OPC UA TSN
A new Solution for Industrial Communication

D. Bruckner[†] R. Blair[¶] M-P. Stanica[*] A. Ademaj[‡] W. Skeffington[§] D. Kutscher[‖] S. Schriegel[**]
R. Wilmes[††] K. Wachswender[‡‡] L. Leurs[x] M. Seewald[xi] R. Hummen[xii] E-C. Liu[xiii] S. Ravikumar[xiv]

[†]B&R Industrial Automation, *dietmar.bruckner@br-automation.com*
[¶]Schneider Electric, *rick.blair@schneider-electric.com*
[*]ABB Automation Products, *marius-petru.stanica@de.abb.com*
[‡]TTTech Computertechnik, *astrit.ademaj@tttech.com*
[§]General Electric Company, *wesley.skeffington@ge.com*
[‖]Huawei Technologies, *dirk.kutscher@huawei.com*
[**]Fraunhofer IOSB-INA, *sebastian.schriegel@iosb-ina.fraunhofer.de*
[††]Phoenix Contact Electronics, *rwilmes@phoenixcontact.com*
[‡‡]Intel Corporation, *karl.wachswender@intel.com*
[x]Bosch Rexroth, *ludwig.leurs@boschrexroth.de*
[xi]Cisco Systems, *maseewal@cisco.com*
[xii]Hirschmann Automation and Control, *rene.hummen@belden.com*
[xiii]Moxa, *ericcc.liu@moxa.com*
[xiv]Kalycito Infotech, *siddharth.r@kalycito.com*

Abstract—The industrial communication market is dominated by Ethernet-based fieldbus systems. Although they share similar requirements and market segments, their implementations and ecosystems differ considerably. The majority of them have a corresponding umbrella organization that is guided and financed by one big market player who drives development of the technology. Stakeholders in the value chain are usually not well aligned in their decisions for particular technologies. As a result, end customers and device manufacturers are faced with a multitude of technologies that need to be produced, run, diagnosed, maintained and kept in stock. While the availability of products and services is largely satisfactory, dealing with multiple solutions generates high costs and limits IoT capability. This joint position paper introduces OPC UA TSN as a vendor-independent successor technology and presents the current view. We have found that – by choosing the right set of features – it is able to fulfill both today's and tomorrow's industrial communication requirements while in the mid-term leveraging the cost benefits of standard Ethernet hardware. The TSN network infrastructure as an evolution of AVB is simultaneously able to carry all types of industrial traffic, from hard real-time to best-effort, while maintaining the individual properties of each method. OPC UA is a major evolution from the OPC communication standards targeting embedded usage. The latest evolution described as Publish/Subscribe goes further and is aimed at embedded devices, optimizing performance in small footprints. It adds a meta model for describing data, as well as a communication infrastructure for exchanging and browsing information. Additionally, OPC UA comes with a built-in security model that helps implement secure systems in accordance with upcoming standards like IEC 62443. We anticipate that OPC UA TSN will quickly reveal itself as a game changer in the field of industrial automation, being the first and only candidate for establishing a holistic communication infrastructure from the sensor to the cloud.

I. Introduction

A. Industrial communication

Industrial communication today is mainly organized according to the automation pyramid (see Fig. 1). On top,
at the computer level, standard IT protocols (Internet Protocol Suite[1]) are used. For machine-to-machine and process communication (the distributed controller level), the role of OPC UA (IEC 62541[2]) is rapidly increasing in significance alongside the traditional Ethernet-based M2M fieldbus systems (PROFINET[3], EtherNet/IP[4], CC-Link IE[5]). Inside the machine (device and sensor levels), protocols with hard real-time capabilities (also known as real-time Ethernet) dominate the field[6]. According to market share, the most significant ones are EtherCAT[7], PROFINET IRT[8], POWERLINK[9] and Sercos III[10]. Although these technologies share common requirements, their implementations differ substantially. Hence, comparing them is a complicated matter and depends heavily on the intended application (process control, motion, I/O, centralized vs. decentralized control, etc.). An endeavor to compare the performance of various real-time Ethernet protocols in a number of categories has been undertaken by the Ethernet POWERLINK Standardization Group (EPSG)[11].

[1]https://en.wikipedia.org/wiki/internet_protocol_suite
[2]https://opcfoundation.org/about/opc-technologies/opc-ua/
[3]http://www.profibus.com/technology/profinet/
[4]https://www.odva.org/Technology-Standards/EtherNet-IP/Overview
[5]https://www.cc-link.org/en/cclink/cclinkie/index.html
[6]Globally, Industrial Ethernet and traditional fieldbus systems currently claim comparable shares of the industrial communication market. New developments primarily use Ethernet-based systems, resulting in a higher growth rate. Devices with traditional fieldbus interfaces are increasingly being replaced and shipped only for legacy products and plants.
[7]https://www.ethercat.org/en/technology.html
[8]http://www.innovasic.com/news/industrial-ethernet/profinet-rt-vs-profinet-irt/
[9]http://www.ethernet-powerlink.org/en/powerlink/technology/
[10]http://www.sercos.org/
[11]http://www.ethernet-powerlink.org/en/downloads/industrial-ethernet-facts/

(a) Levels of the automation pyramid

(b) Today's distinct ecosystems in the automation pyramid

(c) Holistic communication from the sensor to the cloud using OPC UA (and TSN)
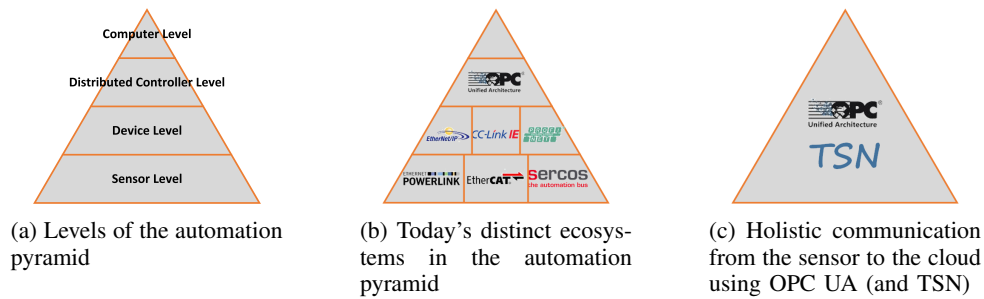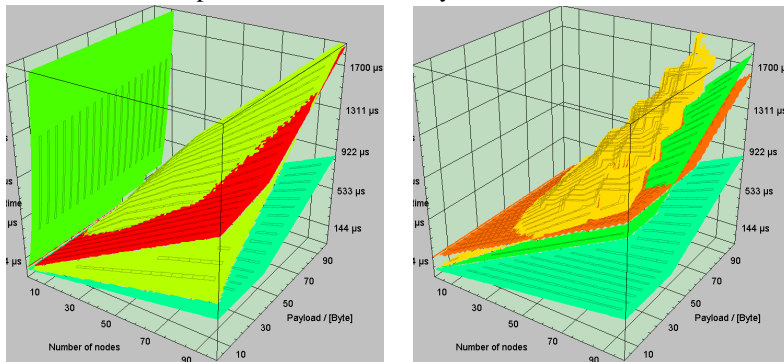
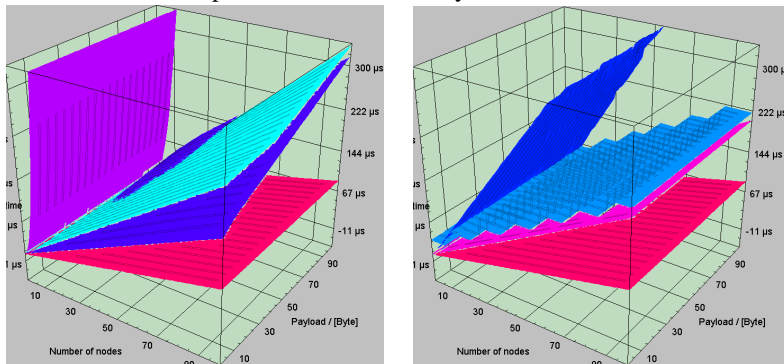Figure 1: Automation pyramid – different levels of communication needs.

Comparison of minimum cycle times @100Mbit.

(a) light green: Modbus/TCP
yellow-green: SERCOS III
red: POWERLINK
aqua: OPC UA TSN

(b) dark orange: Profinet IRT[*)]
green: EtherNet/IP
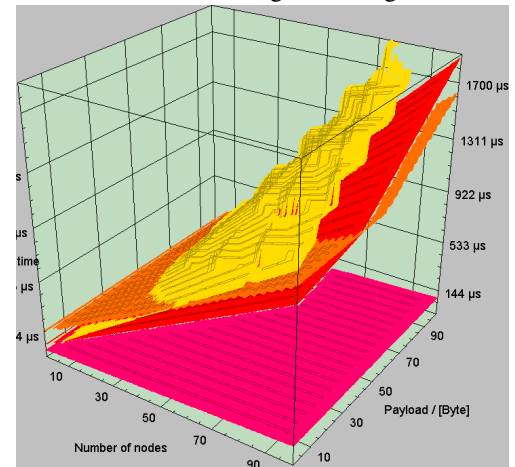light orange: EtherCAT[†)]
aqua: OPC UA TSN

Comparison of minimum cycle times @1Gbit.

(c) purple: Modbus/TCP
dark blue: SERCOS III
light blue: POWERLINK
magenta: OPC UA TSN

(d) grey blue: Profinet IRT[*)]
pink: EtherNet/IP
mid blue: EtherCAT[†)]
magenta: OPC UA TSN

Comparison of minimum cycle times of OPC UA TSN @1Gbit with existing technologies.

(e) dark orange: Profinet IRT[*)]
light orange: EtherCAT[†)]
red: POWERLINK
magenta: OPC UA TSN

Figure 2: Comparison of minimum cycle times. Figures 2a & 2b @100Mbit, Figures 2c & 2d @1Gbit, Figure 2e shows OPC UA TSN @1GBit compared to today's technologies with 100Mbit, all up to 100 devices and up to $100\ byte$ payload. The following parameters have been used:

- Line topology, output data = 40% of input data, cross traffic for 20% of devices
- Forwarding latency @100Mbit: TSN: $3\mu s$, switch: 10 μs, PLK: 0.76 μs, EC: 1.35 μs, SER: 0.63 μs
- Forwarding latency @1Gbit: TSN: 780 ns, Switch: 2 μs, PLK: 0.76 μs, EC: 0.85 μs, SER: 0.63 μs
- 25% of devices are modular I/Os comprised of 20 slices (only affects EtherCAT)

The implementations in the magenta and aqua planes use OPC UA Pub/Sub over raw Ethernet with frame aggregation. However, potentially using Pub/Sub over UDP/IP shows an indistinguishable plane, while potentially using single frames increases the cycle times for payloads over approx. $50\ bytes$.

Figure 2e shows that an advantageous implementation of OPC UA TSN with Gigabit physical layer outperforms existing solutions (based on $100Mbit$) by approximately a factor of 18.

[*)] Profinet IRT cycle times are always multiples of 31.25 μs

[†)] The ridges in the cycle time plane represent the use of a new Ethernet frame

Table I: Notations for computing cycle time

Term	Notation	Unit
Minimum cycle time	Γ	s
Transmission delay	τ	s
Network device latency	l	s
Propagation delay	δ	s
Link capacity	C	$bits/s$
Payload	x	$bytes$
Number of network devices	n	-

B. Cycle time comparison

Over the years, the tendency has been to compare Industrial Ethernet technologies based on their respective feature sets. Even more important, however – particularly in motion control applications – is the performance of the technology, measured in terms of smallest cycle time [1] that can be achieved for a particular application. It can be seen as the most challenging metric, and if a technology fulfills this requirement, it can also be utilized in less timely challenging environments. The smallest achievable cycle time is the time required for a PLC to send all outputs to its slaves[12] and receive all of their inputs in return. It is important that all slaves receive their outputs from the PLC within the same cycle[13]. [2] introduced a basic method for estimating minimum cycle times for several technologies. Their contribution includes a 2D diagram showing the respective minimum cycle times as a function of the number of devices. The following will provide a summary of the basic mechanisms. EtherCAT (short: EC) and Profinet IRT (short: PN) are among the technologies analyzed and shall be used as examples of a technology with frame aggregation and a technology based on switched Ethernet.

The first component of the cycle time is the link transmission delay (for notation, see Table I). This refers to the time needed to send all frames over one wire with a specific link capacity. The basic equation for a summation frame is:

$$\tau = \frac{8(header + \max(remainder, n \times (x + subheader)))}{C}$$

The $remainder$ is the number of $bytes$ needed to fill a minimum-sized Ethernet frame (84 $bytes$ including interframe gap). For EC specifically, the formula translates to[14]:

$$\tau = \frac{8(40 + \max(44, n \times (x + 12)))}{C}$$

It should be noted that this formula considers only one frame. If the maximum Ethernet frame size is not sufficient, at least one more minimum-sized frame must be sent. Additionally, since device sub-payloads cannot be divided across multiple frames, the maximum Ethernet frame size will not be reached, and the data will have to be sent in the second (third, ...) frame. The second component of the cycle time is the propagation delay of frames through the network infrastructure, including

the wires. For EC, the frame is sent through the entire network and back, resulting in a minimum cycle time of:

$$\Gamma = (2n - 1)l + 2n\delta + \tau$$

For PN, one must consider individual frames per node, rendering[14] $\tau = \frac{8(38 + \max(46,6+x))}{C}$ per frame. It will be assumed that the frames are scheduled to arrive at the PLC successively, and the frame of the first slave passes one infrastructure device plus one cable. This results in a minimum cycle time of:

$$\Gamma = \delta + l + n \times \tau$$

All equations introduced here assume simplistic cases, where input and output data volumes are equal and the topology is a perfect line. In real applications, however, the comparison depends on many additional parameters:

- Ratio of input data to output data
- Percentage of devices with direct cross traffic
- Utilization of different cycle times
- Topology (line, star, ring), and hence number of hops between devices
- Availability of modular I/Os with own backplane bus

Results assuming more realistic values are shown in Figures 2a - 2b (using 100 $Mbit$). Using a different link capacity (1 $Gbit$) changes the situation quite dramatically, since only the transmission delay component of the cycle time – and not the network infrastructure component – can be reduced by a factor of 10 (see Figures 2c - 2d). Hence, the performance of technologies with a larger dependence on infrastructure (EtherCAT, Sercos III, POWERLINK) improves, on average, by a factor of $4-6$ when using Gigabit. In contrast, technologies based on switched Ethernet (EtherNet/IP, Profinet IRT) can leverage a factor of $7-10$ for large enough payloads. For small payloads, the transmission delay of a short frame might be smaller than the infrastructure latency, resulting in a lower bound for the minimum cycle time in a line. Today's COTS cut-through switches for Gbit have forwarding latencies in the range of 2 μs (Figure 2d), which translates to a minimum frame size of 250 $bytes$ ($= 2000$ $bits$) (neglecting propagation delay on the wire). Sending smaller frames does not further decrease the cycle time. Thus, in applications with demanding performance requirements, devices with short forwarding latencies are crucial.

The calculation of the cycle time for OPC UA TSN is a combination of the two methods introduced above. The frame transmission delay with values for Pub/Sub – thanks to frame aggregation and an efficient frame format – becomes[14]:

$$\tau = \frac{8(51 + \max(33, n \times (x + 3)))}{C}$$

The total minimum cycle time becomes:

$$\Gamma = \delta + l + \tau$$

It can be noted that the achievable cycle time compared to today's solutions over various parameter combinations is much lower, roughly by a factor of 18 (cf. Figure 2e). Compared to hypothetical devices with Gigabit circuitry based on otherwise unchanged mechanisms of today's fieldbus technology, the factor is close to 2 (cf. Figures 2c - 2d).

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[12]All sensors and actuators, also called "nodes."

[13]There are arguments in favor of shifted cycles, i.e. the cycle starting and ending at a slave with a defined offset compared to the PLC. However, such optimizations are technology- and application-dependent and hence omitted for a general comparison.

[14]The particular numbers in the equations always represent the size of the header, the space for payload in a minimal Ethernet frame, and the size of a sub-message header. For detailed explanations see protocol definitions in other footnotes.

C. Industrial traffic types

Companies developing new OPC UA TSN systems have a variety of TSN standards from which to select the right features for their application. This often involves attempting to match the behavior of the legacy technology as closely as possible. Extrapolated to the industrial automation market at large, what this tells us is that, in order to be broadly adoptable, a solution must support all currently used industrial traffic types simultaneously.

Today's technologies implement a variety of traffic types. Most of them allow for a distinction between periodic and non-periodic traffic, which in turn differ in the nuances of their actual properties – ranging from hard real-time traffic with distinct sending, transmission and receiving times per cycle; to periodic traffic with or without time synchronization; to non-periodic traffic stemming from a multitude of sources, of which TCP/IP is an increasingly significant example. In some cases, network control, diagnostic information and user control messages have distinct priorities. We have evaluated these and arrived at a superset. The traffic types being communicated through industrial communication systems can be summarized in the following Table II. A converged network needs to support all those types (see Figure 7 for an example), even if not used in a particular application. The selection of the shaping mechanisms used for implementation needs to be globally standardized; one currently discussed proposal is presented here.

Note: The main feature of TSN is the possibility of coexistence of different traffic types, while maintaining the timing properties of real-time traffic. Some existing real-time technologies (EtherNet/IP, Profinet) use traffic planning and QoS to ensure real-time behavior under the condition of well-behaving devices. With TSN as data link layer, those technologies can leverage better bandwidth efficiency, since TSN protects the high priority traffic (see for instance ODVA's performance considerations in [3], Table 1) unconditionally.

II. SETUP

Calculating theoretical performance estimates and defining traffic class requirements are one thing – real-world implementations with hardware and/or software limitations are a different matter entirely. 100-Mbit industrial Ethernet technologies have reached a very high level of maturity, meaning that almost all current devices are capable of delivering full network performance. For Gbit technologies, this is not the case. As mentioned above, Gbit increases performance by approximately a factor of 10 on switched networks. Frame aggregation, optimized headers and ultra low cut-through latency can bring further improvement by approximately a factor of 2. In order to exploit this performance in a real product, many of its components need to be optimized.

Many prototype devices have already been implemented and also tested by the authors, for instance in the IIC testbed. Two of those prototypes have been used for evaluation in this paper: one based on a single-port industrial PC running Linux, and an embedded one in the form factor of a head station of a modular I/O block featuring two external network ports, also running a Linux OS. Figure 3 depicts the principal topology of a test setup using these devices, whereas Figure 4 shows a photograph of the test setup. It consists of 200 embedded nodes (B&R) featuring digital I/O modules and one industrial PC. Additionally, it contains five Full HD cameras (Mobotix) and a standard industrial panel. Furthermore, industrial TSN switches (TTTEch) are utilized. The 200 devices are deployed in four lines of 50 devices each. The achievable performance is reported in Section VII.

III. STANDARDS AND TECHNOLOGIES

A. Overview

Figure 5 provides an overview of the protocols and services used by OPC UA TSN and how they fit into the layers of

Table II: Industrial traffic types.
Columns 3 - 9 represent the requirements for each type

ID	Working name	Guarantee	App. synched to network	Phase-aligned actions	Periodic / Sporadic	Bandwidth reservation	Data size	Redundancy mechanism required	Traffic shaper[§]
I	isochronous	deadline	Y	Y	P	Y	bounded	seamless	Qbv
II	network control	priority	Y	-	S/P	-	small	not relevant	SP[†]
III	cyclic	bounded latency[‡]	optional		P	Y	bounded	seamless	Qbv
IV	audio/video	bounded latency[‡]	N/A		S/P	Y[*]	bounded	regular	Qbv+Qav+SP[†]
V	alarms/events	bandwidth	-	-	S/P	Y[*]	unknown	regular	Qbv+SP[†]
VI	management/diagnostics	bandwidth	-	-	S	Y[*]	unknown	regular	Qbv+SP[†]
VII	reserved	user specific							
VIII	best effort	none	-	-	S/P	-	unknown	regular	none

[*] Unused bandwidth can be utilized by lower priority traffic
[†] Strict Priority traffic selection algorithm
[‡] The bounded latency guarantee includes a bandwidth guarantee
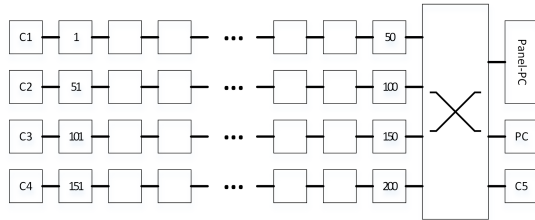[§] Proposal, see Figure 7 for an example

Figure 3: A test/reference setup. It consists of four lines of 50 I/O nodes each, five cameras (C1 . . . C5), one switch (in reality multiple switches that "form" one large switch), and two PCs.
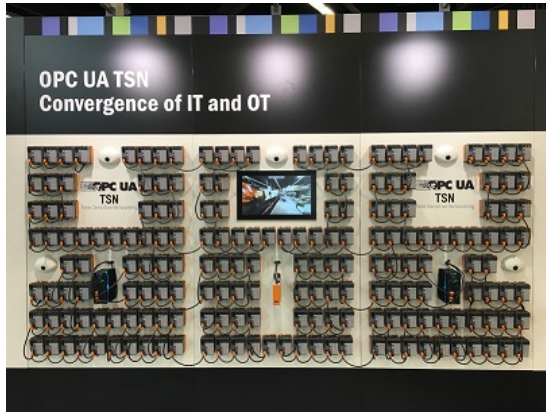

Figure 4: The test setup at the SPS IPC drives 2017 in Nuremberg.

Figure 5: Depiction of OPC UA TSN in the OSI reference model.

the ISO/OSI reference model. The following will discuss the requirements and properties of the respective layers.

B. Physical layer

The following physical media are the most widely used in industrial networks and therefore offered by most vendors:

- Copper-based:
  - Fast Ethernet (100BASE-T/T1)
  - Gigabit Ethernet (1000BASE-T/T1)
- Fiber-based:
  - Fast Ethernet (100BASE-SX)
  - Gigabit Ethernet (1000BASE-SX)

For process automation, a working group has been founded to develop 10-Mbit single twisted pair Ethernet (10SPE). This media could facilitate the spread of Ethernet to even smaller and more cost-sensitive sensor and actuator devices and Zone 1 hazardous areas.

C. Data link layer

The term TSN [4], [5] refers to a family of standards under development by the Time-Sensitive Networking task group of the IEEE 802.1[15] working group. It is worth noting here that 802.1 standardizes Ethernet switches (they call them "bridges"), and 802.3 standardizes Ethernet endpoints. The following list introduces the standards relevant for industrial communication:
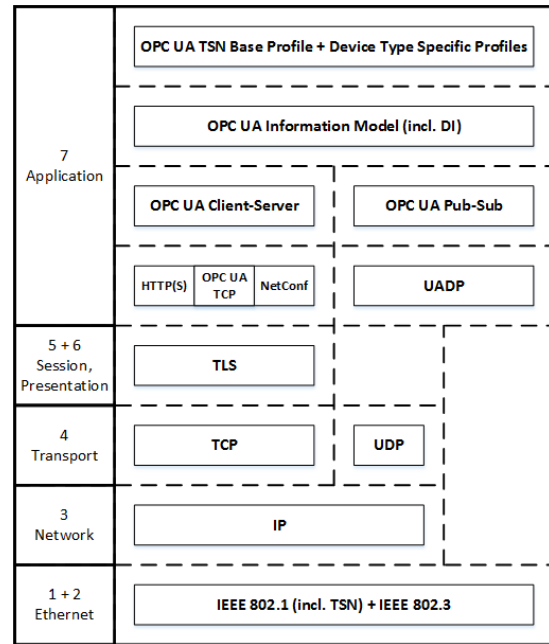
IEEE 802.1AS-Rev A profile of the IEEE 1588-2008 clock synchronization standard was developed and adopted for addressing larger Ethernet systems resulting in IEEE 802.1AS [6]. Unfortunately, the two are not compatible. Within the TSN working group a revision of IEEE 802.1AS (.1AS-Rev [7]) is being developed. This revision addresses the mechanisms for grandmaster redundancy and multiple clock domains (e.g. simultaneous distribution of a working clock (basis for isochronous transmission) and a wall clock (e.g. logging messages)). The publication of .1AS-Rev is planed for 2018; we strongly encourage machine, factory, and process automation vendors to implement .1AS (rather than IEEE 1588) for reasons of interoperability and proximity to the final solution. Also, 802.1AS is the default solution promoted by AVnu and the IEEE TSN Task Group.

IEEE 802.1Qbv is used for isochronous transmissions with real-time guarantees. It specifies the transmission windows[16] in order to guarantee bounded latency and small jitter [8]. Qbv also makes it possible to periodically give egress queues prioritized wire access, so it can also be used to provide bandwidth guarantees.

IEEE 802.1Qav Can be used for periodic transmission, to guarantee bandwidth reservations and bounded latency for certain traffic classes [9]. The primary application is in audio/video broadcasting[17].

IEEE 802.1Qcc This standard provides specification of protocols, procedures and managed objects used for TSN

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[15]http://www.ieee802.org/1/pages/tsn.html

[16]in terms of "gate open and close" timing values

[17]Due to the Stream Reservation Protocol, it would also be tempting to use it for cyclic process data exchange without prior configuration. However, streams added dynamically influence the guarantees of ones that are already configured (without notifying them), which makes it hard to predict behavior over longer periods of time in a converged networks where the system (and the traffic load) is updated.
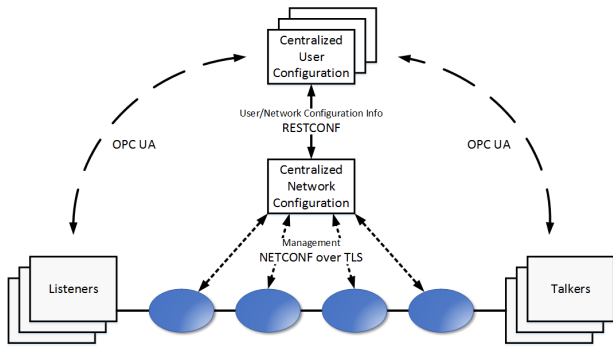
Figure 6: The fully centralized model of Qcc (with OPC UA applications), taken from [4].

configuration, mainly used in an already running system. Three configuration models are described:

1) Fully Centralized Model - suitable for all TSN mechanisms and necessary when using Qbv (see Figure 6)
2) Fully Distributed Model - suitable when no scheduled changes are needed (or no Qbv mechanisms are used)
3) Centralized Network/ Distributed User Model

As isochronous traffic is often used in industrial networks (see example in Figure 7), usage of the Qbv mechanism is inevitable, and thus we use the fully centralized configuration model. This model specifies the CUC (Centralized User Configuration) and the CNC (Centralized Network Configuration) functions [10]. The CUC(s) specify user requirements regarding cycle times and transmitted process data and pass them to the CNC. The CNC calculates the TSN configuration including the communication schedules necessary to satisfy the requirements by using standardized YANG[18] models. The CNC distributes the configuration to switches (bridges) by using a YANG-based management protocol (such as NETCONF[19] over TLS[20]). The CNC sends the endpoint configuration to the CUC. RESTCONF[21] shall be used as the communication protocol between CUC and CNC[22]. The CUC then distributes the endpoint configuration to the corresponding endpoints.

IEEE 802.1CB Used to provide seamless redundancy for ring and mesh topologies [11]. .1CB allows redundancy planning on a per data stream basis, which enables much better bandwidth efficiency than legacy redundancy solutions.

Further standards

IEEE 802.1Qbu & IEEE 802.3br (optional)[23]

Frame preemption [12], [13] can be used to maximize throughput of best-effort traffic in case that scheduled

(Qbv) mechanisms are being used. Preemption is not suitable for traffic types other than best-effort, as it invalidates any guarantees on those. In the case of Gigabit, the gain for best-effort is negligible, however[24].

IEEE 802.1CS (optional)

Extension of AVB's stream reservation protocol. This project has just started. It defines an alternative – currently not compatible – configuration path (aka the "fully distributed configuration model") for applications with only type III traffic (and best-effort), and is hence of limited use for industrial applications.

Summary

Compulsory standards hence are .1AS(-Rev), Qbv, .1CB, and Qcc with fully centralized model plus NETCONF over TLS. AVnu Alliance members are defining the conformance and interoperability guidelines for implementation of these standards.

D. Layers 3-6

For OPC UA Client/Server, TCP/IP connections with optional security (TLS) are supported. For Pub/Sub connections, either UADP[25] over UDP/IP or UADP directly over raw Ethernet are supported. Security is handled in the UADP layer. Other transport options for UADP (i.e. cloud protocols) fall outside the scope of this paper.
NETCONF also uses TCP/IP with TLS.
HTTP(S) is optional for firmware updates and web applications on devices.

E. Application layer

OPC UA is employed on the application layer, including support for the Client/Server and Publish/Subscribe communication models. OPC UA servers on all devices should support the *Embedded Server Profile*. For very resource-constrained devices, only a publisher feature for providing data and a TCB client for network configuration can be utilized.

- Client/Server: Communication model used for device configuration, browsing the information model, registering e.g. for diagnostic information. For secure applications, the device configuration shall provide data integrity (signature) and optional confidentiality (encryption).
- Publisher/Subscriber (short: Pub/Sub): Communication model for cyclic transmission. Optionally signed and/or encrypted using OPC UA message-based security. A header profile with static dataset offsets can be used for efficient dataset extraction in end stations.
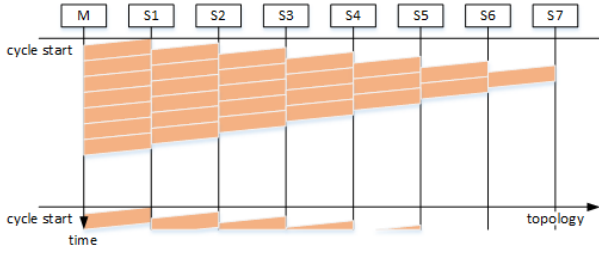
[24]For instance, a maximum-sized Ethernet frame ($1.5\ kB$) requires 12.3 μs transmission time. Given a common cycle time of 1 ms, bandwidth utilization can be improved by $< 1\%$, when preempting one such frame per cycle.

[25]Unified Architecture Datagram Packet

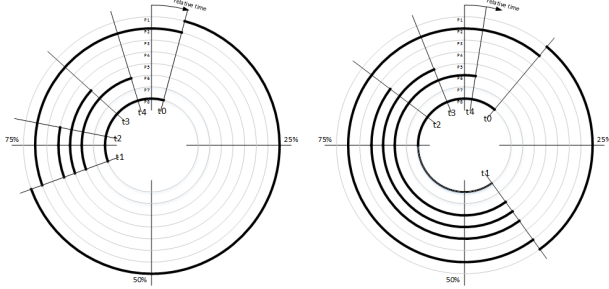[26]The shown schedule represents an optimized schedule to potentially utilize "asynchronous" bandwidth as far as possible at each position in the network. However, for the sake of computational efficiency in computing a schedule, the same schedule as in Figure 7a can be used throughout the entire line.

[27]The individual schedules shown in Figures 7a and 7b are based on the individual times of the devices. However, it is expected that the synchronization between the devices is good enough to support that approach, and – for simplicity – speak of one network-common cycle start time.

[28]In this example, the guarantees for $types\ 4-6\ \&\ 8$ are identical and about 8%. The identical size is used for depiction only and may not have a practical use case.

[18]https://tools.ietf.org/html/rfc6020
[19]https://tools.ietf.org/html/rfc6241
[20]https://tools.ietf.org/html/rfc5246
[21]https://tools.ietf.org/html/rfc8040
[22]If both are hosted on a single device (e.g. engineering tool or PLC), CUC-CNC communication does not necessarily involve a protocol.
[23]There are two standards related to frame preemption – one for the bridge (.1Qbu) and one for the endpoint (.3br).

(a) Time-Space diagram of isochronous input frames in a schedule

(b) Qbv gating events at master's inner port

(c) Qbv gating events at S5's left port[26]

Figure 7: Example for a schedule of a network as introduced in Section II, only smaller. It features a master (M) and seven slaves ($S_1 \ldots S_7$). All slaves send similar-sized frames to the master (Figure 7a) in $type$ 1. The schedule is computed such that the frames reach the master one after the other without pauses, where the first slave sends its frame at cycle start. Figure 7b shows the Qbv configuration of the master's inner port, where it receives the frames (the cycle start is at $90°$). The gate for $type$ 1 opens shortly after cycle start (t_0) and remains open until all frames are received, where it closes (t_1). No other gates are opened during this time. Afterwards, the gates for $types$ $2 - 8$ open simultaneously. $Type$ 2 stays open all remaining time, giving network control traffic highest priority (if such traffic occurs). Next, the gate for $type$ 4 closes (t_2), giving $type$ 5 some time with highest priority and so forth (t_3, t_4). Figure 7c shows the Qbv configuration of S5's left port[27]. The gate for $type$ 1 opens for the three frames towards the master ($t_0 \ldots t_1$) followed by some time where the gates for the other types are opened. Only directly before the next isochronous traffic, the gates for $types$ $4 - 6$ close in similar timely distance as at the master's gate. Thus, the bandwidth guarantees for $types$ $4 - 6$ & 8 are identical throughout the network[28].

F. Additionally required features

The ISO/OSI reference model (Figure 5) provides a quick overview of the protocol stacks involved in OPC UA TSN technology. To satisfy the requirements of industrial communication systems, however, the following additional features are needed:

Device roles Section V introduces features required to orchestrate booting and operation of a network of OPC UA TSN devices. The roles are (almost) independent of the hardware they run on.

State machines End stations in an industrial network must have uniform behavior defined according to a state machine (see Section IV). This makes it possible for a central instance (i.e. a network managing node) to orchestrate the behavior of the entire network. Many industrial Ethernet solutions implement a state machine based on the ideas of CiA [14].

Topology detection Scheduling of real-time traffic requires detailed knowledge about the topology of the network. Topologies can be detected (using LLDP[29]) and imported or created offline in a configuration tool. The CNC (Section V) uses this information to compute the configurations for Qbv and Qav.

Cut-through switching The cycle-time performance that can be achieved on a switched network depends heavily on the latency of frame transmission (cf. Section I-B). In particular, long line or ring topologies pose challenges. Thus, cut-through switching (forwarding a frame as soon as the address information has been decoded)[30] constitutes an indispensable feature of 3-port switches in field devices. When using a Gigabit physical layer, a forwarding latency including PHYs of well below $1\ \mu s$ is required, i.e.

$$l_{target} = 800\ ns$$

Device profiles In industrial communication systems, interoperability needs to be ensured on each OSI layer. The lowest layer that violates interoperability constitutes the highest layer for the interoperability of the entire system, independently of any higher layers. Legacy Industrial Ethernet systems share only the same physical media (cables, plugs), i.e. layer 1. This fact has caused a lot of customer dissatisfaction, because the original marketing message was that Ethernet is Ethernet, so they all should be compatible. To prevent OPC UA TSN technology from falling into the same trap, the goal is to use common implementations of all seven OSI layers (for communication between devices) and moreover to have both a standard device profile and type-specific device profiles. Today, standardized profiles for safety, drives, IO and controller to controller communication are under consideration.

Device description files In the realm of OPC UA, a device is represented by its server instance, whose features can be browsed online "at any time." While online browsing suffices in some industrial use cases, those with a high degree of repetition, such as serial machine building, require an offline method for configuring and programming devices. Hence, all relevant features of a device (OPC UA, application and networking capabilities) need to be described in files, substituting online access to the device.

IV. CONFIGURATION AND BOOT-UP

Almost all fieldbus systems existing today – based on real-time Ethernet or not – provide mechanisms for network

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[29]Link Layer Discovery Protocol [15]

[30]There is no standard available for cut-through switching. The main argument against it is that a frame could be corrupt, which can only be detected using the FCS at the end of the frame. Furthermore, some features of TSN, such as parts of ingress policing, are not compatible with cut-through. However, the performance argument outweighs the disadvantages.
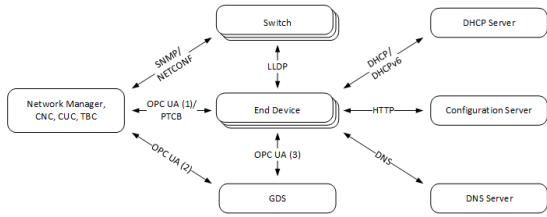
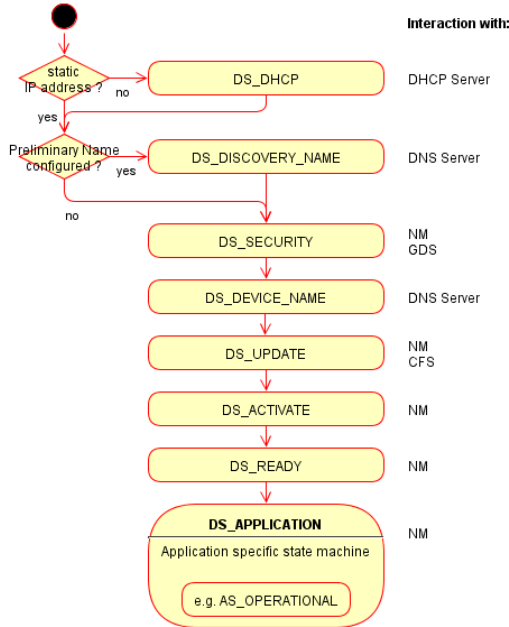Figure 8: Communication relationships during boot-up.

Figure 9: States during boot-up of an OPC UA TSN end station.

management. These mechanisms do things like boot a network device by transitioning it through a series of states into an operational state; enable a device to detect, handle and signal errors during runtime; or implement procedures necessary to replace faulty devices.

States and state-transitions comprise functions such as network device identification (ensuring that the device can be reached on the network, matches the expected vendor/model, etc.). They are also used to perform any necessary configuration/firmware updates and subsequently notify the device to transmit valid process data (if the application on the device is ready to do so) and evaluate received process data (if a central network instance controlling the network decides to do so).

Many existing implementations of network management in the various fieldbus systems combine all of this functionality in one device (i.e. the PLC). The explicit goal in this work is to logically separate and decouple these functions into so-called device roles, such that each could theoretically be implemented on a different device within the network. Multi-instance and device-role redundancy shall be addressed as well. Figure 8 shows the distinct roles and their communication relationships. Figure 9 shows the walk through a state machine of the end device during boot. The states themselves are mandatory. However, most states can be quickly passed, if addresses and configuration are locally stored.

V. ROLE MANAGEMENT

For machine networks, a number of network functions are required in order to reach defined states in the network during start-up and operation. Those functions can be grouped and allocated to device roles. The following is a list of well-known device roles for IT and OT systems as well as new ones for OPC UA TSN. The section is concluded with a list of user roles for developing and running the network.

A. Currently required device roles

TSN switch They constitute the network infrastructure of an OPC UA TSN network. Multi-port switches are used for setting up the network topology from a bird's view, while switches with two external (and one internal) port reside in switched end stations to allow for efficient cabling in a line topology. The state machine of a switch adds states to prevent message storms in case of loops in the network, compared to the one shown in Figure 9.

DHCP (server) DHCP[31] is a mechanism to allocate IP addresses from a pool and assign them to unconfigured devices. Furthermore, most DHCP server implementations allow static binding between Layer 2 MAC addresses and Layer 3 IP addresses. The combination of these features makes it possible to boot unconfigured devices (with unknown MAC address) using a temporary IP address and – after successful identification (and probably authentication) – to assign preconfigured addresses[32].

DNS (server) DNS[33] is a mechanism to resolve descriptive names (i.e. *host names*) to IP addresses. All higher layer protocols and services – including engineering and configuration tools – can then use the easier-to-remember host names.

Grandmaster clock The term originates from the IEEE 1588 standard for precise clock synchronization and has been adopted by IEEE 802.1AS. It refers to the most precise clock device in the network with master capabilities. It will either be selected automatically as the time master for the network by the Best Master Clock Algorithm (BMCA). Or, in .1AS, the clock hierarchy can also be predefined.

OPC UA GDS The Global Discovery Server (GDS) of OPC UA is responsible for enterprise-wide administration of OPC UA servers. It fosters discovery via lists of "capabilities" and addresses, creates and distributes application certificates for secure connections.

Directory services (optional) Such IT services (e.g. Microsoft's Active Directory) are used for enterprise-wide asset, user and role management including personal data, access rights (to files, programs), certificate management and much more. Utilizing these in an OT environment constitutes a quick win in terms of organizational efficiency.

TSN CUC The Central User Configuration (CUC) is a role defined in the IEEE 802.1Qcc standard with the task of configuring the end nodes (or their applications – the

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[31]https://tools.ietf.org/html/rfc2131

[32]In case of security it is highly recommended to use a static IP address configuration, see also [16].

[33]https://tools.ietf.org/html/rfc1034, https://tools.ietf.org/html/rfc1035

users of the network). This includes network configuration, for which it communicates with the CNC.

PTCB The OPC UA Pub/Sub TSN Configuration Broker (PTCB) is a OPC UA standardized implementation of the CUC functionality. The PTCB forwards the requirements to the CNC, which schedules the streams and reports the result back to the PTCB. Finally, the PTCB reports back to the end station on how to use the scheduled streams.

TSN CNC The Central Network Configuration (CNC) has two primary tasks: (i) calculating the network schedule and (ii) distributing the parameters of the network schedule to the infrastructure components (Ethernet switches). For the latter to support interoperability, the selection of the protocol is critical. As of today, NETCONF is the technology of choice because of its wide availability, technical maturity and the possibility to manipulate a shadow configuration.

B. New device roles

The following is a list of logical functions in a network inspired by today's fieldbus architectures. Implementation of these roles is not strictly mandatory in order to operate an OPC UA TSN network. Without them, however, booting and operating a network would require frequent, substantial manual intervention. All device roles are vendor independent and thus interoperable.

Application slave This is the role with the greatest number of instances. It basically features a state machine to manage its operation mode and some functions for remote configuration. Examples are I/Os, drives and valves.

Application master The role for PLCs or Edge Controllers in a classic fieldbus network. From the perspective of network infrastructure, there is no difference between application slave and application master. In terms of computational performance, application features and TSN features, however, they may differ considerably.

Configuration server This can be seen as a (distributed) database containing version-controlled and signed binary artifacts used for firmware and configuration. The content of the files is vendor-specific and can be anything that should reside on a device – from bitstreams for FPGAs, compiled application code and configuration files to images, data sheets and maintenance videos.

Network manager This role connects to the engineering tool and holds all the information about distribution of the application. The network manager guides all devices through the start-up process and triggers required actions like address assignment and firmware/configuration update.

C. User roles

In addition to the device roles (representing "users" on the network authorized to perform certain management functions like upgrading a device's firmware), a set of predefined user roles for human interaction with the network should be available, like Administrator, User, and Maintenance.

VI. Security and certificates

Security has the potential to be one of the key distinguishing features between OPC UA TSN and legacy fieldbus systems, since it cannot be just added to a system. An international standard for implementing electronically secure industrial automation and control systems, IEC 62443 [17], is now as widely accepted as IEC 61508 [18] and IEC 61784-3 [19] for functional safety. The standard mandates utilization of a proper hardware and software development process. Further, it defines five target levels of security protection, from 0 (none) up to 4 (protection against attackers with high education, high motivation and high resources). For each level, it defines requirements and asks questions about the particular implementation of a device.

A. Certificates

Certificates are a means for secure authentication. OPC UA mandates X.509 certificates. A new certificate created for the network manager device role, for example, requires each device with that role to have an instance certificate in order to be able to configure and control devices. All other devices are equipped with the public key network manager certificate and hence can establish a chain of trust. Additionally, each device comes with its own instance certificate, which is derived from a device type certificate, which is derived from a vendor certificate. This way, chains of trust can be established and each vendor can create its own device type family. The device type and network manager certificates can be obtained during the certification process. After first authentication, application certificates for each device are created and deployed, which are used for further authentication processes.

B. Certificate types

- Network manager
- Network manager instance
- Device type
- Device type instance
- Application instance
- (Machine) Configuration

VII. Results

A. Time synchronization

The accuracy of time synchronization is usually measured via external PPS pins (pulse per second) under various environmental conditions [20]. Figure 10 shows the result for a real setup of 50 B&R IO-devices in a line topology using .1AS (actually, one of the lines of the test setup introduced in Section II).

B. Real-time performance

Depending on the capabilities of the engineering tool, there is no real limitation on the size and complexity of an OPC UA TSN system. We expect systems of up to 10,000 devices to appear in the mid-term.
For individual devices, the achievable minimum cycle time depends solely on the hardware and software used. We expect devices with $10 \ \mu s$ cycle time soon. B&R's prototype I/O head stations achieve $50 \ \mu s$ externally and on the backplane bus. Given a powerful PLC, 200 of them can be operated with $50 \ \mu s$ on one wire.

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[34]Precision in .1AS terms is the absolute difference between two clocks in a network. In our case, we always measure against the grandmaster.
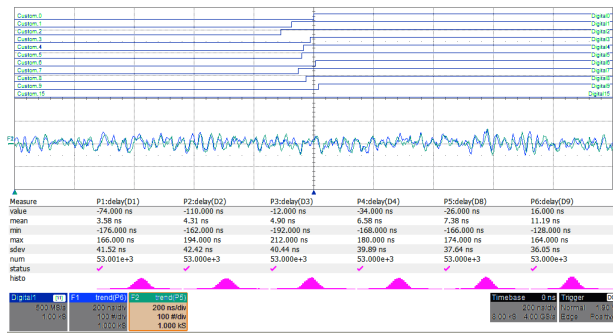
Figure 10: Results of time synchronization using IEEE 802.1AS in a line of 50 devices. Every 10th device has been measured. The standard deviation of the PPS precision[34]is well below $50\ ns$ under laboratory conditions.

C. User experience

The main factor for user experience can be seen in the engineering tool of the device or system vendor. Usually in machine automation, the engineering tool for a customer comes from the PLC supplier. However, the merging of IT and OT seamlessly into fieldbus projects allows a much higher degree of automated configuration than before, independent of the tool vendor – resulting in less human intervention[35]. Additionally, since OPC UA and TSN are not tightly bound to a particular vendor, we expect the surrounding ecosystem to grow considerably larger than for distinct fieldbusses in the past.

VIII. Conclusion and outlook

OPC UA TSN is coming. And it will substitute today's Ethernet-based fieldbusses in a number of applications. The main reasons as outlined in the paper are:

- Vendor independence
- Broad adoption in other fields
- Converged networks
- Large and flexible topologies
- Full IIoT capabilities
- Unmatched performance
- Integrated security and
- Modern data modeling.

The relevant OPC UA standards and TSN standards for industrial use have been already finalized and the few unpublished ones will be published in early 2018. The standards have already been implemented and tested in international test beds like the IIC by numerous international market players – with amazing results. At present, the major chip makers are crafting their offers for connectivity in field devices in order to even match with the costs of today's offerings soon. For single port devices standard Ethernet NICs can be used, hence there is no cost discussion anyway. For 2-port devices 0€ marginal HW costs are expected, as TSN will become an integral part of any competitive industrial SoC in the near future. Hence, OPC UA TSN will become a commodity – just like CAN used to be.

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[35]For instance, the static configuration for infrastructure switches can be automatically computed by the engineering tool and distributed by the PLC.

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