Delay Analysis of Redundant TSN-based Industrial Networks using Network Calculus

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***Abstract*—Many Industrial Internet of Things (IIoT) applications have zero fault tolerance. Redundant networks are hence an important prerequisite for a dependable infrastructure to serve the various data traffic classes required for such applications. In this paper, we perform a delay analysis of a Quality Checks After Production (QCAP) application, which is running on a Time-Sensitive Network (TSN). We evaluate the worst-case delay of all data flows traversing the redundant TSN network using a Network Calculus (NC) based framework. We also evaluate how network parameters and configurations affect the QCAP application's service requirements.**

***Index Terms*—Industrial Internet of Things, Redundant networks, Network Calculus, Fault tolerance, Performance Evaluation.**

I. INTRODUCTION

The IEC/IEEE 60802 standard [1] specifies the criteria for selecting and implementing IEEE 802 TSN standards functionalities for industrial automation. Our goal is to evaluate the delay requirements for QCAP application [2] running on a two-level redundant network architecture, defined in [3]. We extend the usability of our implementation of an NC-based analytical framework [4] to analyse the scalability as well as the redundancy aspects of QCAP based industrial networks. We evaluate the practicality of TSN network methods in terms of meeting application deadline requirements. For example, optimal shaping methods selection and configuration as well as network resources management and scheduling. In addition, we explore the redundant industrial network architecture to support a real-world industrial application, Quality Checks After Production (QCAP). We compute the worst case delay (WCD) for all traffic types while considering TSN interfaces criticality, where large number of flows are expected or multiple high priority flows are waiting for transmission. For. We could also examine and compare the end-to-end WCD of all QCAP processes running on redundant TSN networks.

II. QUALITY CHECKS AFTER PRODUCTION

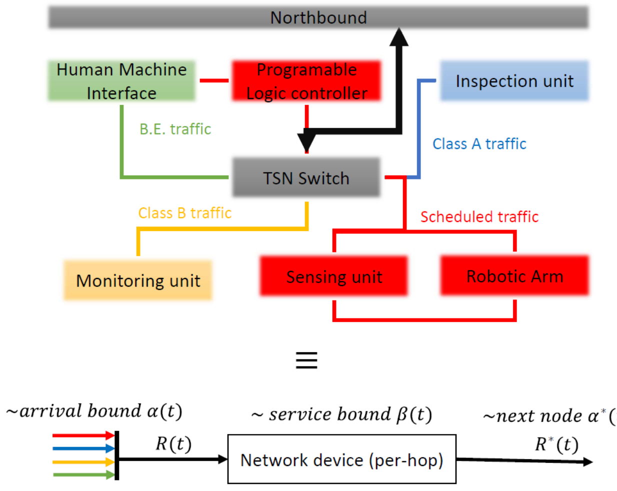

Fig. 1. Single hop model of QCAP TSN node.

Quality control ensures that a faulty product does not leave the manufacturing plant. Quality control in smart manufacturing systems begins immediately after production. Three major procedures make up QCAP application: 1) precise new product arrival detection, 2) gathering product inspection data, and 3) product classification following quality assurance. A QCAP node has the conventional parts and connections needed to carry out the aforementioned operations. These elements include product identification sensors, a product inspection camera, a floor monitoring unit, and a robotic arm that can respond to quality inspection recommendations. A human-to-machine interface for configuration, device monitoring, and diagnostics may also be part of a QCAP node. Figure 1 illustrates the components of a TSN-based QCAP node, while the lower part depicts the equivalent network calculus based model of the arrival, service and departure bounds of a single TSN QCAP hop. Moreover, QCAP Components result in four main traffic classes: scheduled, class A, Class B, and best effort traffic, which are specified in [5]. TSN shaping mechanisms and traffic management, e.g. time-aware shaping(TAS), credit-based shaping (CBS), strict priority, and frame preemption, are implemented by the QCAP node's interface. As a result, it ensures that the various traffic classes' service needs, such as deadlines, are met.

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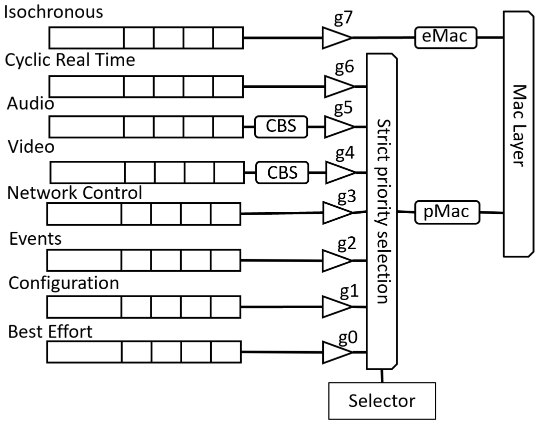

Fig. 2. QCAP TSN interface.

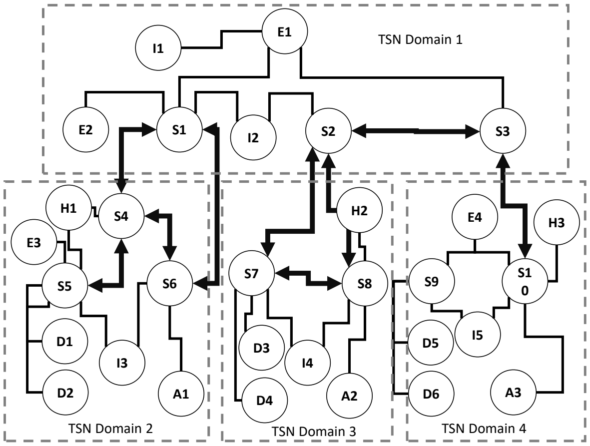

Fig. 3. QCAP redundant industrial network.

III. DELAY ANALYSIS OF MULTIPLE TRAFFIC CLASSES

Eight traffic queues are implemented for each QCAP TSN interface, depicted in Figure 2. Priority code point (PCP) 7 is granted to isochronous real-time flows in scheduled traffic (ST), while PCP 6 is given to non-isochronous cyclic real-time flows. The standard Ethernet and best effort traffic is allocated PCPs from three to zero. Class A and class B traffic is assigned to PCP 5 and 4. Express frames, designated as belonging to scheduled traffic, take precedence over other traffic frames with lower priority (preemptable frames). Additionally, a token-bucket credit-based shaper limits PCP 5 and 4 queues. Furthermore, the de-queuing of all traffic classes is scheduled using the TSN gate control list. The worst-case scenario for scheduled traffic is when all frames from various planned traffic flows arrive at the same hop on the same time, and the smallest scheduled traffic frame is forced to wait for all other scheduled frames to transmit. The worst-case situation for other classes is when credit accumulation is necessary or the control gate closes, forcing that particular class to wait for the subsequent transmission opportunity. The arrival, $\alpha(t)$, and the rate-latency service, $\beta(t)$, curves for the aforementioned traffic types are given in [4] and can be summarized as follows: For ST

$$\alpha_{ST}(t) = \sum_i L_i \times \frac{t}{T_i}, \tag{1}$$

$$\beta_{ST}(t) = c \times (t - \frac{L_{ST,k} - L_{minST,k}}{c}), \tag{2}$$

for class A and class B

$$\alpha_{class}(t) = r_{class} \times t + \sigma_{class}, \tag{3}$$

$$\beta_{class}(t) = R_{class} \times (t - T_{class}), \tag{4}$$

where

$$R_A = \frac{I_A \times [c - r_{ST,k}]}{c} - \frac{I_A \times r_{GB}}{c - I_A}, \tag{5}$$

$$T_A = \frac{L_{ST,k}}{r_{ST,k}} + \frac{L_{minPkt,k} + L_{BE}}{c - r_{ST,k}}, \tag{6}$$

$$R_B = \frac{I_B \times [c - r_{ST}]}{c} - \frac{I_B \times r_{GB}}{c - I_B}, \tag{7}$$

$$T_B = \frac{L_{ST,k}}{r_{ST,k}} + \frac{L_{minPkt,k} + L_A + L_{BE}}{c - r_{ST,k}}, \tag{8}$$

As a result, one can define the delay boundaries of a flow $f \epsilon Z_+^* = \{1, 2, ...\}$ that belongs to traffic class $class \in \{ST, A, B, BE\}$ and travels through a single hop k as follows:

$$D_{f,k} = T_{class} + \frac{\sigma_{class} - L_{min,f}}{R_{class}} + \frac{L_{min,f}}{c}, \tag{9}$$

IV. EVALUATION AND RESULTS

Based on the single hop model of a QCAP node, we take into account a two-level redundant network topology of several TSN domains. Depicted in Figure 3, the QCAP network comprises of six QCAP cells, ten switches, and four Ethernet devices. We implement our network calculus framework using the Real-Time Calculus (RTC) toolbox [6] and assess if the QCAP network performance satisfies the various data flow QoS requirements. We employ standard network setups and data traffic specifications for industrial applications for this study.

Figure 4 depicts the WCD bounds for the traffic flows of the QCAP processes, where we observe the following: For the detection process, without applying an offset time for transmissions, the WCD violates the deadline ($\leq 100 \mu s$) for the highest priority traffic flows. In addition, identifying critical interfaces and increasing their transmission rate reduce the queuing time, which reflect on the WCD for all QCAP processes, which is observed in data legends indicated as *Critical* in Figure 4. Moreover, rearranging the traffic will lower the WCD, allowing class A and class B flows to stay within the scheduled time limit. However, even without traffic regrouping, load distribution, or the addition of an offset, the WCD bounds for other units (Actuation, Ethernet, Human/Machine interface) are within the specified deadline. The aforementioned units operation will fail despite the fact

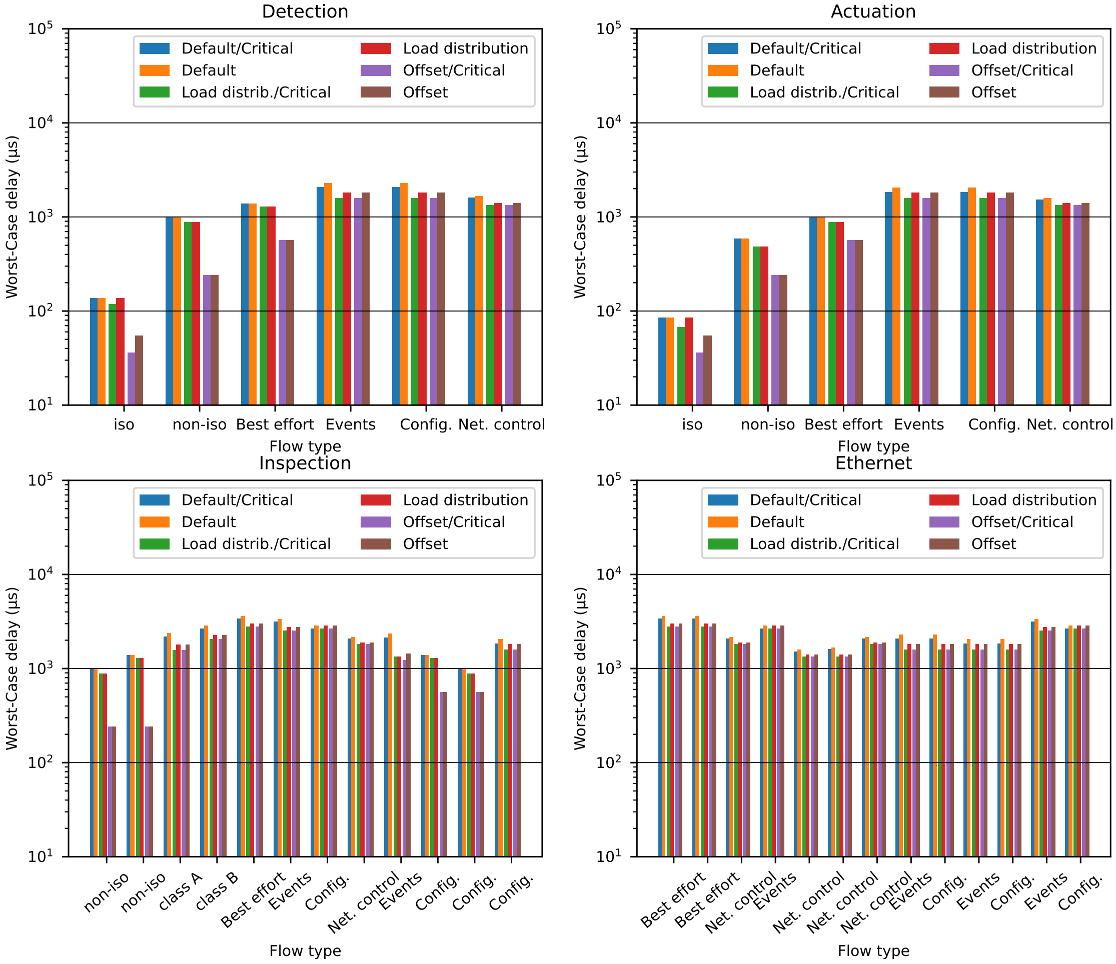

Fig. 4. WCD for multiple traffic classes traversing QCAP network.

that calculating the WCD boundaries for a unit alone indicates otherwise since in a practical arrangement all units actions are dependant.

V. CONCLUSION AND FUTURE WORK

TSN's industrial profile continues to evolve to assist smart manufacturing and industrial automation by assuring data transmission reliability and deterministic latency. Redundant TSN-based industrial networks support zero fault tolerance IIoT applications. In this study, we implement a system based on network calculus to evaluate the feasibility of TSN network configurations in terms of achieving QCAP application deadline requirements. We use our framework to pinpoint the crucial interfaces where a larger bandwidth and the best shaping configurations are necessary for the QCAP process to operate properly. For future work, we intend to integrate our framework with a reinforcement learning-based model to discover the best TSN network configurations.

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