogeneous network domains. In this paper SDN Control Plane architectures for the management of the IIoT are investigated. The investigation includes concepts of SDN for legacy and heterogeneous data planes as well as a migration solution to upgrade communication controllers with TSN functions.

This paper is organized as follows: Section II introduces the state of the art including Real-Time Ethernet, TSN, network configuration, SDN and DetNet. Section III introduces an distributed SDN Control Plane for heterogeneous Time Sensitive Networks. Section IV presents an investigation into QoS, Engineering Efforts, Seamless reconfiguration and Network Resource Efficiency. The paper closes with conclusions in section V and a suggestion for future research needs.

II. State of the Art

This section is structured into seven subsections (a to g). Figure 4 shows an overview including Data Plane, Configuration/ Network Control as well as Application layer trends from the past to the future.

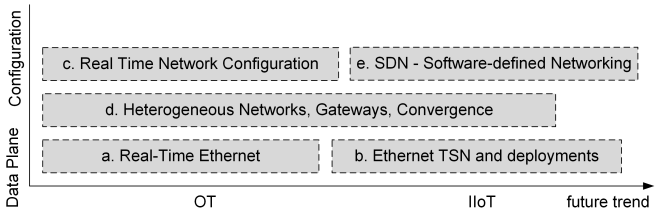

Fig. 4. Overview state of the art: Data, Control and Application Plane Technologies from past to future

A. Real-Time Ethernet Networks and Protocols

Ethernet-based Industrial Communication Systems can be classified into three categories which differ in the real-time performance and the extensions of the IEEE 802 standards [4]. Modbus is a example for class A that offers no special real-time an based on standard IEEE Ethernet. PROFINET RT is a example for class B that uses VLAN prioritization for a better real-time performance. PROFINET IRT and EtherCAT are examples for class C that uses MAC layer extensions for hard real time communication: time controlled media access, frame aggregation/ summation frame, frame fragmentation. Fig. 5 shows the time controlled media access of PROFINET IRT: a MAC layer with additional (to IEEE 802.1d) mechanisms that is defined in IEC 61158 (International Electrics Commission) standards. A PROFINET IRT network domain is interoperable with IEEE 802.1 Ethernet (best effort communication, not the IRT communication).

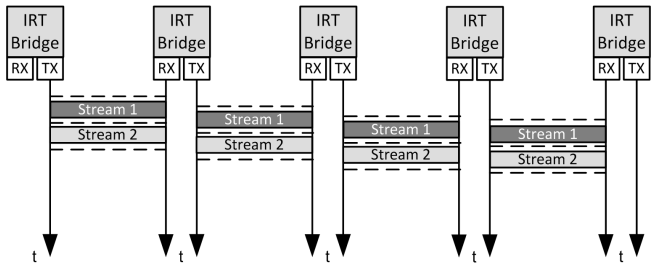

Fig. 5. PROFINET IRT: time triggered communication (IEC 61158/61784)

PROFINET IRT offers synchronization, low latency, reliability and small cycle times, but it needs special hardware and is not flexible (because of fixed send times for each frame that cannot be reconfigured seamlessly). The basic principles of IRT have been introduced to the IEEE for the recent years and are included (and improved) in the new IEEE 802.1 TSN standards.

B. Ethernet TSN Technology and System Deployments

Ethernet TSN is a couple of IEEE 802.1 (internetworking, bridging) standards that aims deterministic IEEE Ethernet communication. The precursor of Ethernet TSN was called AVB - Audio and Video Bridging (IEEE Std 802.1BA-2011)

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which has less QoS requirements and is focused on audio video applications [5] [6]. TSN adds control requirements from automotive and industry applications like low latency and reliability. The main standards are categorized in Time Synchronization (IEEE 802.1AS-Rev), Low Latency (IEEE 802.1Qav, IEEE 802.1Qbv Time Aware Shaper, IEEE 802.1Qbu Frame-Preemption), Reliability (IEEE 802.1CB) and Configuration [3].

Fig. 6 shows that the IEEE 802.1Qbv Time Aware Traffic Shaper (TAS) is using Gate Control lists that reserve specific time slots for specific streams. This is similar to PROFINET IRT but can operate basically without send times per frame and without central scheduling (if less bandwidth efficiency is acceptable).

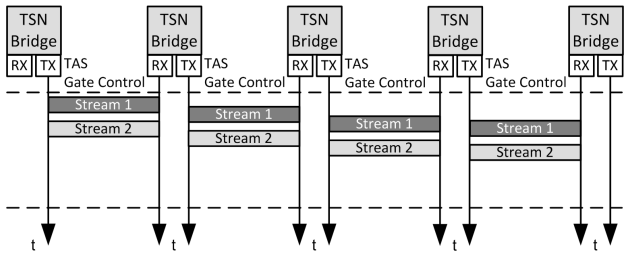

Fig. 6. Ethernet TSN IEEE 802.1Qbv: Time Aware Traffic Shaper

Ethernet TSN is an IEEE framework for deterministic and low latency Layer 2 Ethernet. Different vendors and groups are working on new real-time solutions based on TSN technology or on enhancements of existing systems with TSN. Known Ethernet TSN distributions are for example the following:

- PROFINET TSN: PI - Profibus International [7]
- OPC UA TSN: OPC Foundation, Shapers Group [8]
- SERCOS over TSN: SERCOS International [9]
- EtherCAT TSN Profile: ETG - EtherCAT Technology Group [10]
- Avnu Alliance: protocol independent (http://avnu.org/)

Furthermore there are testbed activities that are pushing the TSN system development and interoperability:

- IIC-Testbed TSN: http://www.iiconsortium.org/time-sensitive-networks.htm (Industrial Internet Consortium)
- LNI 4.0-Testbed TSN: https://lni40.de/ (Lab network Industrie 4.0)

The IETF (Internet Engineering Task Force) started in 2014 a working group regarding deterministic networking (DetNet). DetNet focuses on deterministic communication (bounded latency, packet jitter, reliability) over bridged and routed networks. The focus of DetNet are applications that need Layer 3 communication. DetNet is using TSN in Layer 2. The goal is a common architecture for Layer 2 and Layer 3. In detail DetNet defines an architecture, a Data Plane specification (flow identification and Layer 3 packet forwarding), a data flow information model (flow establishment and control) and YANG models.

C. Real-Time Ethernet Configuration

The configuration of Real-Time Ethernet Networks can be categorized into three models:

- **Unmanaged switched Ethernet network:**
  protocols: PROFINET RT, OPC UA, Modbus
  characteristics: no configuration efforts, complete distributed auto-configuration, no security, no netload control, low QoS
- **Managed switched Ethernet network**:
  protocols: PROFINET RT, OPC UA, Modbus
  characteristics: high configuration efforts, partly-distributed configuration, security, netload control by high configuration efforts
- **Central network configuration (CNC):**
  protocol: PROFINET IRT
  characteristics: high configuration efforts, security, full netload control, high QoS

An unmanaged switched network is relatively easy in the setup. The setup of managed switches can be done using web interfaces or using network configuration tools offered by the vendors. In addition to this basic models the network or system administrator often have to take care of network design rules that are prescribed for the systems. The PROFINET standard for example prescribes a maximum bandwidth usage of 60 % for real-time traffic and a maximum hop count of 64 [11]. A central network configuration offers the best QoS and network resource efficiency but is not very flexible and scalable. In 2017 Wisniewski [12] showed methods for engineering and seamlessly reconfiguring time triggered Ethernet-based systems during run-time, based on PROFINET IRT. In 2014 Schriegel [13] showed how an automatic determination of time synchronization accuracy of PTP networks with the objective of Plug and Work. In the patent ”Port-independent topological planned real-time network” from 2017 [14] a method is described that adapts configurations of a CNC to the physical network and that works distributed. In [15] and [16] auto-configuration approaches of Industrial Automation Systems are shown.
For Ethernet TSN the advantages and disadvantages of central and distributed configuration approaches are controversial discussed in the communities and user groups. The guiding idea of this paper is, that both are needed for the IIoT and that the concepts will be mixed: cascaded CNC, distributed SDN Controllers etc.

D. Heterogeneous Networks, Gateways and Convergence

The brownfield in industrial automation is very large. Additionally devices (PLC, distributed IO), protocols (PROFINET), communication profiles (motion, safety), the network infrastructure (switches, routers), the application and the configuration tool chains are often integrated (remote IO device with integrated switch, PLC with integrated network configuration, engineering with integrated network and PLC engineering, application protocols with integrated network configuration). The life cycle of industrial production systems are long-term.

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Because of this migration strategies and solutions that enable a faster integration of new technology into this legacy systems are valuable. Due to complex machine designs including processes, mechanics, electric and IT today a lot of new machines are delivered with legacy IT technology. Because of this there are and there will be a lot of heterogeneous industrial networks in the field.

Fig. 7 shows a network which uses PROFINET IRT for the machine communication (incl. motion control), Ethernet TSN on the Shop Floor and Ethernet without TSN in the Factory IT as well as an Internet access via router. An Internet-based cloud application as well as a on-premise cloud application are connected to a machine sensor using OPC UA protocol.

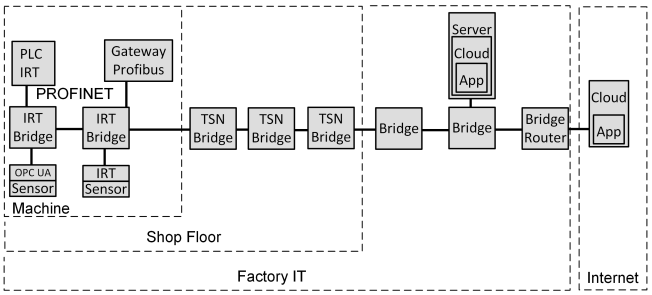

Fig. 7. Heterogeneous Industrial Network

The are two main solutions concepts creating a network with different protocols and link technologies: gateways (Fig. 7) and convergence. Fig. 8 shows how a convergent network with TSN can operate. The protocols PROFINET, OPC UA and a video stream are configured to specific bandwidth resources using the Time Aware Shaper mechanism of IEEE 802.1Qbv.

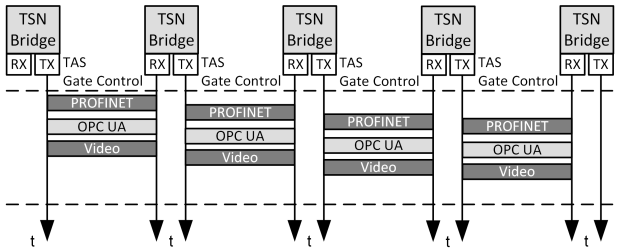

Fig. 8. Application Protocol Convergence with Ethernet TSN

E. Software-defined Networking

A promising network management architecture is Software Defined Networking (SDN) [17] [18]. Fig. 9 shows the basic architecture of SDN: The configuration logic is separated from the physical network. The physical network and the devices that forward packets are called Data Plane. The configuration of the Data Plane is done using a Control Plane that consists of a Central Network Controller (CNC) or of distributed Network Controllers (NC). The Data Plane and the Control Plane are connected via a Southbound interface, exemplary protocols are OpenFlow (ONF - Open Networking Foundation), NETCONF (IETF RFC 6241) or SNMP. Above the Control Plane the Application Plane is responsible for the generation of communication needs. The Control Plane and the Application Plane are connected using the Northbound interface.

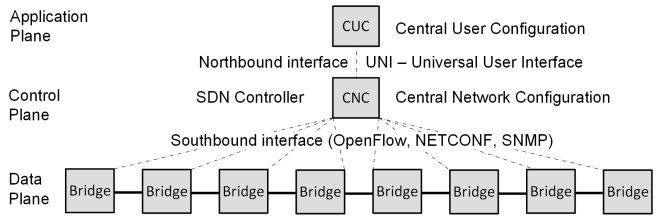

Fig. 9. Architecture of Software-defined Networking

Fig. 10 shows how SDN and IEEE 802.1Qcc Southbound interface, OPC UA and Ethernet TSN can operate in combination.

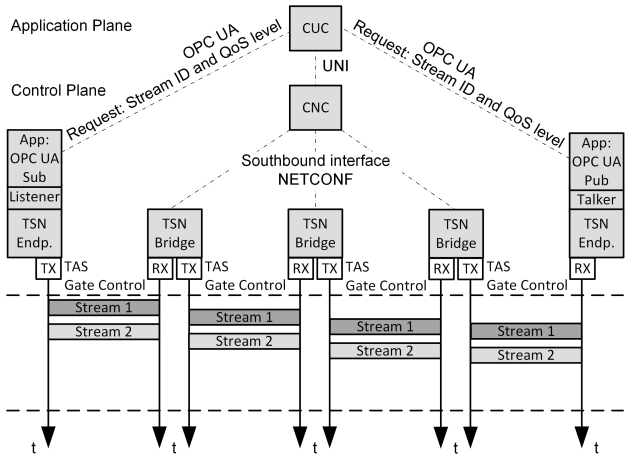

Fig. 10. Centralized Configuration Model of IEEE 802.1Qcc for OPC UA TSN

In 2017 Najak published Time-Sensitive Software-defined Networks for Real-Time Applications [19]. In 2016 Kumar published End-to-End Network Delay Guarantees for Real-Time Systems using SDN [20]. Fig. 11 shows that the SDN Control Plane can be distributed as well. The SDN Controllers of the Control Plane are communicating via a so-called East-West interface among each other.

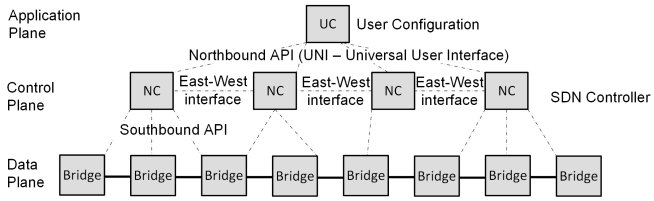

Fig. 11. Distributed SDN Control Plane (cascaded CNC)

In 2014 [21] DISCO - a distributed SDN controller for multi-domain environments was introduced. In 2016 Pop [22] presented a design optimized cyber-physical system using TSN. In 2017 Csaba [23] published a work regarding Ethernet

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with Time-Sensitive Networking tools for Industrial Networks. In 2017 Bannour [24] published a work describing survey, taxonomy and challenges of distributed SDN control plane. Fig. 12 shows that SDN Control Plane architectures can be classified to physical-central and physical-distributed; logical-central, logical-distributed and hybrid. A physical-central Control Plane generates optimal results regarding QoS like low latency as well as optimal network resource efficiency. But it is not scalable. Available SDN Controller implementations are NOX, Floodlight and Beacon. A physical-distributed Control Plane is scalable. The architecture can be flat or hierarchical. Implementations of SDN Controllers supporting a flat design are ONIX, OpenDaylight, ONOS and DISCO. Kando and Espresso are using hierarchical Control Plane architectures. Distributed SDN Controllers communicate via the East-West interface among each other. With increasing detail level of East-West communication a physical-distributed Control Plane gets more logical-central.

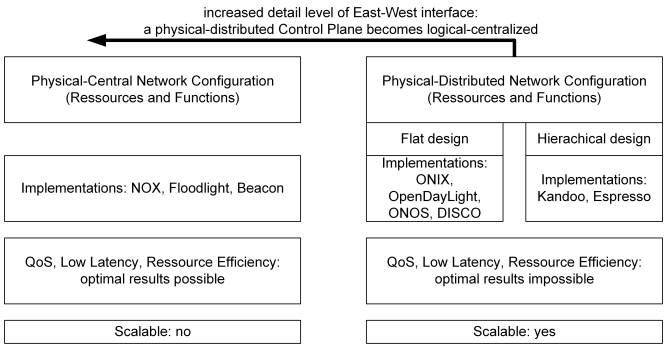

Fig. 12. Classification of SDN Control Plane Architectures: physical-central, physical-distributed, logical-central, logical-distributed and intermediate

In November 2016 the German Platform Industrie 4.0 published a discussion paper Network-based Communication for Industrie 4.0 Proposal for an Administration Shell [25]. Fig. 13 shows that the SDN controller and the assets that are controlled via the southbound interface (the data plane/ bridges) can be a I4.0 component. Doing this the administration shell acts like a Northbound interface because it connects the applications with the network (SDN controller and network resources).

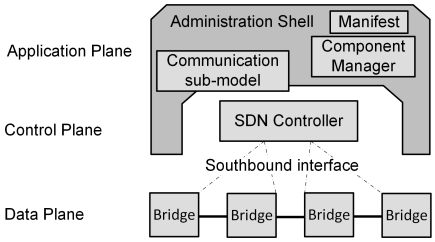

Fig. 13. Industrie 4.0 Administration Shell for SDN [25]

III. Distributed SDN Control Plane Architecture for Heterogeneous Time-Sensitive Networks

In this section a concept of a Distributed SDN Control Plane Architecture (cascaded CNC - cascaded Central Network Controller) for heterogeneous Time-Sensitive Networks is introduced. Because of the brownfield a concept for an SDN Agent for integration of legacy Data Planes to SDN and a TSN Nano Profile that enables an update of legacy hardware (ASICs) with TSN functions complement the basic SDN concept. The major aims are (1) to fulfill communication requirements sensor-to-cloud, convergence, scalability, seamless auto-reconfiguration, QoS (Section I, Figure 3) as well as (2) speed up the migration from the automation pyramid to the IIoT architecture (Section I, Fig. 2). Fig. 14 shows the three concepts as grey boxes.

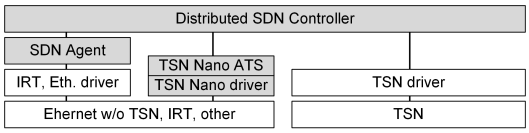

Fig. 14. Overview and association of the three concepts (grey)

A. Distributed SDN Control Plane

Fig. 15 shows the Distributed SDN Control Plane Architecture for a uniform (homogeneous) TSN Data Plane. The machine OT consists of TSN bridges, a PLC and remote devices (sensors, actuators). PROFINET (PN) is used for the PLC to device communication over TSN. An SDN Network Controller (NC), integrated into the PLC, configures the TSN bridges of the machine by southbound IF: stream setting and path information, TAS bandwidth reservation. An OPC UA sensor is connected to the machine network. A cloud-based application receives data from the sensor by OPC UA. This sensor-to-cloud communication is configured by the Distributed SDN Controller.

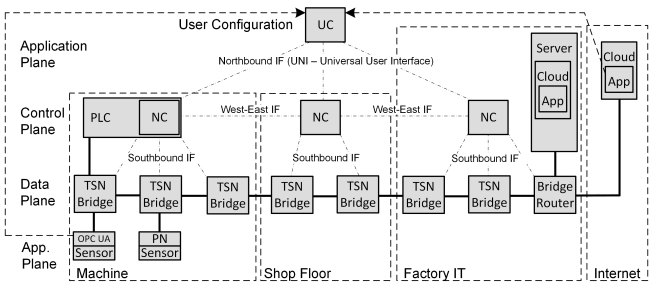

Fig. 15. Distributed SDN Controller (cascaded CNC) for TSN-based Data Plane

Fig. 15 shows that there are four areas of responsibility: machine, shop floor, factory IT, Internet. Each area (or network domain) is using one (local) SDN Controller for Data Plane configuration. The responsibilities regarding network resources, QoS or SLA are clearly assigned. By the help of the West-East interface communication relations that cross more that one of this network domains can be configured as well.

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B. SDN Agent

Fig. 16 shows how legacy Data Planes (here PROFINET RT) could be integrated into an SDN Control Plane using an agent. The agent is a software that communicates with an SDN controller via a Southbound interface. Furthermore the agent contains information about the legacy Data Plane. This can be run-time information (topology, cable length, traffic statistic counter, link speed) and offline information (buffer capacity of the bridges, latency, number of supported queues, number of supported streams). In case of PROFINET this offline information is taken from the device description files (GSDML) and from the PROFINET standard (maximum hop count, maximum real-time netload). The SDN Agent administers the resources of a network.

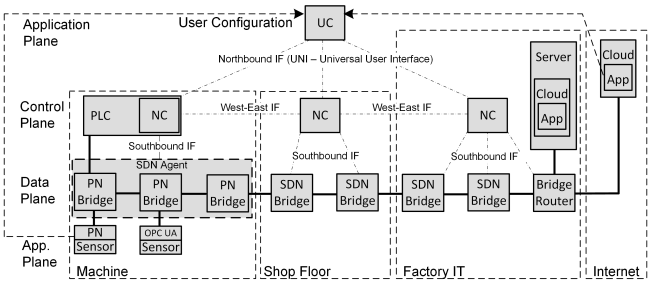

Fig. 16. SDN agent for integration of legacy PROFINET devices and network into a SDN architecture

C. TSN Nano Profile with inverse and cooperative operating Time Aware Shaper (local scheduled acyclic traffic)

A TSN Nano Profile with inverse and cooperative operating Time Aware Shaper is a migration solution to upgrade communication controllers with two external ports (and one internal port for the local application) with TSN functions. The profile and the TSN Nano operation procedure are tailored in order to minimize HW requirements (timestamps and timed transmit from the local port), so that chances are high that TSN Nano Profile can be installed by a driver update to legacy ASICs. The profile include the following standards and hardware requirements:

- IEEE 802.1AS-Rev Timing and Synchronization
  full implementation
  HW requirement: time stamps
- IEEE 802.1Qbv Enhancements for Scheduled Traffic
  Time Aware Traffic Shaper: inverse and cooperative operating mode (ATS)
  HW requirement: timed transmitting of local frames, flexible forwarding table
- IEEE 802.1CB Frame Replication and Elimination for Reliability
  full implementation in SW
  no HW requirement
- IEEE 802.1Qcc Stream Reservation Protocol (SRP) Enhancements and Performance Improvements
  no HW requirement

Fig. 17 shows how the inverse and cooperation Time Aware Shaper (TAS) operates. The streams that are configured for the TAS (from the CNC) are converted into an inverse model: In the unoccupied send time ranges, the frames from the local ports (acyclic traffic) are timed. The TSN Nano line uses a Acyclic Traffic Scheduler (ATS) for the scheduling of the acyclic traffic. The ATS can be integrated into one of the TSN Nano bridges but also to any other network component. The scheduling of the acyclic traffic can be done in advance (unflexible), on demand (flexible bug more management efforts and traffic) or as an combination of both. The specific design of this is not content of this paper. A special role have the borderline bridges that connect a TSN Nano Profile domain with a full featured TSN network or with a Standard Ethernet network. This networks send acyclic traffic unregulated. On this reason the borderline device has to buffer this traffic and forward it timed into the TSN Nano Profile Domain. Because there will be no device that is able to do that in hardware and because the borderline device will be a TSN Nano Profile device in the most cases as well the forwarding has to be handled by software.

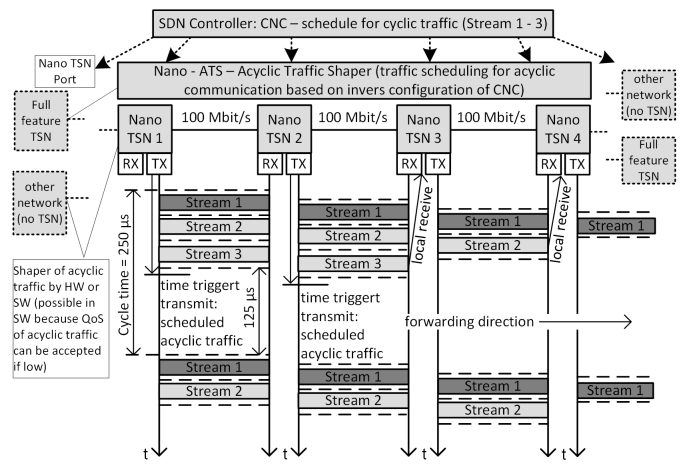

Fig. 17. Ethernet TSN Nano line topology of four devices with Acyclic Traffic Scheduler (ATS) for acyclic traffic: inverse operation to configured cyclic traffic

The disadvantages are that the throughput of acyclic traffic is not optimal, a higher latency of acyclic traffic due to software-based forwarding in the TSN Nano line border device occurs and that the minimum cycle time is limited to 250 µs at 100 MBit/s (no preemtion). A more precise investigation about performance issues is following in the next section.

IV. Investigation into Performance and Interoperability

The previous section showed (1) a general Distributed SDN Control Plane Architecture for Industrial Time-Sensitive Networks, (2) a concept using an SDN agent for integration legacy networks to SDN and (3) a TSN Nano Profile with inverse and cooperative operating Time Aware Shaper. The concepts generate questions that have to be investigated:

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Question: What are the critical issues regarding performance and interoperability of the Distributed SDN Control Plane Architecture, the SDN Agent and the TSN Nano Profile with inverse and cooperative operating Time Aware Shaper?

The approaches were investigated with the help of mathematical analysis as well as physical test environments:

1) SmartFactoryOWL (www.smartfactoryowl.de) and IIC-Testbed Smart Factory Web: Modular Production System
2) SDN test setup: open-source SDN controller OpenDaylight, Northbound Networks Zodiac Data Plane (OpenFlow) and PROFINET devices TPS-1, PROFINET PLC
3) TSN test setup: NXP switches, PROFINET, OPC UA, video traffic

The test environments are used to evaluate the performance (QoS, configuration, network resource efficiency) and interoperability (protocol convergence). The following list gives an overview about the evaluation scenarios that have been carried out:

a Engineering Efforts for a high available (QoS) sensor to cloud communication using OPC UA of SmartFactoryOWL and IIC-Testbed Smart Factory Web
b Convergence, availability, interoperability and seamless reconfiguration of Ethernet TSN
c Interoperability of SDN and PROFINET
d Throughput for cyclic and acyclic traffic of a SDN Agent- and a TSN Nano Profile-Concept
e End-to-End Latency using cascaded CNC

A. Engineering Efforts for high available Sensor to Cloud communication using OPC UA of SmartFactoryOWL and IIC-Testbed Smart Factory Web

The engineering efforts are evaluated using a modular production system in the SmartFactoryOWL. The production system is connected to a cloud based data analytic application. Fig. 18 shows the modular production system. PROFINET is used for the real-time communication. The production system is connected via a shop floor switch and a core switch to a server and to a router.

For implementing a high available OPC UA communication, bandwidth has to be allocated (data path). Each device has to be manually re-configured, what leads to engineering efforts. Different engineering tools and web interfaces are in use: PLC and PROFINET engineering Phoenix Contact PCWorX (device name, IP address, QoS settings, cycle time), machine switch web interface, shop floor switch web interface, core switch, router/ firewall, cloud portal.

Result: The all over engineering time was estimated with 4 hours based on real experiences of the responsible IT Expert of the SmartFactoryOWL.

By the use of SDN (and the SDN Agent and the TSN Nano Profile) the engineering efforts could be reduced and automated (Plug and Play). This is investigated in the next sections.

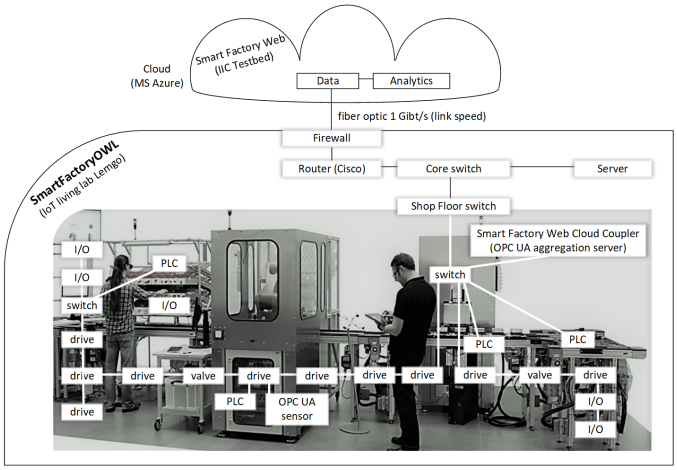

Fig. 18. Modular Production System of SmartFactoryOWL connected to the Smart Factory Web

B. Convergence, availability, interoperability and seamless-reconfiguration of Ethernet TSN

Convergence, availability, interoperability and seamless-reconfiguration of TSN was investigated using NXP switches, PROFINET communication, OPC UA communication as well as a video stream. The NXP switches support time synchronization, Per-stream policing, Credit Based Shaper (IEEE 802.1Qav) and Time Aware Shaper (802.1Qbv). Fig. 19 shows the topology. The Time Aware Shaper was configured for a PROFINET stream, a video stream and a OPC UA communication so that each stream has a locked bandwidth. Additional netload was used to test if the convergent configuration works. It was shown that it is possible to add a OPC UA communication to a running PROFINET communication.

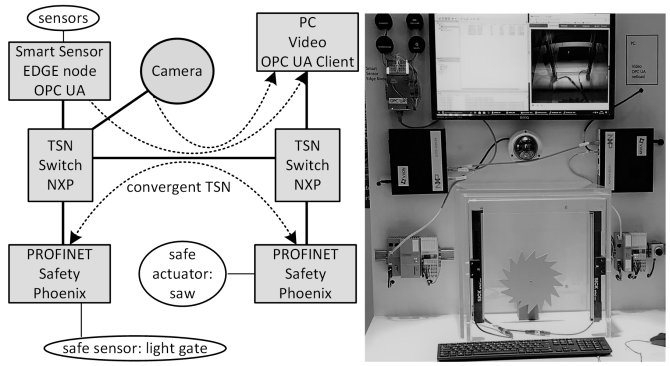

Fig. 19. Test topology (left) and physical test setup (right) for Convergent Ethernet TSN

C. Interoperability of SDN and PROFINET

The interoperability of an SDN architecture and PROFINET was evaluated using the SDN switch Zodiac FX-Rev A from

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Northbound Networks, a PROFINET PLC Siemens S7-1500, PROFINET devices TPS-1 and the SDN controller OpenDaylight (Version Nitrogen, Nov 2017) as well as the user interface DLUX. Figure 20 shows the setup including the engineering tool TIA from Siemens and the usage of GSDML files for the device description. By the help of standard switch functions of OpenDaylight/ OpenFlow (MAC address learning, packed forwarding) cyclic PROFINET communication was established. In addition to that it is possible to program a specific network behavior: switch off the MAC address learning, add static routes or switch off ports.

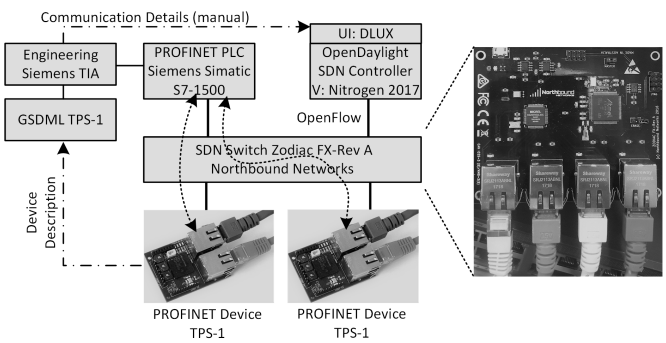

Fig. 20. SDN PROFINET Test Setup: left: topology and information flow; rigth: Zodiac Board

Result: SDN and OpenFlow are basically interoperable (Data Plane) with the PROFINET protocol. But there is no defined interface in the engineering tools today.

D. Throughput for cyclic and acyclic Traffic of SDN Agent and TSN Nano Profile

The maximum throughput T_{Cmax} for cyclic real-time traffic regarding Data Plane (DP) technology and Control Plan (CP) technology and the maximum throughput T_{Amax} for acyclic traffic of TSN Nano Profile was evaluated.
Fig. 21 show the results of the maximum throughput T_{Cmax} for cyclic real-time traffic.

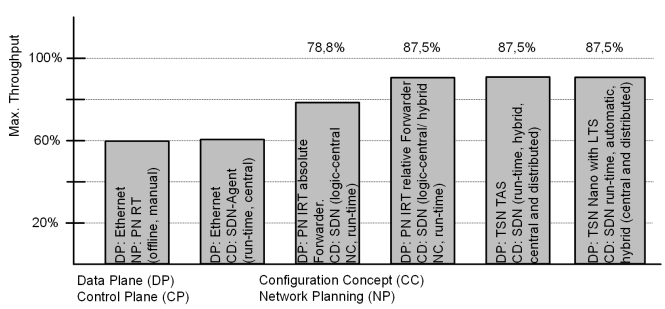

Fig. 21. Max Throughput cyclic traffic T_{Cmax} (cycle time = 1ms, 100 Byte cyclic frames, no preemtion, no fragmentation) depending on Data Plane (DP) and Control Plane Concept (CP)/ Configuration Concept (CC)

In PROFINET RT networks (switched Ethernet) a maximum throughput of 60 % of bandwidth for cyclic real-time traffic allowed by the standard. This is the condition for a specific guaranteed real-time behavior. The Network Planning (NP) is manual by the network engineer. With the help of SDN the network planning becomes automated by the help of SDN Agent. With the help of IRT or TSN the maximum possible throughput increases because of a better traffic shaping possibilities. Formula 1 shows that the maximum throughput $T_{CmaxIRT}$ for cyclic Real-Time Traffic of IRT depends on the number of frames n_{frames}, the cycle time ct, the maximum Transfer Unit MTU (1500 Byte), the $Bitrate$ (100 MBit/s) and the synchronization accuracy SA ($1\mu s$).

$$T_{CmaxIRT} = \frac{ct - (MTU/Bitrate) - (n_{frames} \cdot SA)}{ct} \quad (1)$$

Formula 2 shows that the maximum throughput $T_{CmaxIRTrel}$ for cyclic Real-Time Traffic of IRT with relative Forwarder depends only on the cycle time ct and is equal to TSN TAS ($T_{CmaxTSNTAS}$).

$$T_{CmaxTSNTAS} = T_{CmaxIRTrel} = \frac{ct - (MTU/Bitrate)}{ct} \quad (2)$$

The TSN Nano Profile with inverse and cooperative operating Time Aware Shaper has disadvantages regarding the throughput for acyclic traffic: the throughput decreases. Formula 3 shows that the throughput $T_{AmaxTSNNano}$ for acyclic traffic of TSN Nano depends on the Bridge Delay BD, the Peer Delay PD and of the number of cascaded TSN Nano bridges n_{cb}.

$$T_{AmaxTSNNano} = (MTU/Bitrate) + (PD + LD) \cdot n_{cb} \quad (3)$$

Fig. 22 and 23 show the throughput for the acyclic communication in dependence of the number of cascaded bridges and the minimal required time window that is need for the acyclic traffic (decreasing throughput for acyclic traffic, increasing minimum cycle time).

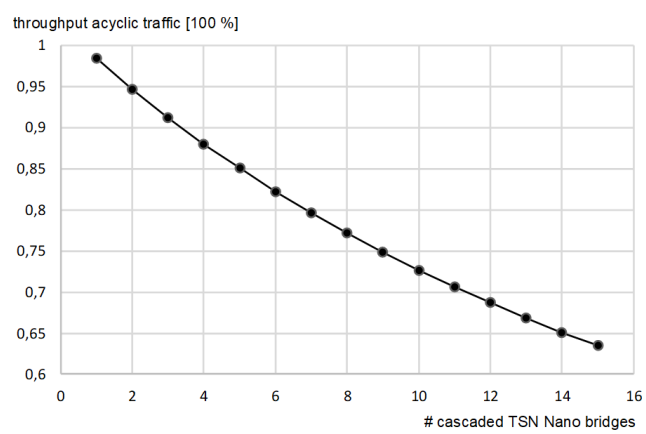

Fig. 22. Throughput for acyclic traffic using the TSN Nano Profile with ATS (cable + bridge delay = 5 µs, MTU = 1500 Byte)

E. End-to-End Latency using cascaded CNC

The End-to-End latency depends on TSN bridge parameter (Bridge Delay BD) and of the configuration. The lowest possible latency can be achieved by logically-central configuration

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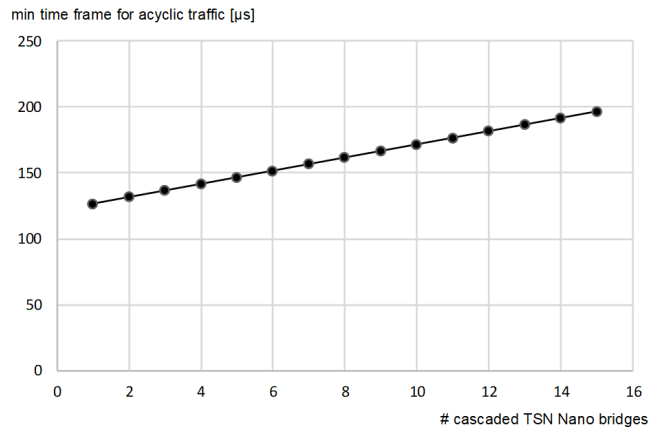

Fig. 23. Minimal required time window for acyclic traffic using the TSN Nano Profile with ATS (cable + bridge delay = 5 µs, MTU = 1500 Byte)

(one CNC) that is able to guarantee Cut Through Switching for frames with low latency requirement. Using cascaded CNC that do no communicate each other (no East West-Interface with timing and scheduling information) the latency increases. Formula 4 shows that the maximum End-to-End Latency l_{E2Emax} in this case depends on the TAS window TAS_{window}, the number of TSN bridges $n_{TSNbridge}$, the number of CNC n_{CNC} and of the Peer Delay PD and Bridge Delay BD.

$$l_{E2Emax} = ((n_{TSNbridge} \cdot (PD+BD)) + (n_{CNC} \cdot TAS_{window}) \quad (4)$$

Based on real maximum forwarding delays of the communication controller TPS-1 [26], [27] the latency was investigated if a distributed Control Plane Architecture (cascaded CNC) is used. Fig. 24 shows the result. It is shown that the End-to-End latency increases by the number of not synchronized and independent configured TSN bridges and by TAS configuration.

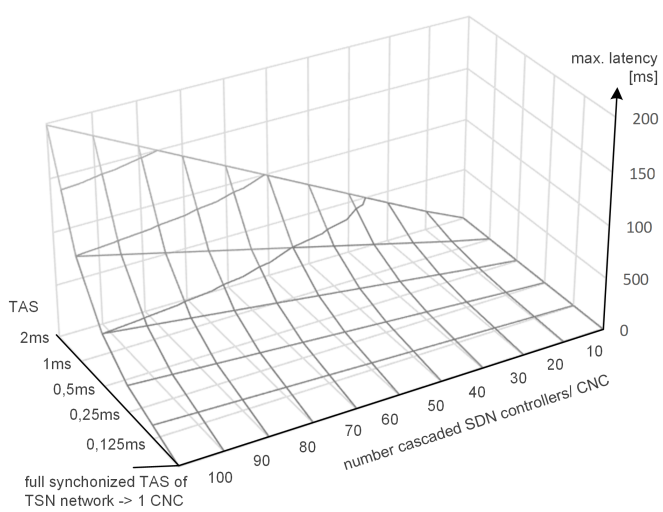

Fig. 24. Max End-to-End Latency of 100 TSN bridges in dependence of number of cascaded CNC and TAS configuration

V. Conclusion and Future Work

In this paper a distributed SDN Control Plane Architecture for heterogeneous Time Sensitive Networks was introduced and investigated. In addition to this an SDN agent for integration of legacy switched networks (example PROFINET) to SDN and the TSN Nano Profile with inverse and cooperative operating Time Aware Shaper for the update of legacy devices (hardware, ASICs) with TSN functions (legacy HW and new FW) was introduced.

Investigations into QoS (latency), engineering efforts, seamless reconfiguration, convergence, network resource efficiency/ throughput and interoperability was shown. The usage of **Distributed SDN Control Plane architectures** has the potential to reduce the engineering effort and to increase the operation efficiency (monitoring, diagnosis, reconfiguration) of the IIoT. SDN Control Planes can be implemented as physical-central, logic-central, distributed or hybrid architecture. The different architectures have specific advantages and disadvantages regarding QoS, network resource efficiency and engineering efforts. A key role takes the East-West interface that handles the communication between distributed SDN Controllers. Without East-West interface the latency increases with the increasing number of cascaded CNC and TAS window.

SDN agents can help to integrate legacy networks to SDN and a **TSN Nano Profile** with inverse and cooperative operating Time Aware Shaper can help to upgrade legacy devices with TSN functions by software. The disadvantages of the TSN Nano Profile are that the throughput for acyclic non real-time traffic is decreased to less than 65 % for 15 cascaded TSN Nano devices, the latency increased and the minimum cycle time of cyclic traffic is limited to 250 µs.

The investigations covering parts of the research field of TSN stream reservation for heterogeneous networks using SDN, cascaded CNC and migration of legacy networks and devices towards Ethernet TSN. In the future we will undertake simulation-based investigations as well as system evaluation using enhanced prototypes and test networks.

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