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Authors	Seliem, Mohamed;Zahran, Ahmed;Pesch, Dirk
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UCC
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TSN-based Industrial Network Performance Analysis

Mohamed Seliem
School of Computer Science and IT
University College Cork
Cork, Ireland
m.seliem@cs.ucc.ie

Ahmed Zahran
School of Computer Science and IT
University College Cork
Cork, Ireland
a.zahran@cs.ucc.ie

Dirk Pesch
School of Computer Science and IT
University College Cork
Cork, Ireland
d.pesch@cs.ucc.ie

***Abstract*—Industrial automation applications enforce strict requirements on the automation network, such as strict timing, upper bounded latency, low jitter, and essentially zero loss. Time sensitive networking (TSN) is an enabling technology for future automation networks. While most studies on TSN for industrial applications have focused on simple approaches to performance evaluation, we provide a comprehensive simulation based analysis for a typical industrial use case. We specify the network traffic produced by automation applications and associated TSN traffic classes. We model different network configurations such as priority queuing, time aware shaping, and credit based shaping to study how they meet the delay constraints of the different traffic classes. To evaluate the performance of our TSN based industrial network, we build and configured a network model and a set of application traffic models to generate realistic network traffic together with defined network design goals in OMNET++. Our simulation results show that a TSN based network meets all application requirements.**

***Index Terms*—Time Sensitive Networking, Industrial Networks, IIoT, Resource management, OMNET++.**

I. Introduction

Industrial automation networks, also called operational technology (OT), have strict requirements in terms of latency, bandwidth, and reliability of data delivery. The outcome of an action not only depends on the successful message delivery, but also on meeting timing bounds. With the introduction of the Industrial Internet of Things (IIoT) as part of the Industry 4.0 vision, operational technology services are being integrated with traditional information technology (IT) services, leading to a mixture of network data traffic with very different requirements. This challenges traditional network solutions to meet determinism and bounded latency requirements. For example, a robotic arm must pick up an object that moves on a conveyor belt at a specific time. Even a small delay in receipt of the message can lead to failure of the operation, as the object may have moved to a different position by the time the robotic arm is triggered. All the while, delay tolerant web traffic to display recent data on production yields may flow through the network at the same time.

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Time Sensitive Networking (TSN), as specified in IEEE 802.1 [1], is a set of standards to bring the notion of time to the network scope to support different types of traffic with different real-time requirements. TSN has three main functionalities, (i) synchronization, (ii) scheduling and traffic shaping, and (iii) fault detection and elimination. TSN is becoming an enabling technology for industrial networks in the realization of the IIoT. This paper focuses on studying a typical IIoT use case with different types of traffic classes through simulation based experiments of an industrial network scenario. Through a comparative analysis, we assess how standard Ethernet and TSN support different quality of services requirements to meet the use case requirements. Our results demonstrate that TSN, in comparison to standard Ethernet, fully meets these requirements.

The paper is organized as follows: Section II presents relevant related work, Section III highlights capabilities of TSN in supporting industrial automation and specifically in deploying our QCAP use case, which is presented in section IV. The network structure, design and traffic simulations model are detailed in section V. In section VI, we explain experimental settings, test environment, and present and analyse obtained results. Section VII concludes the paper.

II. Related Work

Accommodating real-time data traffic in industrial automation has been investigated extensively [2]. Different industrial Ethernet protocols [3] use synchronized time-triggered or asynchronous event-triggered based medium access approaches to provide low latency and determinism. For example, time aware traffic shaping (IEEE 802.1 Qbv) [4] and credit based traffic shaping (IEEE 802.1 Qav) [5]. IEC/IEEE 60802 [6] is a collaboration between IEC SC65C/WG18 and IEEE 802 to provide a standard that defines time-sensitive networking profiles for industrial automation. This standard will guide the vendors to use the TSN features to deploy converged networks, which simultaneously support operations technology traffic and other types such as information technology traffic.

Several works report on theoretical and experimental analysis to assess and validate TSN functionalities. Authors in [7], [8], and [9] investigated the time synchronization accuracy and performance in automotive and industrial automation

networks. Others in [10], [11], [12], [13], [14], [15], and [16] used the network calculus framework for impact, timing, and worst case analysis of the traffic shaping for different TSN applications and use cases. Moreover, the authors in [17], [18], [19], and [20] implemented efficient simulation models based on the OMNET++ INET framework [21] for different TSN traffic shaping and queuing standards. Earlier this year (Jan. 2022), some TSN features were added to the latest version of the INET framework by Levente Mészáros [22] to study TSN in automotive applications. In this paper, we extend this implementation to deploy a converged industrial automation network and make the following contributions: 1) Introduce the Quality Control After Production (QCAP) industrial use case. 2) Implement different types of realistic network traffic simulation models to test the QCAP network performance. 3) Verify and evaluate the performance of the TSN queuing and traffic shaping scheme in an IIoT application

III. Time Sensitive Networking

TSN is a set of standards that support reliable transmission of critical automation system traffic, Operational Technology (OT) traffic, along with Information Technology (IT) traffic, e.g. audio/video and best effort web traffic. The industrial profile of TSN, maintained by IEEE TSN-WG and IEC, provides the following capabilities:

Determinism: TSN incorporates time aware shaping, where timed schedules of transmission gates in each switch control the network traffic pace based on a transmission selection criterion, e.g. traffic priority, ensuring that queuing delay is controlled, hence providing guarantees on end-to-end latency.

Congestion control: TSN incorporates token based shaping, where a defined credit controls the transmissions from a specific class of traffic. This limits the different traffic bursts and improves the bandwidth management, ensuring efficient link utilization and congestion control across the network.

Link utilization: TSN supports transmission of both OT and IT traffic, making sure OT traffic meets timing requirements and ensuring that network links are efficiently utilized.

In addition, unlike Ethernet based proprietary protocols, e.g. EtherCAT developed by Beckhoff [23] Profibus [24] and Ethernet/IP [25], TSN is an IEEE standardized Ethernet based technology that supports interoperability. Thus, it can be integrated easily with other legacy and new industrial networks. Moreover, TSN supports simple networks with expansion capabilities, which eases the scalability of IIoT. Adopting TSN technology and functionalities, in our QCAP use case, leverages the aforementioned advantages. Therefore, we have implemented, deployed and used OMNET++ to evaluate the following key functionalities within our simulation model:

a) Time synchronization: IEEE 802.1 AS, Generalized Precision Time Protocol (gPTP), provides the timing and synchronization aspects for TSN applications. A main/origin TSN switch, S_{origin}, has a master interface, $intf_m^{origin}$, that is connected to the master clock module, Clk_m. The rest of the S_{origin} interfaces, $intf_{i,s}^{origin}$, where *i* is the interface number, act as slaves to $intf_m^{origin}$. Each connected $intf_{i,s}^{origin}$ links to a master interface of another switch,$intf_m^{others}$, at the other end of the Ethernet link. All network devices exchange gPTP messages to ensure that the slave interfaces, $intf_{i,s}^{all}$ are following their associated master interface clock Clk_m. This ensures that all the QCAP devices are synchronized with an accuracy of nanoseconds. gPTP operates at the L2 of the communication stack, where the received and transmitted frames get time stamped. thus reducing jitter and asymmetry in the delay to prevent synchronization inaccuracies.

b) Strict Priority Queuing (IEEE 802.1 Q): Ingress traffic is classified into different priority queues using the 3-bits Priority Code Point (PCP) field of the VLAN tag. Traffic marked with the highest priority is transmitted first, while traffic in lower priority queues waits for the higher ones until they are empty. In the QCAP use case, the highest priority is assigned to the control data traffic (sensing traffic) to ensure that it will not be held up by other network traffic, yielding the lowest queuing delay.

c) Credit based Shaping (IEEE 802.1 Qav): Burst and high-rate data flow is classified into a separate traffic class/queue. A credit based shaping (CBS) is applied to the queue to control its behavior, where $idleSlope$ is the accumulated credit rate when the queue is not transmitting. Upon acquiring sufficient credit and an opportunity for transmission, the queue spends this credit to transmit with $sendSlope$ rate. The queue has a high and low bound on the allowed credit, which are $hiCredit$ and $loCredit$ respectively. The following set of equations are used to calculate the slopes and bounds:

$$idleSlope = \frac{8 \times data_rate \times max_frame_size}{1000} \quad (1)$$

$$sendSlope = idleSlope - port_transmit_rate \quad (2)$$

$$hiCredit = \lfloor \frac{idelSlope \times max_interference_size}{port_transmit_rate} \rfloor \quad (3)$$

$$loCredit = \lfloor max_interference_size \frac{sendSlope}{port_transmit_rate} \rfloor \quad (4)$$

d) Time Aware Shaper (IEEE 802.1 Qbv): Gate Control List (GCL) is a schedule that operates the transmission gates to control the transmissions of the different queued data traffic types. GCL has a defined cycle where the scheduled entries repeat. A single cycle is divided into n slots that map to the GCL entries. Each entry represents the gates' status, e.g. open or closed, for a certain period that is a slot. Slot duration t_{slot} differs, and it depends on the max data length $Lmax_{slot}$ transmitted in this slot as well as the link bandwidth B, $t_{slot} \leq \frac{Lmax_{slot}}{B}$. An upper bound on a time slot relates to the traffic priority and the incoming traffic rate. TSN switches follow the GCL entries for each egress port, which results in time shaping for the data traffic. By controlling the transmission gates, the switches pace the traffic to deliver on time and meet the guaranteed latency requirements. This prevents the low priority traffic from interfering/overlapping with the high priority traffic, yet it dedicates a transmission duration for it. This is to ensure an optimized utilization of the network bandwidth without affecting the time critical traffic.

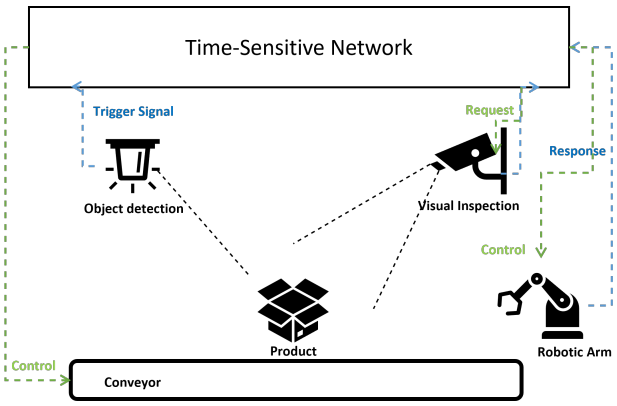


Fig. 1. Quality Control after Production (QCAP).

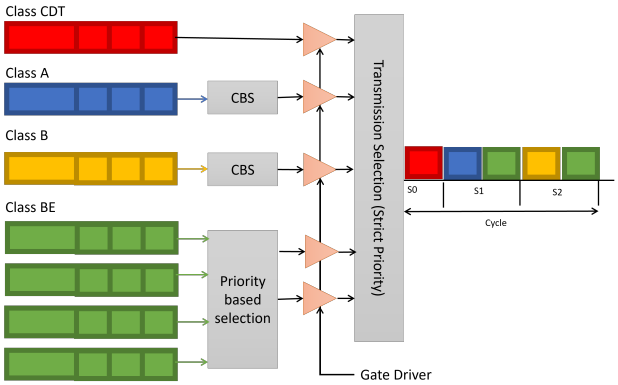


Fig. 2. Egress port of a switch with TSN queueing and shaping support.

IV. Use Case: Quality Control and Classification after Production

Quality control ensures that an imperfect product will not go out of the production facility. In smart manufacturing systems, quality inspection starts right after the production. Figure 1 illustrates this process, which mainly consists of three parts:

Detection: a product of length L arrives at every time interval T. An object detection unit, e.g. photoelectric sensor, transmits a trigger signal across the network, for a period of t_{detect} to initiate the quality checking. Then, the unit reverts to an idle state for a period t_{idle} until a new object arrives.

Inspection: a recording unit monitors multiple production lines, where the camera switches between each line upon notification of a new product arrival. The recording unit starts transmitting high resolution media files of the product for period $t_{inspection}$. The camera is also used to monitor the factory floor.

Classification: the collected data from the inspection part is used to decide on the quality of the product. The robotic arm receives an order to remove the product if imperfect.

Each sensing or actuation function results in a different data traffic type with different QoS requirements. For example, the detection part generates critical traffic that requires strict latency, in terms of microseconds, and guaranteed delivery, e.g. zero packet loss. While for the video inspection traffic a higher bandwidth is required with low latency yet with guaranteed upper bound. The same applies to the video stream of the floor in terms of bandwidth yet with more tolerant delivery requirements. Therefore, not only the OT network of such use case must be time-aware, but also it must be scalable and interoperable to support different vendors and enable the realization of the IIoT.

The floor monitoring data traffic, generated from the inspection unit in the QCAP network, is subject to credit-based shaping to ensure that no congestion occurs at any critical interfaces. Figure 2 depicts the integration of the aforementioned queueing and shaping techniques, which are applied on an egress port of a TSN switch that participate in the QCAP network. The traffic created by the sensing, inspection, and floor monitoring are classified in different queues. In addition, IT traffic, e.g. web based data transfer, is routed over the same network. Each cycle has three slots:

Slot 0 dedicated to critical sensing traffic, where only the highest priority queue transmission gate is open, and the rest of the gates are closed.

Slot 1 both inspection (class A) and IT (class BE) transmission gates are open. In case of the coexistence of both traffic types, the higher priority gets selected for transmission.

Slot 3 both floor monitoring (class B) and IT (class BE) transmission gates are open. This ensures a better bandwidth utilization as well as meeting the different QoS requirements. Credit based shapers are used to control the burstiness of class A and class B traffic, which regulates the overall congestion across the QCAP network.

V. Network and Simulation Model

This section details the network structure to support the QCAP use case. Moreover, it presents the characterization of the traffic models used to generate the network data traffic.

A. Network structure and design

A smart manufacturing system includes many production lines that incorporate quality control of the produced goods. An industrial network connects all the parts of the process. Figure 3 depicts the realization of a structured industrial network that supports the communications between sensing, video inspection, and classification units. Each production line has a detection unit that reports to a computing unit, upon a new product arrival. An associated examination unit is notified, by the computing unit, about the arrival time and accurate location of a product for visual inspection. A robotic arm is used for the product classification (removal if imperfect) after the product is checked. As the examination unit cost is high, it is used to examine and record data for multiple production lines in addition to using the camera to consistently monitor the production floor.

The QCAP network forms a tree topology (see Figure 3). This permits the network to be easily expanded in both vertical and horizontal directions. The network structure is as follows:

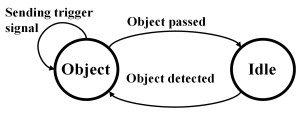
1) central entity, switch 1 (SW1), acting as a root, where all communications are routed through, including the management and network configurations information. In addition, switch 1 connects to an edge computing unit, monitoring unit, and two leave switches, switch 2 (SW2) & switch 3 (SW3).
2) The edge unit processes the sensing traffic, initiates the inspection process, decides on the product quality, and then commands the designated robotic arm for classification.
3) The monitoring unit acts as a sink node for all the streamed traffic from the cameras in the network. Thus, it provides a consistent visual image of the factory floor.
4) The two switches (left and right) extend the network horizontally by incorporating an aggregation IT traffic unit and vertically by connecting to network cells.
5) Three network cells, where each cell consists of 2 production lines, single examination unit, and network switch. Those carry the QCAP functionalities that have been described before.

Through observing the traffic flows across the QCAP network, it is obvious not only that the link between SW1 and SW2 is congested, but also is the critical/bottleneck. In this paper, our focus is to design, configure, and manage the network resources to efficiently utilize the network bandwidth while maintaining bounded latency for the critical flows. We assume that links are not subject to failure, even if implementing a counter measure like IEEE 802.1CB Frame Replication and Elimination (FRER) could overcome such concerns.

B. Traffic models characterization

The network hosts produce four types of traffic (see Tables I and II), which are characterized as follows:

Control Data Traffic: Product detection signals are critical traffic. It requires determinism as well as the least delay ($\sim 50-100\mu s$), failing to do so will lead to a failure in the overall process of the product quality checking. To model this traffic, we consider the following finite state machine:



A production line with an output rate of n units per hour, each unit is of a length L. The production line conveyor is of a speed S. The detection unit remains in idle state till a new product arrives, every $3600/n$ seconds, then it changes to object state where it notifies the edge unit before it goes back to idle state once the object has passed. The traffic parameters are as follows: 1) Packet size = 174 bytes (128 payload + 46 headers), 2) Packet interval = $500\mu s$. Thus, the data rate is 2.8 Mbps while in object state and drops to zero in the idle state. $t_{detect} = \frac{L}{S}$, $t_{idle} = \frac{3600*S-L*n}{n*S}$ define the transmission and idle periods. Additionally, the commands issued by the edge unit to instigate the visual inspection or to control the

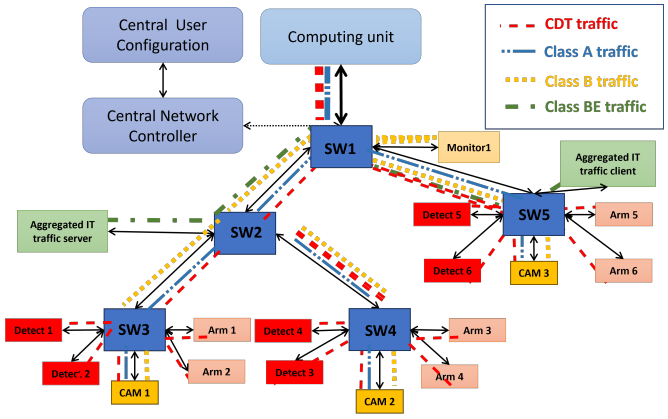


Fig. 3. Network structure for QCAP.

robotic arms are critical. All the critical traffic has the highest Priority Code Point value 6, which is included in the VLAN tag of the transmitted frames from the critical traffic sources. Therefore, when configured, the network devices identify those and moreover process them with the highest priority. **Class A Traffic:** inspection recordings of the targeted product, which are transmitted when the inspection unit receives a trigger from the edge unit. This type of traffic requires high bandwidth, guarantees on delivery as well as deterministic latency. It is important for the edge unit to complete the product quality checking at a specific time. Thus, the robotic arm can classify the product based on the check results. To model this traffic, we consider its dependency on the event of product arrival, which leads to burstiness in the outgoing traffic from the inspection unit. The following parameters define the traffic nature:

1) inter-arrival time between frames = 50 ms,
2) number of packets per frame = 8,
3) packet size = Truncated Pareto distribution with $alpha = 1.1$, $L = 180$ bytes, $H = 558$ bytes,
4) packet interval = Truncated Pareto distribution: $alpha = 1.1$, $L = 125\mu s$, $H = 500\mu s$, and
5) burst duration = 2.0 seconds.
6) high priority traffic (PCP = 5).

Class B Traffic: video streaming service of the floor using the cameras, which are embedded in the inspection units. All the class B traffic has the same destination that is the monitor unit. Each camera produces 24 frames per second with 1280 x 720 resolution, MJPEG compressed format, and triple stream support (RTP/RTSP, Unicast RTP, Multicast RTP). To model this traffic, we consider that a consistent great image quality and robustness are required. While such characteristics requires high bandwidth and storage demands, it will be a realistic stress test for the backbone network performance. The following parameters define the traffic nature:

1) inter-arrival time between frames = 40 ms,
2) number of packets per frame = 8,
3) packet size = Truncated Pareto distribution with $alpha = 1.2$, $L = 20$ bytes, $H = 1246$ bytes,

TABLE I
TRAFFIC MODEL CHARACTERIZATIONS (CDT, CLASS A, CLASS B).

	PCP	Packet Size (Bytes)	Packet Interval (ms)	[Idle, Active]	Max. data rate (Mbps)	Max. delay
CDT	6	174	0.5	$[t_{idle}, t_{detect}]$	2.8	100 μs
Class A	5	α = 1.1, L = 180, H= 558	α= 1.1, L = 0.125, H= 0.5	$[(3600-2n)/n, 2]$	35.7	60 ms
Class B	3	α = 1.2, L = 180, H= 1246	α= 1.2, L = 0.5, H= 5	Always active	19.94	70 ms

TABLE II
TRAFFIC MODEL CHARACTERIZATION FOR WEB TRAFFIC.

		Class Best Effort (BE)	
		Browsing	File Transfer
Total Size	Main object size	μ = 8.37, σ = 1.37, a = 100 B, b= 2 MB	μ = 14.45, σ = 0.35, a = 100 B, b = 5 MB
	Embedded object size	μ = 6.17, σ = 2.36, a = 50B, b= 2MB	-
	Embedded objects per page	α = 1.1, L = 2, H= 55	-
Timing	Reading time	λ = 0.033	λ = 0.006
	Parsing time	λ = 7.69	-

4) packet interval = Truncated Pareto distribution with $alpha = 1.1$, $L = 500\mu s$, $H = 5ms$, and
5) priority traffic (PCP = 3).

Class Best Effort Traffic: information technology traffic, non-critical flows, that coexist with the critical industrial traffic. BE traffic has priority code point set to zero (PCP = 0), which will be transmitted in case a free slot exists. In addition, when a credit-based shaper is applied, the shaped traffic gain credits upon successfully transmitting BE traffic. To model this traffic, we consider two sources of data flows:

Web browsing: Client unit issues n requests per session to model HTTP 1.1 with keep alive behaviour, where n is a random variable that has exponential distribution with $\lambda = 5$. For each request, the HTTP server provides a reply that has a total size equal to the main size, main object size, plus the total size of the embedded objects in a requested page, equals to embedded object size times embedded objects per page. Those parameters [26] are random variables with the following distribution characteristic:

1) main object size follows a truncated log normal distribution with mean of 11 KB, standard deviation of 26 KB, minimum size of 100 bytes, and maximum size of 2 MB.
2) embedded object size follows a truncated log normal distribution with mean of 7.75 KB, standard deviation of 125.2 KB, minimum size of 50 bytes, and maximum size of 2 MB.
3) embedded objects per page follows a truncated Pareto distribution: $alpha = 1.1$, $L = 2$, $H = 55$. In addition, reading time, which is time gap between requests, and, parsing time, which is time gap between sessions, are random variables with exponential distribution function ($\lambda = 0.033$ $\lambda = 7.69$ respectively).

File transfer: Client unit issues an FTP request to fetch a data file from the FTP server with the following parameters:

1) File size (main object size) follows a truncated log normal distribution with a mean of 2 MB, standard deviation of 0.724 MB, minimum size of 100 bytes, and maximum size of 5 MB.
2) reading time is exponentially distributed with an expected rate of occurrences = 0.006.

VI. RESULTS AND DISCUSSION

To evaluate the QCAP network performance, we use OMNET++ [27] to simulate the network behaviour in Figure 3, Section V.A. The network and simulation configurations are summarized in Table III.

TABLE III
NETWORK AND SIMULATION PARAMETERS

Parameter	value
Simulation time	90 s
Processing delay of a switch	1 μs
Network link speed	100 Mbps
Propagation delay	0.05 μs
Max. queue size	1000 packets

And the configurations of the nodes are as follows:

1) Detect 1-6: detection sensors, which are configured as hosts (Standard or TSN). Each unit runs a UDP application (source) that generates CDT class traffic upon the arrival of a new product.
2) CAM 1-3: inspection and monitoring cameras, which are configured as hosts (Standard or TSN). Each unit runs two UDP based applications: a) inspection: generates class A traffic upon receiving a trigger signal from the edge unit. b) monitoring: generates class B traffic that is transmitted to the Monitor1 unit.
3) ARM 1-6: robotic arms, each unit runs a UDP application (sink) that receives an action, from the Edge unit, to perform.
4) Aggregated IT client-server traffic: running HTTP and FTP Servers/Clients to model the best effort traffic exchange over QCAP network.
5) Edge computing unit: running 15 UDP based applications: six for the detection, three for the inspections and another six to control the robotic arms.
6) Monitor 1: running three applications to analyse the streamed traffic.

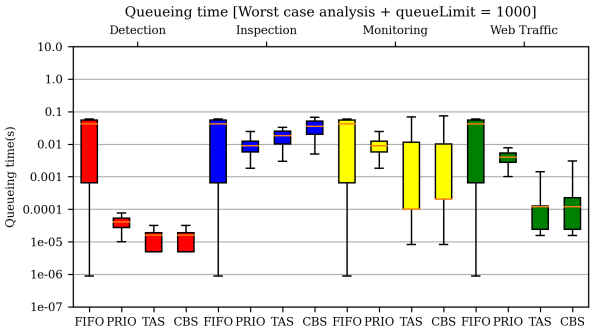


Fig. 4. The distribution of the queuing time of different network configurations for the different traffic types.

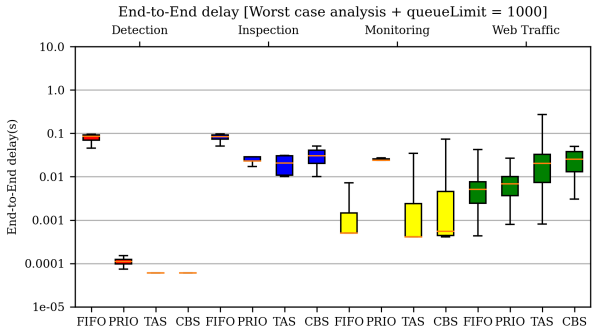


Fig. 5. The distribution of the end-to-end delay of different network configurations for the different traffic types.

We compare the network performance, in terms of end-to-end delay and delivery ratio, for four different switch configurations:

1) Standard Ethernet: nodes are configured as Standard Ethernet nodes where the egress ports of the network switches are configured with First in First Out (FIFO) queuing disciplines.
2) Priority Queuing: Standard Ethernet nodes but egress ports of the network switches are configured with priority queuing disciplines, where different traffic is classified in different queues based on the traffic priority. Control data traffic is of the highest priority, while web traffic is of the lowest. Such configuration is meant to minimize the delay for the critical traffic.
3) TSN Time-Aware shaping: nodes are configured as TSN nodes, where all nodes are synchronized with the master clock module connected to SW1. Egress ports are controlled by gates that operate according to a GCL schedule. In addition, strict priority is used as a transmission selection algorithm to decide on the transmitted data in case multiple gates are open at the same instance.
4) TSN Time-Aware shaping + Credit based shaping: nodes are configured as TSN nodes with the same configuration as the previous case (TSN Time-Aware shaping) but with an added functionality of credit based traffic shaping added to control Class A, Class B, and best effort traffic data transmission rates.

First, we assess the queues' performance on the congested link between switch SW1 and switch SW2. Figure 4 depicts the distribution of the queuing time measurements for the different parts of the QCAP case and the coexisting web traffic. For the standard configuration (FIFO) all traffic shares the same queue and therefore experience the same queuing time, which is in the range of 100 ms. This will impact the delay in the detection system, which increases the chances of failing in identifying the product location and therefore conducting proper inspection. The priority queuing (PRIO) configuration provides better performance as the queuing time has been sharply reduced for high priority traffic, e.g. in the range of 100 μs. Both TSN configurations (TAS and TAS + CBS) provide almost the same performance as PRIO in queuing time for high priority traffic. However, they provide better performance with reduced queueing time for the lower priority traffic of the monitoring system. Secondly, we assess the end-to-end delay distribution and compare the results with the maximum permitted end-to-end delay for the designed QCAP use case. Figure 5 shows that although PRIO prioritizes the detection system traffic, the data distribution surpasses the 100 μs upper bound. However, both TSN configurations provide deterministic upper bounds that are below the design target. In addition, the results show that using the PRIO configuration, for the monitoring system, a higher end-to-end delay is expected. This is due to the bursts in class A traffic, yet the TSN configurations provide better control to limit those and therefore prove overall better end-to-end delay for all the subsystems. While the TAS configuration provides almost the same performance, in terms of latency, as using TAS + CBS, the latter provides a more uniform distribution for the inspection system and web traffic. Moreover, as depicted in Figure 6, the TSN configurations with both time-aware and credit based shaping provide the highest delivery ratios for all the subsystems and the web traffic. In addition, standard Ethernet [FIFO] provides a high delivery ratio for the monitoring system, high bandwidth demand, yet the critical traffic delivery ratio drops to 73%. For the priority queuing configuration, the critical traffic delivery ratio rises to be 100% and traffic class A to 88%, but at the expense of reducing the delivery ratio of the lower priority traffic. A summary of the simulation results is shown in Table IV.

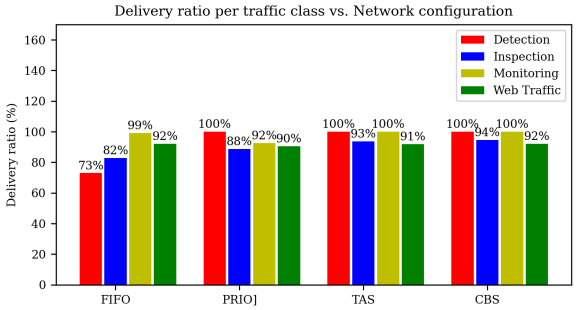


Fig. 6. The delivery ratio of different traffics for different network configurations.

TABLE IV
RESULTS SUMMARY OF THE AVERAGE END-TO-END DELAY AND DELIVERY RATIO FOR QCAP SIMULATIONS.

	Standard Ethernet [FIFO]		Standard Ethernet [PRIO]		TSN [TAS]		TSN [TAS+CBS]	
	Avg. end-to-end delay (s)	Delivery ratio (%)	Avg. end-to-end delay (s)	Delivery ratio (%)	Avg. end-to-end delay (s)	Delivery ratio (%)	Avg. end-to-end delay (s)	Delivery ratio (%)
CDT	75×10^{-3}	73	111×10^{-6}	100	61×10^{-6}	100	61×10^{-6}	100
Class A	79×10^{-3}	82.8	49×10^{-3}	88.7	35×10^{-3}	93.7	48×10^{-3}	94.6
Class B	13×10^{-3}	99.1	61×10^{-3}	92.6	5.7×10^{-3}	100	6.5×10^{-3}	100
Class BE	78×10^{-3}	92.1	10×10^{-3}	90.6	24.5×10^{-3}	91.9	24×10^{-3}	92.1

VII. CONCLUSIONS AND FUTURE WORK

This study evaluates the performance of a TSN based industrial network design for our QCAP use case through computer simulation. We evaluated four queuing disciplines, e.g. FIFO, priority queuing (PRIO), time aware traffic shaping (TAS) and time aware traffic shaping with credit based shaping (TAS + CBS). The simulation results show that using both, TAS and TAS + CBS can satisfy the delay requirements of our use case. The experimental results illustrate that the average end-to-end delay of the critical traffic has a guaranteed value of 61 μs with no losses. We expected that priority queuing might yield similar delay guarantees for high priority traffic, yet the use of TSN [TAS + CBS] outperforms PRIO in many aspects, including the coexistence of more IT traffic while meeting the QoS requirement of the OT traffic. In the future, we plan to experimentally evaluate the scalability of TSN-based industrial networks.

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