Analysis of the TSN Standards for Utilization in Long-life Industrial Distributed Control Systems

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***Abstract*—Large complex industrial Distributed Control Systems (DCS), e.g., power distribution systems, are expected to function for long time, up to 40 years. Therefore, besides having a long system verification phase for all subsystems, the design phase should consider various aspects when it comes to selection of which technologies to utilize when implementing such systems. In this paper, we study and investigate key challenges of using the Time Sensitive Networking (TSN) technology when it comes to design, maintenance and evolution of long life-span complex DCS. We also identify issues and challenges, and propose mitigation strategies for using the TSN technology in long-life system design. Our investigation and analysis shows that many of the TSN standards are in their evolution phase and may as a consequence be subject to different interpretations and implementations. Therefore, achieving a full capacity of using the TSN technology may not be possible, in particular when it comes to design of systems having an expected long life.**

***Index Terms*—long-life systems, distributed constrol systems, DCS, time-sensitive networking, TSN, standards**

I. INTRODUCTION

In the context of industrial Distributed Control Systems (DCS), new technologies, like Time Sensitive Networks (TSN), opens for next generation solutions having potential to give a competitive advantage when it comes to capabilities and performance. If an embedded solution is too late in adopting and leveraging on using a new technology, in the context of competitors already embracing such solutions, there is a risk of the competing companies advancing to superior solutions when it comes to efficiency, performance, features, etc. On the other hand, if a company is too early in utilizing a new technology there is a risk for the company of ending up being stuck with a technology that is not completely finalized, possibly only used by a few users, resulting in a high price. In the worst case, there is a risk for the company of having systems and products relying on a technology that did not ”fly”, i.e., a technology that is only used by a low number of companies, implementations and products. This gives in turn life-cycle problems often inherent in, e.g., the support being suspended early compared to other similar technologies such as the technology that in the end turned out to be the technology selected by the markets.

Given these challenges, when new technologies become available, there are, for a company producing systems and products, a few options (in decreasing level of risk): either i) one can take a chance that one is investing time and money on ”the correct” technology, time will tell if the investment was correct or not, or ii) one can develop and/or maintain the technology ”in house”, which in turn also result in cost of time and money but on the positive side the company is in control of the technology, or iii) one can replace technologies at a higher phase, as is often the case when it comes to short life-cycle products such as is common in, e.g., consumer industries, or iv) one can decide to only use mature technologies, resulting in a possible shorter life-cycle and less competitor advantage.

For large complex DCS systems, e.g,. power transmission and distributions systems, power plants, railways, etc., with an expected long life-time, up to 30-40 years, this question becomes even more complex. These systems typically have a long system verification phase, up to a few years, before the complete installation is deployed commercially and the expected life-time starts. Already before conducting system verification, where all the subsystems are tested together, the different subsystems with different requirements on interfaces, latency, throughput, operator interaction, control and protection functions, integrated fire protection, etc. have been developed and type-tested against different requirements. Usually such a revision of such a subsystem will be used in more than one system delivery, as depicted in Fig. 1.

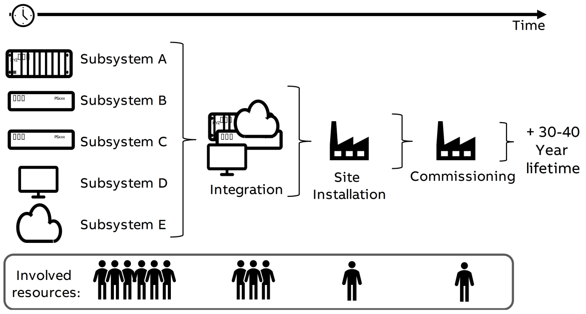

Fig. 1: From subsystem to complete system implemented on site.

Depicted in Fig. 2, building a large industrial DCS with a lot of parallel Ethernet networks with different types of traffic, consolidating such a system into one network will be a cost saver when it comes to hardware, installation, spare part management, configuration and cyber-security auditing. In this consolidation the requirements from the different subsystems, e.g., latency for a control or protection function and throughput of a web server solution, must be fulfilled. TSN opens up for co-existence of multiple subsystems on the same network, with its 8 different priority levels, together with the possibility to verify the different subsystems independently.

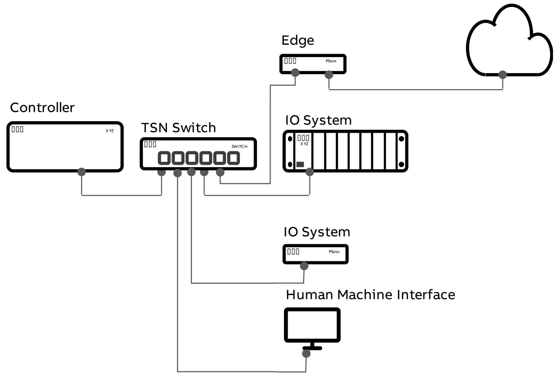

Fig. 2: Consolidated system to one network spanning from process level, IO, to Cloud connectivity.

During the 30-40 years expected lifespan of the long-life systems targeted in this paper, the system components will have to be replaced. Reasons for such replacement during the life time of the system include, e.g., obsolete components not anymore available for purchase. When such components are replaced it is usually not possible to perform a full retesting of the complete system, not even a complete subsystem test. Instead a replacement component with equal/equivalent functionality is needed to avoid costly retesting.

In addition to component replacement, the system will be subject to updates concerning addition of new features, e.g., new cloud connectivity to support new functions relying on machine learning, as shown in Fig. 3. Such addition of functionality should be supported without at the same time making changes to the already existing subsystems' behaviors.

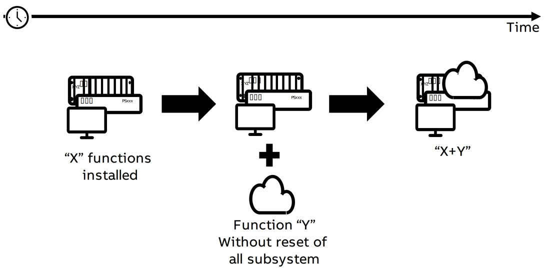

Fig. 3: Over time, new functionality will be added to the system, e.g. cloud connectivity.

Considering the above mentioned challenges towards designing and building a DCS for long life-span, several issues should be considered in particular when adoption of the TSN technology is in the plan. Therefore, the main contributions of this paper are to i) identify, classify and discuss key challenges and issues of using the TSN technology when it comes to design, maintenance and evolution of DCS systems with long life-span, and ii) identify issues and challenges, and propose mitigation strategies for design of such systems.

The outline of the paper is as follows: Section II presents a brief overview of the TSN standards. Section III describes the problems of designing long-life industrial systems. Section IV investigates and analyses key challenges and issues, along with mitigation strategies, of using the TSN technology in designing long-life DCS systems. Then, Section V provides a list of related works, while Section VI concludes the paper and points to direction of future work.

II. TSN STANDARDS

The TSN task group specifies several features of the emerging TSN technology, and most of the features are still under development and, as a consequence, possibly subject to modification. In this section, we describe a brief overview on key features according to the latest revisions of the standards.

The TSN task group publishes two categories of standards, known as *base standards* and *ongoing projects*. The base standards are usually notated by capital letters and published as the main TSN standards to be followed by developers. Examples of this category include IEEE 802.1Q-2018 [1] for transmission mechanisms and IEEE 802.1AS-2020 [2] for clock synchronization mechanisms. On the other hand, there are several ongoing projects in the task group that enhance new features. Such standards are normally notated by small letters in the standardization. From this category we can mention IEEE 802.1Qbu-2016 [3] and IEEE 802.1Qbv-2015 [4]. The details, news and list of all ongoing projects and publications can be found on the task group page [1].

A. Base standards

The primary goal of the TSN standards is to provide forwarding and transmission mechanisms for hard real-time applications. Among them, the IEEE 802.1Q-2018 standard defines various classes of traffic, including Stream Reservation (SR) classes, e.g., classes A and B, as well as a Best Effort (BE) class. Class A has higher priority than class B, while the BE class is used for non-real-time traffic. The standard defines a Credit-Based Shaper (CBS) algorithm for the SR classes. According to the CBS algorithm each SR class has a specified credit. The frames in this class can be sent only if the credit is zero or positive, otherwise the frame is pending in a FIFO queue until the credit raises to zero. During the frame transmission the credit is consumed with a constant rate, whereas it is replenished with a constant rate when there is a pending frame in the class but the port is busy with transmission of other traffic. The non-SR traffic do not undergo the CBS algorithm. In addition to the CBS mechanism, the standard provides mechanisms to reserve bandwidth (allocate the credits) per queue on the path of a frame, which is known as Stream Reservation Protocol (SRP).

Another important base standard is the IEEE 802.1AS-2020 standard that describes protocols to synchronize network devices in a network. Synchronization is a prominent key for applications that use periodic transmission which can bring low-latency and low-jitter frame transmission. The background of this standard goes back to the IEEE 1588 standard with some modifications.

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[1] https://1.ieee802.org/tsn/

The TSN standards provide features to address reliability in the design of a network. These mechanisms are described in the IEEE 802.1CB-2017 standard. Frame replication in the source nodes crossing redundant paths and elimination of the frames in the destination nodes are described in this standard.

B. Ongoing projects

There are several ongoing projects that define features and are published by the task group. In this section, we only mention the important ones due to the page limit restriction.

The IEEE 802.1Qbv-2015 project provides a mechanism to support temporal isolation for the Scheduled Traffic (ST). The ST traffic is the periodic traffic that require a very low jitter. This type of traffic is scheduled offline and it is transmitted without any interference coordinated by the gate operation defined in the standard. The gates are associated with each queue of a switch port and transmission in the queue is allowed only when the gate is open. Whenever an ST frame is activated for transmission, the gates of other queues are closed to provide the temporal isolation. The gate operation follows a cyclic table that is defined by the network designer. In addition, the IEEE 802.1Qbu-2016 standard introduces two modes for traffic classes, being *express* and *preemptable*. Express traffic can preempt the preemptable traffic, but it cannot be preempted itself. Preemption support can be combined with the CBS and the gate mechanism. An example of using the combined mechanisms is to use the ST class as means for express traffic, and classes A and B will be preemptable. If the preemption is enabled then any ST frame can preempt other classes, while the transmission of classes A and B are coordinated by the CBS algorithm.

Other well-known projects within the TSN standards include the IEEE 802.1Qca-2015 standard, that defines mechanisms for path control and bandwidth reservation, and the IEEE 802.1Qcc-2018 standard that brings some improvement in the SRP protocol to be used in hard real-time applications.

III. PROBLEM DESCRIPTION

A. Problem in the general context

No matter what kind of embedded system that a company is producing, from a system with a total cost below 10 EURO to a large complex system serving a country wide critical infrastructure, e.g., power plants, smart energy transmission systems etc., there has been a significant investment conducted in generating the idea, design of the system, negotiating with clients, sales work, verification of the functionality, installation and commissioning at site. In this process a competitive advantage is definitely if new technology, e.g., TSN, could be used to enhance the solution in any way, e.g., reducing cost, improving performance, reducing need for maintenance, simplifying commissioning, to mention a few scenarios. On the other hand, the cost will increase significantly during the product life-time if the chosen technology has to be replaced during the life-time of the installation. A change of technology would then in most cases require a significant re-design, installation, and re-verification, and may in some cases be almost impossible since the installation has evolved during the 10-15 years that has past since its installation and the previous test systems are not available anymore.

B. Problem in the context of TSN

TSN could be one of such new standards that are now getting into the market, giving new possibilities for the designers, and is going to remain as market standard for a long time. However, as is often the case when other new technologies have been introduced, the TSN technology is evolving and is in many cases subject to modifications. The evolution and modifications have resulted in the TSN device vendors to carefully implement the standards, commonly on re-programmable FPGA platforms, to be able to adapt to the (likely) coming modifications easily over time. Moreover, the ongoing TSN projects are still discussing fundamental and interesting features, discussions conducted and/or led both by the TSN device manufacturers themselves and by the research community. For example, the very recent work in [5] showed that the proposed credit behavior in the IEEE 802.1Q-2018 standard in combination with the gate mechanisms can lead to credit overflow and unfairness, causing potential problems in corner cases. Similarly, the effects of using various features in combination can lead to potential complex network configurations without having any tool to support the configuration process. These issues can potentially hinder the utilization of the TSN full capacity in the design of systems with expected long-life. In the next section, we evaluate the aspects of maturity of the TSN standard, from a life-cycle perspective, when it comes to maintaining a product during its life time based on the standard.

IV. ANALYSIS

In this section, we discuss the challenges of using network devices that are developed based on the TSN standards. Moreover, we identify opportunities with TSN network devices in large industrial networks.

A. Identified challenges

We identified several challenges that can affect the design of industrial networks based on the TSN standards when we consider a long-life utilization. The details of the identified challenges are described in the following subsections.

1) Some standards are not finalized: As discussed in Section II, several ongoing projects are still working on developing various interesting features of the TSN standards. However, these projects, although published, are not finalized as the final standard draft. For instance, the P802.1DC standard describes the quality of service features which is not specifically to TSN switches, e.g., to nodes. The initial draft is published in 2019 and it is an ongoing project. This issue will affect the design and development of TSN networks, both concerning simulation and configuration tools. Table I shows some of the TSN standards with their current status. In case of designing a TSN network for application in industry we can currently rely on the published standards, although even those standards are most likely subject to some minor changes in the future. Therefore, several of the proposed features will not even be considered and cannot be extended for future development if the design should support a long-term utilization. A TSN network designer who is developing the network for a long-term utilization with as little expected changes as possible, needs to focus only on features that are fully settled and therefore subject to a very low chance of future changes and/or modifications. E.g., one of the main challenging tasks of a network designer is to configure a network where a credit-based shaper is used in combination with scheduled traffic and preemption. There are many unknown variables in configuring such a system and the research community is still working on extracting a full view on the design and configuration issues. Recent work include dynamic configuration of TSN networks [6], using simulation models for TSN configuration [7], and studying configuration methods for efficient utilization of TSN networks in industry [8].

To summarize, a network designer targeting systems subject to long-term utilization should consider the above-mentioned issues. One of the main examples is the combination of a credit-based shaper with scheduled traffic support and preemption, which can lead to complicated design and configuration issues where no tool support yet is available. Therefore, at this stage, combination of legacy operational traffic with the control signals might be challenging given the status of the standards and their respective development.

2) Different standards are implemented: Since the standards contain a number of different amendments, and the manufacturers do not need to implement all of them to become compliant to the standards, we can expect that an existing switch, in a number of years, does not support the same features as a new one. In the best case only support for new standards are added and none of the existing ones is removed.

In the following we have investigated the TSN support by different switch vendors, e.g., Cisco, Belden/Hirchmann, B&R, Phoenix, Rockwell automation and Moxa, to understand whether there is any significant difference with respect to their support of TSN features. Additional to the ”off-the-shelf”-switches we have also investigated the equally important component and IP provides, e.g., Xilinx, TTTech and SoCe, that provide part of the vital infrastructure needed to build the switches, if it is not built by the switch vendors themselves. Typically, low-level hardware support is needed to implement TSN functionality, e.g., time synchronization for IEEE 802.1AS, to be fully implemented. Such hardware support is realized utilizing an FPGA or an ASIC, as shown in Fig. 4. FPGA platforms are the most common platform that are used by manufacturers for TSN devices due to the flexibility when it comes to support of hardware updates. In long-run and large production, using ASIC platforms can be beneficial, however, the product has to be stable for production due to high cost in designing ASIC platforms.

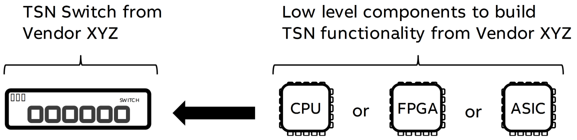

Fig. 4: Illustration of using different components in switch development.

The different switch vendors are all actively promoting TSN on their web pages, e.g., Cisco presenting their TSN portfolio as part of the ”Smart Manufacturing”[2], Belden as TSN-Ready heterogeneous industrial networks used by Industry 4.0 [3] and Moxa as actively supporting the digital transformation in Industry 4.0 / IIoT[4]. B&R, Phoenix and Rockwell automation are also actively promoting new products to be released to the market in the near future. In fact, only Cisco has a product, today, that supports one of the TSN standards, IEEE 802.1Qbv (scheduled traffic) in its 4000 series products. All the others are either describing, like Belden/Hirchmann, that some of their products are TSN ready and can be updated via software in the future, or no specific standards are mentioned but a product will be available in the near future.

Moving the focus to the component level, i.e., FPGA and FPGA-IP solutions the support for the different standards is more mature. Likely this support will also be provided by the switch vendors, presented above, in their coming releases. Xilinx and Altera are examples of FPGA manufacturers that have different IP cores available for TSN, e.g., Xilinx 100M/1G Multiport TSN Switch IP Core[5] supporting a wide range of features, e.g., time synchronization, frame replication and elimination, forwarding and queuing enhancements, frame preemption and link recovery. Other vendors are supporting more generic platform independent IPs, e.g., TTTech[6] has a number of IP solutions supporting a large variety of features, e.g. scheduled traffic, time synchronization, frame preemption and credit-based shaper. Other examples from IP providers include NetTimeLogic[7], SoCe[8] and Fraunhofer IPMS[9].

Additional to providing components/IP also some of the manufacturers provide evaluations boards, e.g., TTTech MFN100[10], Kontron C-102-2 TSN Starter Kit[11], SoCe MTSN kit- multiport TSN Switch[12], all vital components needed to be able to evaluate a future TSN implementation in a simple way.

To sum up, a different selection of standards are supported by the different TSN switch vendors. Table II presents a

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[2] https://www.cisco.com/c/en/us/solutions/industries/manufacturing/connected-factory/time-sensitive-networks.html

[3] https://beldensolutions.com

[4] https://www.moxa.com/en/spotlight/industrial-ethernet/tsn/index

[5] https://www.xilinx.com/products/intellectual-property/1gtsn.html

[6] https://www.tttech.com/

[7] https://www.nettimelogic.com/tsn-products.php

[8] https://soc-e.com/mtsn-multiport-tsn-switch-ip-core/

[9] https://www.ipms.fraunhofer.de/en/research-development/wireless-microsystems/ip-cores/tsn.html

[10] https://www.tttech.com/product-filter/time-sensitive-networking-tsn/

[11] https://www.kontron.com/products/systems/tsn-switches/network-interfaces-tsn/kbox-c-102-2-tsn-starterkit.html

[12] https://soc-e.com/mtsn-kit-a-comprehensive-multiport-tsn-setup/

TABLE I: The current status of TSN standards.

Standard	Description	Status
IEEE 802.1Q	forwarding and transmission mechanisms and reservation protocols	base standard - published in 2018
IEEE 802.1AB	specifying the link recovery protocols	base standard - published in 2016
IEEE 802.1AS	time synchronization for TSN	base standard - published in 2020
IEEE 802.1AX	link aggregation to increase the throughput	base standard - published in 2014
802IEEE 802.1CB	frame replication and elimination for reliability	base standard - published in 2017
IEEE 802.1CM	mechanisms to enable TSN for Fronthaul	base standard - published in 2018
P802.1CS	link-local registration protocol	ongoing
P802.1CQ	multi-cast addressing and local address allocation	ongoing
P802.1DC	provisioning of quality of service in the network	ongoing
P802.1DF	the profile for TSN service providers	ongoing
P802.1DG	automotive in-vehicle communication	ongoing
IEEE 802.1Qbu	frame preemption support	2016 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qbv	enhancements for scheduled traffic	2015 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qca	path control and reservation	2015 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qav	forwarding and queuing enhancements for time-sensitive streams	2009 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qch	cyclic queuing and forwarding	2017 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qcc	SRP enhancements and performance improvements	2018 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qci	per-stream filtering and policing	2017 and rolled into IEEE 802.1Q-2018
IEEE 802.1Qat	Stream Reservation Protocol (SRP)	2010 and rolled into IEEE 802.1Q-2018

list of TSN support provided by the different manufacturers of TSN switches. Based on this investigation, we can see that the switch developers have a very limited support of TSN features today, however the FPGA / IP based companies support a larger set of features, including frame preemption. The ongoing projects, i.e., CS, CQ, DC, DF and DG, are not supported by any manufacturer. Probably most of the switch vendors are using FPGA-based designs and therefore we can expect them to, enabled by software updates, in the near future, provide a significant larger support of standards, i.e., the same support as provided by the FPGA/IP manufacturers today. Another observation is that none of the manufacturers have reported support for the IEEE 802.1Q standard, which is due to the fact that a large set of the features are included in this base standard, e.g., the IEEE 802.1Qbu standard, and is not supported by many manufacturers.

3) A standard does not specify everything: According to our investigation, several variables and parameters are not fully specified. This will affect the development of TSN devices and developers are limited to the device description sheets. The selection of those parameters should also be considered in the configuration and simulation tools. For instance, the standards are not defining the buffer sizes for the transmission queues. Looking at work that has been published by the research community we cannot find solutions that address the backlog study of buffers for TSN queues, and the presented solutions are mostly considering timing constraints with an assumption of having an infinite buffer. The available simulation tools, e.g., Core4INET and NESTING, have a parameter to set to define the buffer size in terms of number of messages. This parameter is specifically hard to find in the TSN hardware specifications. A network designer usually assume a common value for this parameter and design the network hoping that in a full-load situation there will not be any packet drops. This can be addressed when ST is used, while it is not easy to compute for the sporadic background traffic that may use CBS. The network developers of long-life systems should consider these issues normally with best proposed practices provided by the TSN device manufacturers.

4) Configuration: As many features are provided by the different TSN standards, design and development of a network based on TSN devices becomes non-trivial. Many solutions have already mentioned this complexity and various approaches have been proposed to address it. However, a tool that can be used to configure a network is still not fully developed. Most of the network designers use their own tool, not available to public. One recent example of such a configuration tool is announced by TTTech[13].

To simplify the configuration of the TSN network, different standardization bodies are working on defining *TSN profiles* for specific application areas, by defining mandatory and optional features, i.e. the configuration of devices in the network will be simpler and leading to a lower cost for the manufacturers. Examples of ongoing standardization works include IEC/IEEE 60802 *Time-Sensitive Networking Profile for Industrial Automation*[14], *P802.1DG TSN Profile for Automotive In-Vehicle Ethernet Communications*[15] and *P802.1DF TSN Profile for Service Provider Networks*[16]. Similar activities have been done in the past for other larger initiatives, e.g., the Precision Time Protocol (PTP) IEEE-1588 that supports several types of profiles such as PTP industry profile IEC62439-3 and Power Profile IEEE C37.238. A possible risk with standardizing on profiles is that several different profiles cannot coexist in a mixed system due to different requirements. Examples of such problems with co-existence within PTP are described in [9]. An advantage with standardized profiles is that the vendors of TSN equipment gets an understanding of which features that are needed for a specific industrial segment, e.g., industrial automation, and

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[13] https://www.tttech.com/tttech-releases-worlds-first-vendor-independent-tsn-configuration-software/

[14] https://1.ieee802.org/tsn/iec-ieee-60802/

[15] https://1.ieee802.org/tsn/802-1dg/

[16] https://1.ieee802.org/tsn/802-1df/

TABLE II: Various TSN features supported by manufacturers.

		IEEE 802.1																		
		Q	AB	AS	AX	CB	CM	CS	CQ	DC	DF	DG	Qav	Qbu	Qbv	Qch	Qca	Qcc	Qci	Qat
Switch Vendors	Cisco	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨ x	▨	▨	▨	▨	▨
	Belden/Hirschmann	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Moxa	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	B&R	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Phoenix	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Rockwell Automation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
FPGA / IP	Xilinx		X	X		X							x	x	x					
	Altera			X									x		x					
	NetTimeLogic			X									x	x	x	x		x		
	Fraunhof			X									x	x	x					
	SoC-e		X	X		X							x	x	x			x	x	x
	TTTech			X		X								x	x			x		

☐ = Standard is not published ▨ = New features will be provided by Firmware update or not released

can pay extra attention to support them in future generations of products. This advantage however depends on if the users accept the specific profile to be used in a broad range of installations.

5) Not all types of traffic is allowed: All types of legacy Ethernet traffic is not allowed to be used in a TSN network today. For instance, EtherCAT traffic do not allow VLAN tags to set priority levels. The EtherCAT foundation has solved this issue by adding a stream adaptation layer to wrap a legacy EtherCAT frames when it passes a TSN network. Similar changes in the future can impose unexpected updates in the industrial control systems during their life-cycle.

6) Cyber security: A cyber attack can occur due to many reasons such as access to critical information, black mailing, harm assets and change settings in a machinery to make physical damage. In case of TSN devices, the manufacturer is subject to provide security policies. The main challenge with respect to TSN security is that a user may mix different traffic types on the same hardware. For example, cloud-based traffic which are mostly used by a system in operation may be combined with critical process traffic without having any security policy implemented. One hardware device, i.e., a TSN switch, will then have to handle security requirements from the internet facing traffic, i.e., high requirements on patch ability, short expected times before the detection of a vulnerability is detected until it has to be fixed, vs. the process bus side with a requirement on 24/7 up time and maintenance stops maybe every 1-3 year for doing any updates to the system. Workaround in this case is not to use the full possibility to integrate everything or build the system redundant to allow for updates in a stand-by system, with the risk of not having redundancy during the update time. A risk many critical infrastructure systems would not like to take, instead an additional level of redundancy is needed, giving a higher cost and complexity. The maturity of the standards opens up a future possible update when more users start to use the TSN devices and find possible security flaws. To summarize, TSN switches will most likely not be more vulnerable compared to the non-TSN switches by the same manufacturer. A strong recommendation for the network developers is to prevent using any mixed traffic with different security requirements on a single network.

B. Identified opportunity

Standardizing a functionality is something positive when it comes to the possibility to find second sources for a specific function, and that will also be valid for TSN in the future. If only one manufacturer is supporting a solution the user is completely dependent on the manufactures' strategies, e.g., for how long the specific product is manufactured before a last-time-to-buy is issued. A good example from the electronic world is the TTL logic 7400 series introduced by Texas Instrument in 1966 that became an industrial standard, and compatible parts were produced by several other companies, e.g., Motorola, AMD, Fairchild, Intel, National Semiconductor, giving a user a wide range of manufacturers to choose from. From a TSN perspective the support from different parts of the industry is large, which is mentioned in the text above highlighting the names of large industry contributors, e.g., Cisco, Xilinx, Belden and TTTech, but also other industrial initiatives are supporting TSN, e.g., the Industrial Ethernet consortium[17] and an industrial group containing industrial leaders, e.g., ABB, Belden, Bosch Rexroth, B&R, Cisco, Hilscher, KUKA, National Instruments, Rockwell Automation, Parker Hannifin, Phoenix Contact, Pilz, Schneider Electric, TTTech and WAGO, to support OPC-UA/TSN to address real-time device-to-device and device-to-cloud applications [18]. A more technical TSN related opportunity is the possibility to reserve space for future network traffic, e.g., not allowing the current system to use the full potential of the network, instead reserve a time slot for future use. By this the verification done

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[17] https://www.iiconsortium.org/time-sensitive-networks.htm

[18] https://www.automation.com/en-us/articles/2018/opc-ua-over-tsn-a-realistic-future-for-a-unified-i

previously does not have to be redone later on when new functionality is added.

To summarize, standards have the positive effect that more than one manufacturer could have products that support the same features, giving a second source for spare parts, i.e., try to follow standards if possible. TSN opens up for reserving network performance for future use, i.e., no need to retest already implemented parts if new features are added.

V. RELATED WORK

In 2012, the Time Sensitive Networking (TSN) task group is established with the aim of extending the enhancements to support time-sensitive traffic. The main contributions to the existing standards were to introduce time-triggered transmission on top of the other traffic classes. Among several enhancements, the main support from TSN include enhancement for scheduled traffic, frame preemption support and clock synchronization. Many works have investigated different aspects of TSN, including applying different time-aware shapers [10], scheduling policies [11], load balancing in TSN networks [12] and fault tolerance issues [13]. Moreover, applicability of using TSN for vehicular on-board communication has also been studied recently in few works, e.g., [14] and [15].

In order to guarantee the timeliness of traffic in TSN networks, some works addressed the analysis and simulation of TSN networks. Few works have addressed the schedulability analysis of traffic from classes A and B. An analysis is given in [16] to compute the worst-case delay of frames in TSN considering the time-aware shaper for single-switch networks. Moreover, the work presented in [17] proposed an analysis technique for time-aware shaper and peristaltic shaper, while a very recent work in [18] presented an analysis based on network calculus.

When it comes to using new technology in a product an important aspect will be how mature the technology is, e.g., defined by the Technology Readiness Level (TRL) [19] or the position on the Technology Hype cycle [20].

The Gartner Hype curve, as depicted in Fig. 5, was introduced in 1995, as a mean to explain a typical progression of an emerging technology from over-enthusiasm to a mature position on the market. The first of five stages is the *Technology trigger* which is an event that generates significant press and interest, e.g., large vendors express their active contribution in development of the new emerging TSN technology. Next stage is *Peak of inflated expectations* which contains over-enthusiasm and unrealistic expectations. Some technologies passes this stage and some fails. *Trough of Disillusionment* is entered when the technology fails to meet the expectation and the press usually abandon the topic and technology. During *Slope of Enlightenment* the covering of the technology is low in the press but the business continues to use the technology and starts to learn how to use it in practical applications. The *Plateau of Productivity* is the stage of main stream adaption where the technology is broadly adopted on the market. Similar stages can be found in the technology maturity s-curve [21], containing technology stages, *introduction*, *growth*, *maturity*, where the performance reaches its peak and finial aging.

The Gartner Hype curve can also, among others, be extended with an *Adoption curve*, as shown in Fig. 6, giving an indication of the amount of users relative to the location on the Hype curve.

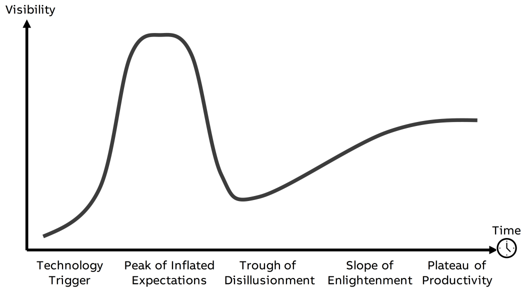

Fig. 5: The Hype Curve.

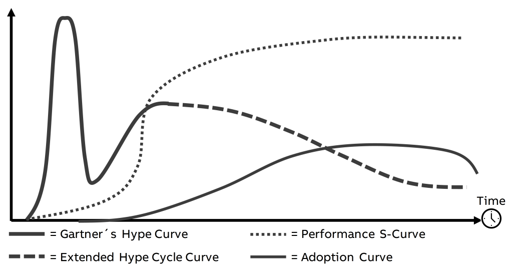

Fig. 6: Extended curve with Performance and level of Adoption.

Valid both for the Gartner Hype curve and the s-curve is that the TRL is increasing on the up-slope since more R&D effort is added. Research is ongoing to extend the TRL levels, that are more R&D related, to also include the product life cycle perspective [22], Commercial Reediness Index (CRI) [19] [23], or System Reediness Level (SRL) [24] and extending the TRL level beyond number 9 with a level for proven operation, e.g., flight-certified maturity [25].

TSN is a new technology that is about to climb in the TRL levels as several of the standards are not yet released and research studies are ongoing in all fields.

VI. CONCLUSIONS AND FUTURE WORK

Early tech adopters with a long expected life time of their systems and products have a challenge to handle when it comes to being aware of whether a technology will be available in the long run. At the same time, new technology opens for potential competitive advantages, e.g., higher performance, enabling of independence between subsystems, mixing of critical and non critical signals. Such advantages could result in getting a competitive advantage over the competition on the corresponding markets. However, embracing new technologies (potentially) opens up for new unexplored attack surfaces, for example introducing issues when it comes to cyber security.

The TSN standards are not, today, yet fully developed, but the work forward is supported directly or indirectly by

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[19] https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

many large industrial partners giving TSN a solid ground to stand on. From the point of view of major switch vendors, e.g., Cisco, TSN is still something new and only a limited support is provided on the market. On the other hand there is a larger support among the chip vendors or IP providers, e.g., TTTech/Xilinx, giving a fairly complete portfolio of TSN features to use or evaluate. Since the switch vendors most probably use these components/IP to build their products we can expect that the corresponding TSN features will be provided as software updates of the switches in the near future. Exactly that will be supported by "off-the-shelf" switches is not obvious, but as long as one is planning to use the most basic functionality that today is supported by most of the chip vendors / IP providers, e.g., scheduled traffic (supported by IEEE 802.1Qbv), frame prevention (supported by IEEE 802.1Qbu), forwarding and queuing enhancements for time-sensitive streams (supported by IEEE 802.1Qav) and time synchronization (supported by IEEE 802.1AS), one should have a fair chance to find a replacement part in the future. Still we should note that the standards do not specify everything, e.g., buffer sizes. Hence, changing to another vendor could give a new behavior of the system. One central open issue is the tool chain needed to configure and maintaining the network. No generic tools are available. Instead the user is dependent on the manufacturer and may therefore need to change tools over time depending on the vendor. An important addition to the configuration will be future TSN profiles, e.g., *IEC/IEEE 60802 Time-Sensitive Networking Profile for Industrial Automation*, currently in draft state, allowing TSN vendors to understand what features that are central to different application areas and must be supported also in future releases.

To summarize, if the advantages of introducing a TSN network are large, e.g., consolidating network traffic, evaluation of such a solution should be performed. However, one must be aware that the technology, from a network vendor perspective, is still not mature. As a consequence the developer should expect to be vendor dependent when it comes to tools/features over the next coming years. In a 10-15 years perspective the use of a feature based on a standard is positive and will allow for a larger set of vendors to choose between, if one does not have to rely on the availability of one specific manufacturer or FPGA/IP provider.

Our future work will be to go into detail concerning a number of the different features, e.g., frame preemption, to investigate the corresponding Technology Readiness Levels (TRLs), open issues and improvements. In addition, several efforts are ongoing to adopt wireless communications, e.g., 5G technology, in the automation industry. That will raise new challenges and issues related to compatibility of TSN networks with 5G communication. The deeper investigation in this regard remains for the future work.

ACKNOWLEDGMENT

This research has been performed with the support from the Swedish Knowledge Foundation (KKS) under the FIESTA project and from the Swedish Governmental Agency for Innovation Systems (VINNOVA) under the DESTINE project.

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