A Methodology to Map Industrial Automation Traffic to TSN Traffic Classes

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***Abstract*—**
This paper identifies that existing industrial automation standards, such as IEC/IEEE 60802 and IEEE 802.1Q, often have inconsistent definitions of traffic types. In the context of utilizing time-sensitive networking (TSN) standards for future automation systems, clear and consistent traffic characteristics and use cases should be defined to benefit from TSN features. Besides that, to facilitate the integration of TSN into the automation systems, the current standards provide a recommendation for mapping the automation traffic to the TSN traffic classes. In this paper, we propose an alternative mapping methodology for automation traffic to TSN traffic classes after presenting the existing automation traffic and their characteristics. Finally, through a case study, we show the potential of the new mapping methodology compared to the standard mapping strategy.

***Index Terms*—Traffic Mapping, Time-Sensitive Networking (TSN), Industrial Communication, Industrial automation**

I. Introduction

The evolution of the industrial landscape is characterized by a surging need for enhanced connectivity and intelligence, pushed by the transformative nature of Industry 4.0 and the Industrial Internet of Things. This evolution has led to a growth of interconnected devices and advanced automation technologies, with a significant increase in the scale and complexity of industrial automation networks [1]. This growth presents considerable challenges for traditional communication frameworks in meeting timing and reliability demands [2], [3]. In particular, a key aspect of novel industrial systems is the convergence of traditionally separate networks into one flat infrastructure, which supports Information Technology (IT) and Operational Technology (OT) [4], [5]. This convergence aims to enhance the operations, improve adaptability, and reduce operational costs [6]. To effectively support this convergence, novel industrial networks must still adhere to critical requirements such as reliability and determinism to support critical tasks traditionally executed by industrial systems, e.g., closed-loop control and safety-critical applications.

Time-Sensitive Networking (TSN) [7] emerges as a crucial technology to support the integration of IT and OT communications over a single network with diverse guarantees [8]. In particular, TSN defines a series of standards to provide Ethernet with real-time, fault tolerance, and online configuration mechanisms. These TSN standards can be combined to enable the convergence of diverse traffic types, including time-critical operational data and less time-sensitive informational data, onto a single network infrastructure [6], [9]. Nonetheless, the convergence of IT and OT networks introduces inherent complexities due to the simultaneous handling of various traffic types with diverse requirements [6]. These traffic types often have varying latency and jitter requirements, which demand careful management of the traffic. It is crucial to ensure that time-insensitive, often modeled as the Best Effort (BE) traffic, does not negatively impact the transmission of time-sensitive and mission-critical traffic.

The existing standards such as IEEE 802.1Q [10], IEC/IEEE 60802 [7], and Industry IoT Consortium (IIC) [11] provide different, often inconsistent, definitions of traffic types [4]. The inconsistencies amongst the standards make it difficult to translate traffic specifications into concrete TSN configurations. The lack of known or specified engineering practices and processes for converged IT/OT networks further complicates configuration and deployment efforts. To facilitate this integration, the IIC [11] introduced a strategy to map industrial traffic types to TSN traffic classes and TSN mechanisms. However, we identify a critical limitation in this mapping strategy. Specifically, it assigns several industrial traffic types with timing requirements to the TSN BE traffic class. As a consequence, the mapped traffic cannot guarantee bounded end-to-end latency, despite having the latency requirements. This lack of guaranteed end-to-end latency could be problematic in high-utilization scenarios, potentially leading to violations of the timing requirements for such traffic.

Contribution: We propose an alternative methodology for mapping industrial automation traffic types to TSN traffic classes, which maps all traffic with timing requirements to TSN traffic classes and mechanisms that provide timing guarantees. To this end, we first identify various traffic types in automation and control systems based on studying specifications and standards. Then we map the categorized specification of automation traffic types to TSN traffic classes via an intermediate step. The intermediate step utilizes a modified version of an existing Ethernet mapping tool, LETRA [12]. While LETRA focuses on mapping legacy Ethernet traffic to TSN traffic classes, our methodology targets the mapping of industrial automation traffic to TSN. We show, via a use case example, that the proposed mapping provides timing guarantees for the traffic, while the standard mapping cannot provide such guarantees.

II. Background and Related Work

A. Time-Sensitive Networking Overview

TSN is a collection of IEEE 802.1Q standards that extend standard Ethernet to support deterministic communication for time-sensitive and mission-critical applications [10]. Providing the timing guarantees required by many industrial control systems and other time-sensitive applications using traditional Ethernet can be challenging [11]. TSN addresses this limitation by introducing mechanisms to schedule traffic and reserve bandwidth to facilitate end-to-end timing guarantees within a single network infrastructure with diverse traffic types. In industrial automation environments, where critical traffic with strict timing requirements and less critical or BE traffic coexist, TSN ensures that time-sensitive data is delivered reliably and on time, without being disrupted by other BE traffic [6].

At its core, TSN employs several key mechanisms to achieve its goals, such as Time-Aware Shaper, frame preemption, traffic shaping, and redundancy. TSN achieves these core mechanisms through a collection of IEEE 802.1Q standards and amendments, as follows.

IEEE 802.1Qbv (Enhancements for Scheduled Traffic): Often referred to as the Time Aware Shaper (TAS), this standard is crucial for achieving deterministic low-latency transmission [6]. TAS introduces time-aware scheduling by controlling the gates of priority queues at the egress ports of TSN bridges based on a Gate Control List (GCL) [13]. GCL defines when each queue can transmit traffic in specific time slots. This time-triggered approach ensures that critical traffic has dedicated transmission windows. The schedule is predictable and deterministic, thus minimizing interference from other traffic. Hence, it provides the means for low-latency and jitter-controlled transfer.

IEEE 802.1Qav (Forwarding and Queuing Enhancements for Time-Sensitive Streams): The core concept of IEEE 802.1Qav is the Credit-based Shaper (CBS), developed by the Audio-Video Bridging (AVB) Task Group [9]. CBS regulates traffic by assigning and managing transmission credit for different traffic classes, typically Class A and Class B, and for streams like audio and video. By limiting the bandwidth available to high-priority traffic, CBS promotes fairness across traffic classes and helps prevent starvation of lower-priority streams. This regulation also reduces congestion and minimizes buffer buildup in ingress queues. Furthermore, CBS provides a smoothing effect on event-driven bursty traffic. We adhere to the two AVB traffic classes in this study.

B. Traffic Mapping by Standards

The IIC specifications [11] offer one of the few publicly available guidelines for mapping industrial traffic to TSN mechanisms. While not a formal profile, these recommendations aim to support standards development and vendor implementation, making them a relevant baseline for evaluating our proposed mapping. The IIC defines traffic mappings using four recommendation levels: Mandatory, Recommended, Optional, and Conditional. These classifications apply to various Quality of Service (QoS) and TSN mechanisms, including Qav (Credit-Based Shaper) and Qbv (Time-Aware Shaper), which respectively correspond to the AVB and Scheduled Traffic (ST) traffic classes.

C. Ethernet to TSN mapping approach

There are very few mapping strategies for Ethernet to TSN traffic classes. Among them, Legacy Ethernet-based Traffic Mapping (LETRA) [12] maps legacy Ethernet frames into three TSN traffic classes using five input parameters: Periodicity (P), Jitter Input (JI), Jitter Output (JO), Deadline (D), and the Hard Real-time (HRT). P reflects whether the frame is cyclic, and JI indicates if the message has a jitter input requirement at the transmission node. This reflects tolerance to timing variation before entering the TSN network. JO indicates if traffic has jitter constraints on the reception node. It limits the allowed variation in the arrival time of periodic messages at the destination. D indicates if traffic includes a deadline, which specifies the maximum end-to-end latency. In LETRA terminology, HRT means whether the traffic has a hard real-time constraint, such as bounded delay or deterministic delivery. Based on the parameters for the Ethernet frames, LETRA categorizes Ethernet traffic into three TSN classes: ST, which represents synchronized traffic with zero jitter; AVB traffic, which is shaped using CBS; and BE traffic, which does not have any timing guarantees. AVB class itself constitutes Class A and B in this tool. Nevertheless, the mapping in LETRA is solely based on the general Ethernet traffic parameters without considering automation traffic types exclusively.

D. Related work

Previous works have aimed to classify traffic and map them to TSN mechanisms. Sasiain et al. [13] explore scheduling strategies for synchronized traffic and present mappings between traffic types and Virtual Local Area Network (VLAN) priorities based on IEEE 802.1Q traffic classification. However, their model remains general and does not distinguish the traffic types and application-level traffic classes, and they rely on fixed traffic models that assume pre-classified streams without addressing the challenges of traffic classification itself. Zhang et al. [14] propose an Interleaved Regulator (IR)-based model to analyze latency in simulated industrial networks using a set of four TSN traffic classes as High priority Control Data Traffic (Isochronous), Stream Reservation A (Cyclic) and B (Audio and video), and BE (traditional Ethernet traffic) classes. This classification lacks the variation of traffic class assignment in the BE class. They map all traditional Ethernet traffic, including types that require timing guarantees, to the BE class, which does not provide such guarantees.

Seliem et al. analyze delay performance using a network calculus framework based on Quality Checks After Production (QCAP) use case [15]. Their work follows the IEC/IEEE 60802 standard's four defined TSN traffic classes as ST, AVB Class (A and B), and BE, and models their impact under various shaping and scheduling strategies. Yet, the justification for mapping industrial traffic types to TSN classes is not provided. Neher et al. take a use-case-driven approach by identifying communication needs of automated guided vehicles and autonomous mobile robots across scenarios such as video control, localization, and cooperative driving [16]. Although they provide detailed traffic properties, their classification remains use-case-centric and is not applicable to all industrial automation domains.

Ulbricht et al. [17] focus on testbed validation under various shaping techniques, such as TAS. Their TSN measurements utilized a variety of traffic types based on three use cases: Generic, Machine Delivery, and Robot Spot. Although each traffic set reflects real-world conditions for its respective use case, the selection of traffic types was not directly referenced from any industrial standards, and the traffic characteristics remain generic.

In addition to the academic studies, industrial standards such as IEEE 802.1Q, IEC/IEEE 60802, and IIC provide guidelines for applying TSN mechanisms. IEEE 802.1Q specifies shaping and queuing mechanisms and includes a traffic type to traffic class mapping in Annex I. However, the classifications are generic and do not capture the full diversity or application-specific needs of industrial automation traffic. IEC/IEEE 60802 introduces more application-aware classifications, but still treats traffic with timing guarantees to the BE class.

In contrast to these fragmented approaches, we propose a unified traffic specification model that consolidates definitions from IEEE 802.1Q, IEC/IEEE 60802, and IIC sources. We identify and resolve the conceptual overlap between traffic types and application classes. We then map the resulting traffic types to the input structure of the LETRA framework.

III. Proposed Traffic Mapping Methodology

This section investigates industrial automation traffic specifications and presents the approach taken to categorize traffic types, and the methodology for mapping these categories onto TSN traffic classes. Our review of industrial standards and related documents, including IEEE 802.1Q, IEC/IEEE 60802, and the IIC, reveals a common effort to define consistent traffic specifications for industrial automation networks. These documents, while valuable individually, exhibit a lack of coherence when compared to one another. This inconsistency leads to broad guidance that lacks practical application for engineers. Since TSN networks require precise traffic specification as a key configuration input, there is a need for a unified reference that current guidelines do not provide.

Fig. 1 illustrates various phases in the proposed methodology for mapping automation traffic to TSN traffic classes. The first two phases of the proposed methodology, "Aggregation of Traffic Specification" from various sources and "Traffic Type and Application Class Distinction," will be explained in Section III-A. These phases produce "Aggregated and Categorized Traffic Types," which serve as input for the "Traffic Mapping to LETRA Model" phase, where traffic specifications are mapped to the input parameters of the LETRA model. The final mapping to the corresponding TSN traffic classes occurs in the "LETRA Traffic Mapping to TSN" phase. These last two phases are discussed in Section III-B.

A. Categorization of traffic specification

The first phase of the methodology starts by Aggregation of traffic specifications based on studying specifications and standards, illustrated in Fig. 1. By this aggregation, we intended to identify commonalities and differences across the sources. During this process, we found an overlap between traffic types and application-level traffic classes. For instance, the standards labeled the Alarm and Event, Configuration, Video, and Voice as traffic types, each of which corresponds to application-level messages rather than a traffic type. At the same time, the standard also categorizes isochronous, Cyclic-Synchronous, and Cyclic-Asynchronous as traffic types. This categorization shows a mix between application-level messages and network-level traffic types, which can be hard to interpret and even lead to collisions. As an example, video traffic generated by an application might be classified as Cyclic-Synchronous traffic due to its strict timing requirements. In contrast, it could also fall under the broader Video traffic class. As a result, the same traffic may be assigned to two different types.

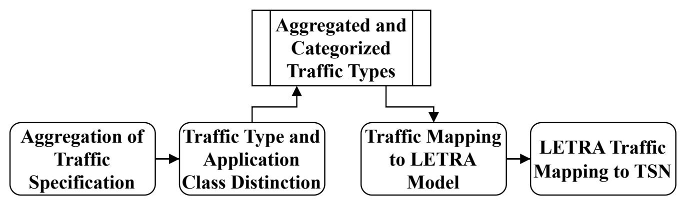

Fig. 1. High-level overview of various phases in the proposed methodology.

To address this issue, we decided first to clearly define a set of common traffic specifications exhibited by most traffic, namely periodicity, synchronization to the network, and jitter tolerance. We then classify traffic into four distinct **types**, as outlined in Table I. We must also note that jitter constraints, defined in terms of reception jitter, are applicable only to periodic traffic and are not relevant to aperiodic traffic. We next describe the four traffic types:

- Isochronous: periodic and network-synchronized traffic with zero jitter tolerance.
- Cyclic-Synchronous: periodic and synchronized, but allows bounded jitter, constrained by the latency.
- Cyclic-Asynchronous: similar to Cyclic-Synchronous in terms of timing, but the source is not synchronized to the network.
- Acyclic/Sporadic: aperiodic and non-synchronized traffic, typically event-triggered or bursty.

This clear distinction of **traffic types** allows us to identify and categorize corresponding application-level traffic without ambiguity. This is done in the second step of Fig. 1, i.e., "Traffic Type and Application Class Distinction". The specified application class, their respective traffic type, and other traffic specifications are presented in Table II. To support consistent classification and comparison, a unique identifier,

TABLE I
INDUSTRIAL AUTOMATION TRAFFIC TYPES AND SPECIFICATIONS

Traffic Type	Periodicity	Synchronization	Jitter Tolerance
Isochronous	Periodic	Yes	0
Cyclic-sync	Periodic	Yes	$< \tau$
Cyclic-async	Periodic	No	$< \tau$
Acyclic/Sporadic	Aperiodic	No	N/A

Traffic ID, was defined for each traffic, based on a combination of its defined application class and traffic type. We identified 13 distinct application-level traffics in industrial and process automation domains. It is important to emphasize that this categorization process does not introduce new terminology, but instead aims at homogenizing the existing terms used in different manners in the standards.

The categorization aims to introduce a more flexible approach to defining traffic specifications. For instance, rather than assigning a fixed cycle time to each traffic type, we adopted range recommendations from the IEC/IEEE 60802 standard in comparison to the specific cycle time presented in the IIC. In cases where a standard explicitly recommended a single value and provided no alternative, we respected that and made no further recommendations, such as latency specified for Event, Video, and voice traffic. For transmission guarantees, we followed the definitions provided in the IEC/IEEE 60802 standard, as it offers concrete classifications. These guarantees may include deadline, frame latency, flow latency, or no transmission guarantee. In some instances, latencies depended on the message's cycle time; in others, they were specified within a fixed range, typically from milliseconds to seconds. Criticality levels were categorized as High, Medium, or Low, based on the traffic sensitivity adopted from the IIC standard. Among all traffic types, only Control-Iso and Control-Sync traffic were identified as not tolerant to message loss. In terms of message size, the IEC/IEEE 60802 standard often describes message sizes as unconstrained, whereas IIC provides specific size ranges.

We classify voice and video traffic into two categories: non-critical and critical. Non-critical traffic, such as voice and video from surveillance systems, is treated as AVB messages. When voice or video traffic needs real-time guarantees, we assign it to one of the control categories: Control-Iso, Control-Sync, or Control-Async, depending on its specific timing requirements. We also note that BE traffic encompasses multiple subcategories, as it includes a wide range of traffic within the network. Standards refer to these subgroups using terms like BE high, BE low, excellent effort, or background. For simplicity, we treat them as a single category in this study. However, each subgroup may form different business traffic groups with different priorities.

It is important to highlight that the data presented in Table II are representative of approximately 80% of industrial use cases, though variations may occur depending on specific application contexts [11].

B. Traffic mapping Methodology

In this phase, we present the methodology to map each traffic specification to the input parameters used in LETRA [12], shown as "Traffic Mapping to LETRA model" in Fig. 1. We assign P, JI, JO, D, and the HRT parameters used as input parameters in LETRA based on traffic specifications. In LETRA, each parameter is represented as a Boolean value, indicating whether the property applies (1) or not (0). In addition to binary values, they use 'X' to indicate that a parameter is not applicable for a given type. For example, jitter constraints do not apply to non-periodic traffic, so those entries are marked with 'X'. We adhere to the same method and mapped the categorized traffic specification as follows.

If the traffic defines a cycle time, we mark it as periodic using (1). Equation (2), sets the D parameter, if the traffic holds a latency or deadline requirement. For the JO parameter, we set it to 1 only when the traffic has low jitter tolerance. According to the resources, only Control-Iso and Control-Sync traffic types exhibit low jitter constraints. All other traffic types are considered to have high jitter tolerance, corresponding to 0 as shown in (3). We use the criticality specification to determine the HRT parameter. HRT traffic has hard deadlines that cannot be missed. The criticality of high was considered one, and other criticalities (medium and low) were considered 0 as shown in (4). Let $\mathbb{i}\{x\}$ be the indicator function that returns 1 if the condition x is true, and 0 otherwise.

$$P = \mathbb{i}\{CycleTime > 0\} \tag{1}$$

$$D = \mathbb{i}\{Latency > 0\} \tag{2}$$

$$JO = \mathbb{i}\{Traffic\ Type \in \{Control\text{-}Iso, Control\text{-}Sync\}\} \tag{3}$$

$$HRT = \mathbb{i}\{Criticality == High\} \tag{4}$$

Further, LETRA categorizes TSN traffic into three classes of ST, AVB, and BE represented in (5), (6), and (7). As the standard does not specify an explicit JI requirement, and since this parameter typically belongs to messages from non-TSN (legacy) protocols and is application-dependent, we modify Equation (6) by omitting this parameter, as legacy communications are not considered in our assessment. This final phase is presented as "LETRA traffic mapping to TSN" in Fig. 1.

$$ST = P\&(JO\|D)) \tag{5}$$

$$AVB = D\&!(JO\&HRT) \tag{6}$$

$$BE = !(JO\|D) \tag{7}$$

We then generate Table III based on the adapted LETRA model and categorized traffic types, which represents the mapping process's inputs and resulting TSN traffic classes.

Table III illustrates how our systematic mapping differs from the standard mapping. Specifically, traffic classes such as Control-Async, Diagnostics-Cyclic, Diagnostics-Acyclic, Config, Command-Cyclic, and Command-Acyclic are proposed to be classified as AVB, whereas the standard implicitly

TABLE II
SUMMARY OF INDUSTRIAL AUTOMATION TRAFFIC SPECIFICATIONS

Traffic ID	**Application Class**	**Traffic Type**	**Cycle Time(T)** [11]	**Transmission Guarantee** [7]	**Latency (L)**	**Criticality** [11]	**Jitter Tolerance** [7]	**Loss Tolerance** [11]	**Length Variability** [11]	**Length** [7], [11]
Control-Iso	Open/Closed (Distributed) Control Loop and Motion Control	Isochronous	µs–10s of ms [7]	Deadline	<T [11]	High	0	No [7]	Fixed	30-500
Control-Sync	Open/Closed (Distributed) Control Loop and Motion Control	Cyclic-Synchronous	100s of µs–100s of ms [7]	Frame Latency	<T [7]	High	<L	No [7]	Fixed	Unconstrained
Control-Async	Factory Automation and Non Synchronized Control	Cyclic-Asynchronous	ms - s [7]	Frame Latency	<90%*T [11]	High	<L	1 - 4 Frames	Fixed	Unconstrained
Event	Control Events and Alarms	Acyclic	N/A	Flow Latency	10 - 50 ms [11]	High	N/A	Yes	Variable	Unconstrained (100-200)
Voice	Voice	Cyclic-Asynchronous	Sample Time	Flow Latency [11]	10ms [10]	Low	<L	Yes	Variable	1000-1500
Video	Video	Cyclic-Asynchronous	Frame Rate	Flow Latency [11]	100ms [10]	Low	<L	Yes	Variable	1000-1500
Network	Network Control and Inter-network Control	Cyclic-Asynchronous	50 ms - 1s	Flow Latency	-	High	<L	Yes	Variable	Unconstrained (50-500)
Command-Cycle	Operator Commands and HMI Interactions	Cyclic-Asynchronous	-	Flow Latency [11]	<2s [11]	Medium	Yes	Yes	Variable	100-1500
Command-Acycle	Operator Commands and HMI Interactions	Acyclic	N/A	Flow Latency [11]	<2s [11]	Medium	N/A	Yes	Variable	100-1500
Config	Configuration and Management	Acyclic	N/A	Flow Latency	Up to Seconds [7]	Medium	N/A	Yes	Variable	Unconstrained (500-1500)
Diagnostic-Cycle	Diagnostics and Monitoring	Cyclic-Asynchronous	ms - s	Flow Latency	100 ms [11]	Medium	Yes	Yes	Variable	Unconstrained (500-1500)
Diagnostic-Acycle	Diagnostics and Monitoring	Acyclic	-	Flow Latency	100 ms [11]	Medium	N/A	Yes	Variable	Unconstrained (500-1500)
Best Effort	Best Effort	Acyclic	N/A	NO	N/A	Low	N/A	Yes	Variable	Unconstrained (30-1500)

TABLE III
MAPPING OF TRAFFIC SPECIFICATION TO TSN TRAFFIC CLASSES

	Input Parameters				**Proposed Mapping**			**Standard Mapping**		
Traffic ID	P	JO	D	HRT	ST	AVB	BE	ST	AVB	BE
Control_Iso	1	1	1	1	1	0	0	1	0	0
Control_Sync	1	1	1	1	1	0	0	1	0	0
Control_Async	1	0	1	1	1^*	1	0	0	0	1
Event	0	X	1	1	0	1	0	0	1	0
Voice	1	0	1	0	1^*	1	0	0	1	0
Video	1	0	1	0	1^*	1	0	0	1	0
Network	1	0	0	1	0	0	1	0	0	1
Commands_Cycle	1	0	1	0	0	1	0	0	0	1
Commands_Acycle	0	X	1	0	0	1	0	0	0	1
Config	0	X	1	0	0	1	0	0	0	1
Diagnostics_Cycle	1	0	1	0	1^*	1	0	0	0	1
Diagnostics_Acycle	0	X	1	0	0	1	0	0	0	1
BestEffort	0	X	0	0	0	0	1	0	0	1

categorizes them as BE. The standard does not explicitly state BE classification, but the only mechanism it offers for these traffic types is strict priority according to IEEE 802.1Q, which lacks timing guarantees and may cause significant delays and blockages. This shortcoming underscores the rationale behind TSN's development. Furthermore, these traffic types explicitly require flow latency transmission guarantee, as acknowledged in the standards themselves, making their classification as BE gives them no timing guarantee. Furthermore, the criticality of these traffic types is medium or high, meaning the standard categorizes certain high-criticality traffic types as BE, highlighting an issue. Among these, Control-Async traffic is particularly critical since it may be transmitted from high-critical devices without synchronization capabilities or situations where ST resources are insufficient and a synchronized traffic needs some timing guarantees. Thus, the recommended alternative is AVB rather than the strict priority recommended by the standard. Regarding other traffic types, the mapped class remains the same as the standard's mapped class.

In the cases where both ST and AVB classes in Table III were applied, two key considerations guide our evaluation. Firstly, synchronization is assessed; if traffic lacks synchronization to the network, assigning it to the ST class is generally not recommended, as it could unnecessarily introduce load on higher-priority queues. However, if this traffic requires low latency and jitter, ST assignment might still be a suitable alternative. In these situations, AVB shaping provides a better timing guarantee for traffic transmission. Secondly, we default to using the lower-priority AVB class unless further analysis explicitly justifies using ST. For instance, in Table III, both ST and AVB are listed as suitable for Control-Async traffic. Although ST can technically support this type, it requires a network schedulability analysis to ensure sufficient resource availability. If the analysis confirms resources are adequate and network schedulability is maintained, ST can be utilized,

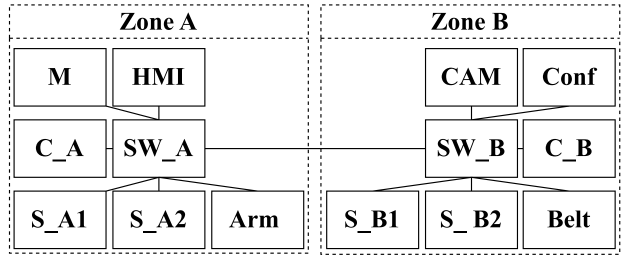

Fig. 2. TSN-based industrial use case.

though this comes at the cost of critical resources, such as occupying ST queues. Thus, if ST resources are limited, AVB remains the preferred choice if analysis states traffic meets the deadline. In other scenarios, if AVB traffic class experiences deadline misses after a response-time analysis, reevaluation for possible assignment to ST should be considered. Therefore, in our evaluations, ST recommendations labeled as 1^* are interpreted as 0.

According to the IIC, the Qav (AVB) mechanism is recommended for voice and video traffic, and is optional for alarm and event categories. On the other hand, Qbv (ST) is marked as mandatory for Isochronous and Cyclic-Synchronous traffic types. This approach differs from our mapping in assigning a specific shaping mechanism to traffic types. Our methodology takes a more systematic view, considering the traffic Specification.

IV. EVALUATION USING AN INDUSTRIAL USE CASE

This section presents the usability and evaluation of our proposed methodology on an industrial use case. We ran scheduling for ST traffic [18] and Worst-case Response Time (WCRT) analysis for AVB traffic [19] against the mapping recommended in the IIC approach discussed in Section III.

A. Evaluation Setup

Our experimental testbed adopts the industrial TSN use case proposed by Seliem et al. [20], also depicted in Fig. 2. The setup consists of two zones: switches are connected in a line topology between zones, while each zone uses a star topology. Zone A includes a robotic arm (ARM), controller (C_A), sensors (S_A1 and S_A2), a Human Machine Interface (HMI), and a monitoring node (M). Zone B contains a conveyor belt (Belt), controller (C_B), sensors (S_B1 and S_B2), a network configuration node (Conf), and a video surveillance camera (CAM). Two TSN switches connect these two zones, namely SW_A and SW_B. All the links in the network can carry 100 Mbps bandwidth. Each port of the switch contains four priority queues. Queue 1 is dedicated to ST traffic, Queue 2 and 3 are dedicated to AVB class A and B, and Queue 4 is for BE transmissions.

This network setup can generate various converged traffic from Isochronous to event-based traffic to resemble a realistic industrial setting. All traffic flows and their specifications, including source, destination, deadline, periodicity, and length of the messages, are listed in Table IV. The traffic specifications and values are based on the traffic specification in Table II.

The aggregated message exchange across all links occupies 309 Mbps bandwidth, and each individual link can carry at most 100 Mbps. The period and deadline of the messages are provided in microsecond scale, and the length of each message is presented in Bytes. The period assigned to acyclic traffic is the minimum inter-arrival time, which resembles periodic messages in the worst-case scenario. Jitter reception is considered 100 μs for ST traffic and zero for all other traffic. In most cases, deadlines are considered equal to the period for smooth evaluations. A deadline value of zero is used for BE and Network types to denote that these types do not have any specific deadline constraints.

TABLE IV
EVALUATION'S TRAFFIC FLOWS AMONG NODES

Traffic	Source	Dest	P	DL	Length
Ctrl_Iso 1	S_A1	C_A	300	300	400
Ctrl_Iso 2	S_B1	C_B	400	400	300
Ctrl_Iso 3	ARM	C_A	500	500	300
Ctrl_Iso 4	C_A	ARM	500	500	300
Ctrl_Sync 1	ARM	C_A	1000	1000	600
Ctrl_Sync 2	C_A	ARM	1000	1000	400
Ctrl_Sync 3	C_A	C_B	1000	1000	300
Ctrl_Async 1	S_A2	C_A	1000	1000	1200
Ctrl_Async 2	S_B2	C_B	1000	1000	1400
Ctrl_Async 3	Belt	C_B	5000	5000	1000
Ctrl_Async 4	C_B	Belt	5000	5000	500
Event 1	C_A	ARM	4000	4000	400
Event 2	C_B	Belt	5000	5000	300
Event 3	C_A	C_B	2000	2000	500
Video	Cam	M	3000	500	1500
Cmd_Cyc 1	C_A	HMI	30000	30000	800
Cmd_Cyc 2	C_B	HMI	30000	30000	800
Cmd_Acyc 1	HMI	C_A	10000	10000	200
Cmd_Acyc 2	HMI	C_B	10000	10000	200
Cmd_Acyc 3	HMI	ARM	10000	10000	400
Cmd_Acyc 4	HMI	Belt	10000	10000	300
Config 1	Conf	SW_A	500000	500000	1500
Config 2	Conf	SW_B	500000	500000	1500
Config 3	SW_A	Conf	500000	500000	1500
Config 4	SW_B	Conf	500000	500000	1500
Network 1	SW_A	SW_B	50000	0	500
Network 2	SW_B	SW_A	50000	0	500
Diag_Cyc 1	C_A	M	100000	100000	800
Diag_Cyc 2	C_B	M	100000	100000	800
Diag_Cyc 3	Arm	M	100000	100000	1000
Diag_Cyc 4	Belt	M	100000	100000	1000
BestEffort 1	X	HMI	100	0	1500
BestEffort 2	HMI	M	100	0	1500

The following considerations guided the choice of message sources and destinations in the experimental setup: S_X1 sensors are synchronized sensors that transmit either Control-Iso or Control-Async updates to their respective controllers, C_X. S_X2 sensors, on the other hand, are asynchronous and exclusively transmit Control-Async updates. The robotic arm's actuator uses isochronous communication and thus utilizes Control-Iso messages, whereas the conveyor belt operates within lower criticality and communicates using Control-Async messages. The HMI employs Command-Cycle and Acycle communication with controllers for condition monitoring purposes. Consequently, controllers handle a mixture of cyclic and acyclic traffic. The configuration node exchanges configuration messages bidirectionally with both switches. The monitoring node collects Diagnostic-Cycle messages and receives data from controllers and actuators. Additionally, the experimental setup includes a limited number of BE traffic characterized by large message sizes and low periodicity to impose delay on AVB queues. Detailed discussion of the experimental procedure and results follows in subsequent sections.

B. Results and Discussions

We conducted scheduling for ST traffic and applied worst-case response time analysis for AVB traffic within the presented use case to be able to compare the proposed mapping and the standard mapping.

Table V presents the mapping classes for both the proposed and standard approaches. In addition to mapping classes, the last two columns report the results for both the worst-case response time analysis and the scheduling of the ST traffic sets. If the ST traffic is schedulable under a given mapping, it is indicated as Schedulable (SC). For AVB-classified traffic, the corresponding worst-case response time analysis in microseconds is provided. If the traffic is classified as BE, no timing guarantee or response time analysis is offered, and these cases are marked as Not Guaranteed (NG). Additionally, if the worst-case response time exceeds the deadline, it indicates that AVB traffic fails to meet its timing constraint. In this situation, the entry would also be marked as NG. However, in the presented use case, such scenarios did not occur.

As shown in Table V, the proposed solution ensures timing guarantees for traffic with defined deadlines. It's important to note that AVB can support more than just the two standard traffic classes, A and B. Conversely, the standard mapping does not offer sufficient transmission guarantees for certain traffic classes that require predictable performance, such as Control-Async. Although the standard mapping achieves lower worst-case response time for event and video streams, it falls short in guaranteeing timely delivery for other classes. Both the proposed and standard mappings yielded identical schedulability percentages across scenarios.

Unlike the IIC approach, which leaves several crucial traffic types (e.g., Control-Async, Commands, or Diagnostics) without explicit shaping mechanisms, our mapping methodology systematically assigns appropriate TSN mechanisms such as Qav (AVB) and Qbv (ST) based on traffic Specifications. From 13 proposed traffic classes, our approach assigns approximately 70% of traffic to AVB and approximately 15% to the ST class. Standard assigns the same proportion to ST but only 23% of them to the AVB class. Although this increased allocation to AVB in comparison to standard's mapping might add complexity to TSN configuration, it enhances timing guarantees for critical traffic and reduces the probability of deadline misses.

V. Conclusion and Future Works

Converged industrial automation networks, particularly networks employing TSN amendments for scheduled traffic,

TABLE V
TRAFFIC MAPPINGS AND EVALUATED WCRT AND SCHEDULING UNDER BOTH THE STANDARD AND PROPOSED METHODOLOGY

Traffic	Proposed Mapping	Standard Mapping	Proposed WCRT/Schl.	Standard WCRT/Schl.
Ctrl_Iso 1	ST	ST	SC	SC
Ctrl_Iso 2	ST	ST	SC	SC
Ctrl_Iso 3	ST	ST	SC	SC
Ctrl_Iso 4	ST	ST	SC	SC
Ctrl_Sync 1	ST	ST	SC	SC
Ctrl_Sync 2	ST	ST	SC	SC
Ctrl_Sync 3	ST	ST	SC	SC
Ctrl_Async 1	AVB	BE	381.68	NG
Ctrl_Async 2	AVB	BE	430.96	NG
Ctrl_Async 3	AVB	BE	530.32	NG
Ctrl_Async 4	AVB	BE	530.32	NG
Event 1	AVB	AVB	728.08	353.84
Event 2	AVB	AVB	562.32	64.72
Event 3	AVB	AVB	1354.88	433.28
Video	AVB	AVB	1867.84	390.08
Cmd_Cyc 1	AVB	BE	614.48	NG
Cmd_Cyc 2	AVB	BE	1483.84	NG
Cmd_Acyc 1	AVB	BE	521.84	NG
Cmd_Acyc 2	AVB	BE	1043.36	NG
Cmd_Acyc 3	AVB	BE	293.68	NG
Cmd_Acyc 4	AVB	BE	760.48	NG
Config 1	AVB	BE	106.16	NG
Config 2	AVB	BE	1991.20	NG
Config 3	AVB	BE	880.96	NG
Config 4	AVB	BE	887.68	NG
Network 1	BE	BE	NG	NG
Network 2	BE	BE	NG	NG
Diag_Cyc 1	AVB	BE	1083.92	NG
Diag_Cyc 2	AVB	BE	2200.00	NG
Diag_Cyc 3	AVB	BE	773.68	NG
Diag_Cyc 4	AVB	BE	199.12	NG
BestEffort 1	BE	BE	NG	NG
BestEffort 2	BE	BE	NG	NG

necessitate precise configuration. The foundational element of this configuration process is the detailed specification of traffic, each defined by various specifications. However, current industrial standards lack a unified definition for these specifications. Our proposed systematic methodology first unifies existing traffic specifications into a comprehensive summary. Secondly, our work systematically categorizes traffic based on an application-aware classification, which aids in distinguishing traffic types and application-level traffic classes. Lastly, we mapped each traffic specification onto the corresponding TSN traffic classes as ST, AVB, or BE. We validated our proposed mapping through an evaluation using an industrial automation use case. Our evaluation comprised scheduling for ST traffic and response-time analysis for AVB traffic. Results highlighted the limitations of the IIC standard mapping. They offer no guarantees for traffic with specific latency requirements. In contrast, our proposed mapping provides timing guarantees for a broader range of traffic classes. Future work includes extending the mapping methodology to other communication protocols, such as Open Platform Communications Unified Architecture (OPC UA).

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