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Research Article

Delay Analysis of IEEE 802.1BA Audio Video Bridging Networks: Recent Advances and Evaluation of Realistic Industrial Communication Use Cases

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Abstract

Effective control of real-time systems such as automotive, avionics, and industrial automation necessitates a high-bandwidth and low-cost real-time communication with low and bounded latency. Herein, real-time variants of IEEE 802.3 Ethernet are anticipated to be a key solution to provide timing guarantees to time-sensitive traffic in future industrial platforms. IEEE 802.1 *Time-Sensitive Networking* (TSN) task group is the leading organization that aims to standardize Ethernet-based deterministic communication technologies, which build upon *Audio Video Bridging* (AVB) technology. Simulation and theoretical analysis are important means for temporal analysis of TSN to ensure that timing requirements of applications are satisfied. In this paper, an in-depth review of the recent work on delay analysis of TSN is provided. An Omnet++ simulation is developed to analyze the temporal performance of realistic in-vehicle and industrial automation use cases transmitting AVB streams. Furthermore, the worst-case network performance is also evaluated via theoretical analysis using *AVB Latency Math*. Our experimental results reveal that, using the in-vehicle use case, none of the *End-to-End* (E2E) latency values reported by Omnet++ exceeds the 2 ms deadline requirement of the AVB standard for time-critical streams, while the values reported by AVB-LM for 13 streams out of 31 violate this requirement. Our experiments also show that there is an apparent decline in E2E latency of the transmitted streams with respect to the *idle-slope* (isl) parameter of *Credit-Based Shaper* mechanism used by AVB, such that E2E latency values resulting from Omnet++ and AVB-LM peak at 131.56 μs and 696304.26 μs, respectively, when isl gets its smallest value, namely 0.15. Our work is an important research effort to support the national goals of the society regarding automotive, aerospace, and manufacturing industries, which require computer-based real-time control systems, taking into account that these industries are highlighted as the priority research targets by the *12th Development Plan of Republic of Türkiye.*

Keywords

"Audio video bridging, Time-sensitive networking, Delay analysis, Omnet++ simulation, In-vehicle communication, Industrial automation"

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1. Introduction

1.1. Motivation

The rapid development of distributed real-time control systems for automotive, avionics, and industrial automation domains with a high-bandwidth and low-cost data exchange demand necessitates the design of innovative real-time communication technologies. Traditional technologies such as *Controller Area Network* (CAN) and *FlexRay* can no longer address the requirements of current real-time systems since they have certain deficiencies that harden to meet market needs. These deficiencies include limited bandwidth, lack of support for network traffic with mixed-criticality levels, lack of precise timing, limited supplier network, lack of standardization causing an interoperability issue, and lack of security (Avnu Alliance, 2025). Ethernet-based real-time data communication solutions have the capability to eliminate all of these deficiencies, and hence are strongly anticipated to be a key solution to provide timing guarantees to critical traffic in future industrial platforms (Li & George, 2017; Ashjaei et al., 2017; Thiele et al., 2015). IEEE 802.1 *Time-Sensitive Networking* (TSN) is a set of Ethernet-based standards, which provide bounded and deterministic latency for real-time networking applications (Bello et al., 2020). TSN protocols are becoming accepted solutions in several safety-critical industrial domains with an increasing complexity due to the high number of components and the integration of complex functionalities.

According to *Fortune Business (FB) Insights,* underlining that TSN is an evolving technology with important applications across manufacturing, automotive, communications, and healthcare industries*,* the global TSN market size was valued at USD 453.9 million in 2024, which was dominated by Asia Pacific region with a share of 36.2%, and is projected to grow to USD 3,517.7 million by 2032 (Fortune Business Insights, 2025). Their analysis highlights that the fundamental factors driving the increasing demand for TSN include *i)* the growing demand for industrial automation and real-time monitoring in industries such as oil & gas, manufacturing, and broadcasting, leading to boosted efficiency, decline in downtime, and enhanced productivity, *ii)* the efforts by leading research, standard, and certification organizations, such as the *IEEE TSN Working Group*, the *Industrial Internet Consortium* (IIC), and *AVNU Alliance* to advance TSN standards, and *iii)* the COVID-19 pandemic triggering the transition to the 5G wireless network services which boosted the demand for TSN support in IoT devices. The AVNU Alliance retains a certification program ensuring the compliance and interoperability for devices using TSN standards. According to the report by *FB Insights*, the global TSN market is dominated by the manufacturing industry with a share of 30.3% in 2024, and there are several key companies operating in this market such as *PROFIBUS Nutzerorganisation e.V.* (Germany), *Cisco Systems Inc.* (US), *Texas Instruments Incorporated* (US), and *TTTech Group* (Austria) just to mention only a few of them.

IEEE 802.1 TSN offers augmented capabilities building upon the *Audio Video Bridging* (AVB) standard (Bello et al., 2020). AVB technology is specified by IEEE 802.1BA, which extends Ethernet technology by providing real-time capabilities for data communications in automotive and industrial control domains. It is considered as a promising network solution especially for the transmission of real-time audio and video along with control data in automotive networks, thanks to its high data transmission rate and dedicated credit-based bandwidth for real-time traffic (Maxim & Song, 2017). Open specification, low cost, and reduced cabling are other significant advantages offered by AVB (Ashjaei et al., 2017). It classifies the network traffic according to their priorities and features *Credit-Based Shaper* (CBS) mechanism specified by 802.1Qav to regulate the AVB traffic within each switch to prevent traffic bursts, which would otherwise cause the non-real-time *best-effort* (BE) traffic to experience starvation. CBS can be used in combination with the *Time-Aware Shaper* (TAS) mechanism specified by 802.1Qbv standard to provide real-time guarantees for AVB and time-triggered traffic class, namely *TT*. TAS introduces the *TT* class, requiring transmission based on a pre-computed time schedule called *Gate Control List* (GCL) to achieve low and bounded latency for the most critical control data traffic. GCL is computed offline and specifies when a traffic queue is enabled or disabled for transmission by opening or closing a *gate* located at the front of the respective queue.

Temporal behavior of AVB streams transmitted in a TSN-based network should be predictable to meet the hard real-time communication requirements in a safety-critical system. For this reason, the analysis of end-to-end latency of AVB traffic is a fundamental issue, which should be coped with at the design phase of a TSN network (Li & George, 2017). Simulation and theoretical analysis are important means to analyze the temporal performance of a TSN network, since the standard itself does not provide a formal latency guarantee (Thiele et al., 2015). Simulation provides valuable insights into the average temporal network behavior by exposing a lower bound on the latency of transmitted streams, whereas theoretical methods offer a worst-case upper bound, which is required to be determined for the temporal verification of safety-critical systems (Li & George, 2017). As the latency of traffic streams depend on different factors such as the specifics of the underlying real-time communication technology, network topology, and traffic scenarios, it is essential to create a comprehensive experimental setting for the temporal performance analysis of TSN networks to achieve reliable conclusions (Diemer et al., 2012).

1.2. Limitation and contribution

In this paper, an in-depth review of the recent research work on the delay analysis of TSN is provided. Furthermore, Omnet++ simulation models are constructed to analyze the average temporal performance of realistic TSN-enabled in-vehicle and industrial automation use cases, where AVB streams with varying properties are transmitted. The worst-case performance of our experimented networks is evaluated via theoretical analysis using *AVB Latency Math* (AVB-LM) tool from (Laursen et al., 2016). Our main contributions overcoming the deficiencies of the previous studies are itemized as follows:

- To the best of our knowledge, our work is the first survey study in TSN literature, which specifically addresses the delay analysis of TSN. The existing surveys on TSN either address all the aspects of TSN in a single study in a coarse-grained manner (Seol et al., 2021; Peng et al., 2023) or provide a study on scheduling algorithms for TAS (Stüber et al., 2023).
- Using realistic use cases, our work provides a comparison of the AVB performance results obtained via Omnet++ simulation models with the theoretical delay evaluation achieved by AVB-LM. Although existing research work underlines that AVB-LM yields pessimistic analysis results, they do not offer any comparison with simulative analysis to demonstrate the extent of this pessimism (Laursen et al., 2016).
- By providing a simulative and theoretical infrastructure for TSN experimentation, our work is an important research effort to support the national goals of the society regarding automotive, aerospace, and manufacturing industries, which require computer-based real-time control systems. Taking into consideration that these industries are highlighted as the priority research targets by the *12th Development Plan of the Republic of Türkiye* (Presidency of Strategy and Budget, 2023) and there is a lack of research work targeting the usage of TSN in these industries, our work has the potential to inspire other TSN-related research efforts nationwide.

The remainder of this article is organized as follows. Section 2 provides our literature survey, while Section 3 presents the IEEE 802.1BA AVB standard. Section 4 introduces the Omnet++ simulation models used for our experiments. Section 5 covers the experimental results, while Section 6 concludes the paper.

Symbols and Abbreviations

TSN	*Time Sensitive Networking*
AVB	*Audio Video Bridging*
CAN	*Controller Area Network*
CBS	*Credit-Based Shaper*
BE	*Best-Effort*
AVB-LM	*AVB Latency Math*
TAS	*Time-Aware Shaper*
FB	*Fortune Business*
TT	*Time-Triggered*
GCL	*Gate Control List*
ML	*Machine Learning*
NC	*Network Calculus*
WCD	*Worst-Case Delay*
RTC	*Real-Time Calculus*
GB	*Guard Band*
DRR	*Deficit Round-Robin*
AFDX	*Avionics Full Duplex Switched Ethernet*
BLS	*Burst Limiting Shapers*
ATS	*Asynchronous Traffic Shaper*
GRASP	*Greedy Randomized Adaptive Search Procedure*
KSP	*K shortest-path*
MTR	*Multi-Topology Routing*
PS	*Peristaltic Shapers*
CPA	*Compositional Performance Analysis*
FIFO	*First-In First-Out*
CQF	*Cyclic Queuing and Forwarding*
k-NN	*k-nearest neighbors*
GNN	*Graph Neural Network*
ES	*End-system*
ADAS	*Advanced Driver Assistance Systems*
HU	*Head Unit*
ECU	*Electronic Control Unit*
CU	*Control Unit*
RSE	*Rear Seat Entertainment*
E2E	*End-to-End*
ssl	*Send-slope*
isl	*Idle-slope*

2. Related Work

It is of paramount importance to guarantee that hard real-time temporal requirements will always be met in a safety-critical communication enabled by TSN, which necessitates the development of tools to analyze the network performance. The related work on the delay analysis of a TSN network can be categorized into theoretical approaches, network simulations, and machine learning (ML)-based methods.

2.1. Theoretical Approaches

Table 1 summarizes the recent literature on theoretical delay analysis of TSN, where the publications providing no experimental results or targeting a nonspecific experimental domain are indicated by *NA* and *Generic* in *Experimental Domain* column, respectively, while the type of traffic being evaluated in each publication is specified in *Traffic Type* column.

2.1.1. Network Calculus

In the study by Azua et al. (2014), favoring the *Network Calculus* (NC) approach for *Worst-Case Delay* (WCD) analysis of AVB traffic due to its accuracy, efficiency, and scalability, a performance evaluation of AVB traffic is realized based on the NC framework, without considering the impact of TT traffic on the latency of AVB streams. In NC, delay bounds for a traffic stream passing through a network node is determined based on the traffic arrival pattern represented by the so-called *arrival curve* and the availability of the node described by the so-called *service curve*, which are defined through the use of *min-plus* convolution. In the work by Azua et al. (2014), the performance of the proposed analysis method is evaluated using a traffic scenario inspired by the automotive industry. In the research by Queck (2012), using an example in-vehicle scenario with camera and infotainment devices, NC is exploited to compute the WCD of AVB traffic by underlining that network simulations may not capture the rare events in contrast to theoretical performance analysis. Still, Queck (2012) highlights that the upper bounds resulting from simulations are more likely to be reached in a real network. In the work by Mohammadpour et al. (2023), the WCD bounds of TSN achieved by typical NC-based analysis approaches are enhanced through an improved NC-based scheme, which provides a packet-level analysis rather than a bit-level one. On the contrary, the common NC-based approaches derive a bit-level arrival curve from a packet-level arrival curve, that results in a loose delay bound.

Table 1. Summary of the recent literature on theoretical delay analysis of TSN

Reference(s)	Method	Traffic Type	Experimental Domain
[Shalghum et al., 2022] [Maile et al., 2022] [Zhao et al., 2018a]	Network Calculus	AVB	Automotive
[Mohammadpour et al., 2023] [Ren et al., 2020]	Network Calculus	AVB	Generic
[Zhao et al., 2023] [Zhao et al., 2020a] [Zhao et al., 2018b] [Zhao et al., 2017]	Network Calculus	AVB	Aerospace
[Zhao et al., 2018c]	Network Calculus	TT	Aerospace
[Zhao et al., 2020b]	Network Calculus	TT	Aerospace & Automative
[Thomas et al., 2022]	Network Calculus	Generic	Automotive
[Tabatabaee et al., 2023] [Zhao et al., 2022] [Finzi & Mifdaoui, 2020]	Network Calculus	Generic	Aerospace
[Seliem et al., 2023]	Network Calculus	Generic	Industrial Automation
[Yan et al., 2025]	Network Calculus	PLC	Aerospace
[Zhang et al., 2019] [Reimann et al., 2013]	Real-Time Calculus	AVB	Automotive
[Boyer & Daigmorte, 2019]	Real-Time Calculus	AVB	Generic
[Laursen et al., 2016] [Pop et al., 2016]	AVB Latency Math	AVB	Aerospace & Industrial Automation
[Demir & Cevher, 2023]	AVB Latency Math	AVB	Automotive & Industrial Automation
[Ojewale et al., 2021]	Compositional Analysis	TT & AVB & BE	Automotive
[Thiele et al., 2015]	Compositional Analysis	TT & PS	Automotive
[Cao et al., 2018]	Eligible Interval	AVB	Generic
[Xu & Kong, 2025] [Maxim & Song, 2017]	Eligible Interval	AVB	Automotive
[Cao et al., 2016]	Eligible Interval	AVB	NA
[Smirnov et al., 2017]	Busy Period	AVB	Automotive
[Yuan et al., 2022]	Busy Period	TT	Generic
[Lv et al., 2020]	Model Checking	AVB	Generic
[Li & George, 2017]	Trajectory Approach	AVB	Automotive
[Torres-Macias et al., 2024]	Petri Net	Generic	Generic

In the research by Reimann et al. (2013), taking into consideration the specific requirements of heterogeneous automotive architectures with support for several cooperating real-time networking technologies, a delay analysis scheme based on *Real-Time Calculus* (RTC) is presented for AVB streams with static routing. RTC is based on the NC theory and relies on *min-plus* and *max-plus* algebra. A comparison of analytical and simulation results is also provided, showing that the proposed analysis technique achieves tight bounds for communication between sensor and actuator nodes in an automotive architecture. In the study by Zhao et al. (2018a), a new priority class for AVB streams is introduced in addition to existing classes A and B to improve the WCD performance. Furthermore, a new NC-based delay analysis approach is proposed to calculate the worst-case queueing delay resulting from the newly introduced priority class under CBS. Experimental results show that the proposed approach achieves tighter delay bounds than the existing techniques, which is beneficial to the configuration of AVB communication for in-vehicle networking. In the work by Ren et al. (2020), an NC-based delay model is proposed for AVB traffic taking into account the impact of TT traffic, that is evaluated in a real network setup. Due to an accurate calculation of the arrival curve of TT traffic, the proposed approach determines a service curve for AVB traffic, which better describes the ability of the network switch to process incoming AVB frames and hence leads to a more precise queueing delay estimate. In the research by Zhao et al. (2023), an NC-based model for configuring a minimum idle slope for CBS is proposed, while satisfying the deadline at the same time. For this purpose, an analytical-based optimization method is developed, which has a very low computational overhead by taking only a few seconds. In contrast to this work, idle slope has a default input value in the previous NC tool introduced by the authors in study Zhao et al. (2018b). In CBS, each AVB queue is granted a credit value, initialized to zero. When an AVB gate is closed, the associated credit becomes frozen. When it is open, the credit value is either decreased with a send slope during the transmission of an AVB frame or increased with an idle slope when the transmission of awaiting AVB frames is blocked due to the ongoing transmission of other higher-priority traffic or a negative credit.

In the work by Daigmorte et al. (2018), using an extended NC-based analysis approach, upper bounds on network delay and memory usage are determined for a TSN network with mixed-criticality support including TT, AVB, and the lowest-priority BE traffic classes. In the research by Zhao et al. (2018b), an NC-based approach to perform WCD analysis of AVB traffic is proposed by considering both non-preemption and preemption modes. A *guard band* (GB) mechanism is used in non-preemption mode to define a time window preceding a gate opening event for TT traffic. During GB, AVB frames are prohibited from being forwarded if there is not sufficient time available to transmit the entire frame before the opening of the TT gate. GB mechanism leads to a wasted bandwidth, but ensures no interference of the lower-priority AVB traffic. On the other hand, in preemption mode, higher-priority TT frames are allowed to interrupt the ongoing transmission of lower-priority AVB frames, which provides low latency for high-priority TT traffic. In the research by Zhao et al. (2018b), the impact of higher-priority TT traffic on the latency of AVB is investigated and the proposed method is evaluated using realistic test cases including the *Orion Crew Exploration Vehicle*. In the study by Zhao et al. (2020a), considering TT, AVB, and BE traffic types, NC-based timing analysis of AVB traffic is extended to arbitrary number of AVB classes in contrast to the related work. It also takes into account both frozen and non-frozen behaviors of the CBS mechanism during GB. Diagmorte and Boyer (2019), argue that the non-frozen behavior of credit during a GB as defined by TSN standard is not fair so that the standard should be updated accordingly. In the works by Diagmorte and Boyer (2019) and Zhang et al. (2019), assuming that GCLs are given for the critical streams, an analysis framework exploiting RTC is proposed to perform the feasibility analysis of a TSN network by determining the delay, memory, and resource utilization bounds for the critical traffic being transmitted. In the research by Shalghum et al. (2022), underlining that timing requirements of AVB traffic may not be satisfied under non-overlapping TT transmission windows, the WCD analysis of AVB traffic is realized using NC with non-preemption and preemption modes for the case that the transmissions of TT frames may overlap in a node to provide more bandwidth for unscheduled traffic. The concept of overlapping-based TT windows is in contrast to the previous TT scheduling approaches, which require a complete isolation between TT windows to prevent TT streams from interfering each other.

In the study by Zhao et al. (2018c), allowing a mixture of TAS specified by 802.1Qbv and the priority-based shaping, a WCD analysis of TT traffic is performed based on NC and the proposed model is validated through synthetic and real-world use cases. TAS relies on a pre-computed TDMA-like schedule table, which ensures the satisfaction of the hard real-time temporal requirements of the time-critical control traffic transmitted in a network. In the study by Zhao et al. (2018c), it is also underlined that the proposed approach can be integrated into a GCL optimization process to estimate the WCD of TT streams and select the solution leading to minimum delay. In the work by Zhao et al. (2020b), an NC-based WCD analysis approach is presented for safety-critical TT traffic relying on window-based GCLs, which was proposed in the literature to provide more flexibility in the configuration of GCLs by removing the mutually exclusive gate opening requirement of the previous approaches (Reusch et al., 2020). This requirement prevents the gates of multiple TT queues to be opened at the same time and hence provides more determinism at a cost of reduced solution space for GCL computation. The proposed approach is validated using synthetic and realistic industrial use cases showing that the pessimism on delay bounds is significantly reduced compared to the related work.

In the research by Thomas et al. (2022), the impact of packet replication and elimination mechanism of TSN on the timing behavior of real-time streams is investigated. This mechanism replicates network packets onto redundant paths to increase the reliability of the network and removes duplicate packets at the point where the redundant paths merge. This replication function can lead to a burstiness increase along the paths of replicates and packet mis-ordering at the intermediate switches, that can increase the network delay. Using the NC framework, a WCD analysis is provided for TSN by giving bounds on the increase in burstiness due to packet replication and elimination as well as on the amount of reordering. The interactions with scheduling mechanisms are analyzed via an industrial use case. In the study by Tabatabaee et al. (2023), the *Deficit Round-Robin* (DRR) scheduling algorithm is applied to TSN, where the egress queues are visited in a round-robin manner. Taking into account TSN with DRR, the authors investigate the WCD bounds of real-time streams using an NC-based framework. Experiments on an industrial network show that the proposed analysis scheme leads to delay bounds as good as the state-of-the-art. In the work by Finzi and Mifdaoui (2020), a WCD analysis of enhanced *Avionics Full*

Duplex Switched Ethernet (AFDX) networks incorporating *Burst Limiting Shapers* (BLS) of TSN is performed based on NC to evaluate realistic avionics use cases. BLS is a type of CBS granting a transmission credit to each real-time flow and modifying this credit value accordingly to prevent traffic bursts so that network traffic with different mixed-criticality levels is supported. In the research by Zhao et al. (2022), the performance of various traffic shapers including TAS, *Asynchronous Traffic Shaper* (ATS), CBS, and strict priority is analyzed based on NC to allow network designers to choose the right combination of shapers for their applications in TSN. ATS achieves zero congestion loss and deterministic latency without requiring time synchronization, that reduces the complexity of a TSN implementation since synchronization introduces certain challenges such as lost timing frames and clock inaccuracy. Being the first work in TSN literature that provides a performance comparison of the major traffic shapers, various experiments are carried out using synthetic and realistic traffic scenarios to determine the upper bounds of delay and jitter resulting from the evaluated shapers. In the study by Seliem at el. (2023), underlining the importance of TSN for Industry 4.0, an NC-based analysis framework is proposed to evaluate the delay characteristic of a realistic industrial use case, which transmits four different types of traffic with varying priorities. The performance of the proposed method is compared with that of an Omnet++ simulation model to validate the presented approach. The evaluation results show that the framework proposed for the industrial domain provides tighter delay bounds compared to the existing work. In the work by Maile at el. (2022), a centralized admission control mechanism is proposed for TSN networks with CBS that provides deadline-guaranteeing flow allocations. The proposed approach relies on the NC framework to compute the WCD resulting from the newly admitted traffic streams. Using synthetic and realistic traffic scenarios, the experimental results show that the proposed centralized model achieves a better resource utilization than the standardized decentralized approach. In the research by Zhao et al. (2017), the performance difference arising from the replacement of the existing strict priority scheduling mechanism of AFDX with CBS is investigated through an NC-based analysis. Although the CBS mechanism prevents high-priority traffic bursts from completely obstructing low-priority streams, a strict priority approach with two different priority levels cannot provide such a guarantee. Experimental results show that CBS is able to avoid the blockage from the high-priority traffic at a cost of a higher WCD. In the study by Yan et al. (2025), inspired by TSN, a customized CBS mechanism is designed for its integration within airborne *Power Line Communication* (PLC) networks to optimize traffic management, where configuration parameters of the proposed mechanism are determined based on an NC-based delay analysis model. Through a PLC network, installation costs and weight of an aircraft are reduced due to enhanced cabling overhead, leading to an increased fuel efficiency. Experimental results show that deterministic real-time guarantees can be ensured by the proposed approach, which is essential for the safety and reliability of avionics communication systems.

2.1.2. AVB Latency Math

A *Greedy Randomized Adaptive Search Procedure* (GRASP)-based meta-heuristic is developed by Laursen et al. (2016) and Pop et al. (2016) for the route planning of AVB streams with the initial solutions computed using the *K shortest-path* (KSP) approach. In each iteration of GRASP, an initial solution is firstly constructed followed by a local search, that is performed on the initial solution to achieve a local minimum. In these works, TT routes and GCLs are assumed to be known in advance and AVB-LM is used for the WCD analysis of AVB streams since it is computationally efficient. AVB-LM computes WCD for each hop in the network by providing delay equations for end-systems and switches. AVB-LM is extended in the study by Laursen et al. (2016), to consider the effect of TT traffic on the latency of the AVB flows. In the work by Demir and Cevher (2023), a novel optimization approach relying on KSP algorithm is developed to solve the AVB routing problem based on the *Multi-Topology Routing* (MTR) concept. IETF standardized MTR as extensions to OSPF and IS-IS, that supports virtual topologies which have the same network graph as the physical topology, but with different link weights. In order to determine the WCD of AVB streams resulting from their approach, an extended AVB-LM tool is used.

2.1.3. Compositional Performance Analysis

In the research by Thiele et al. (2015), the WCD bounds for TAS and *peristaltic shapers* (PS) of TSN are evaluated through *Compositional Performance Analysis* (CPA) using a realistic automotive use case. In CPA, a component-based model is derived for a network by relying on three different components including processing resources, tasks, and events, where tasks are mapped to the resources. CPA models a network as a directed graph, where nodes and edges correspond to tasks and their dependencies, respectively. Whenever a task finishes its execution, it signifies an event to activate its dependent tasks. Classifying the incoming frames based on priority and arrival times, PS splits the time into equally-sized alternating time slots with even or odd indexes such that any frame received in an even slot is scheduled to be transmitted in the next odd slot and vice versa. In the study by Diemer et al. (2012), evaluating different network topologies in industrial automation, a fast and highly scalable CPA approach is applied to perform the delay analysis of AVB traffic. Mapping the scheduling problem of frames at the output of Ethernet switches to the scheduling of tasks on a processing resource, well-known methods for the performance analysis of processor scheduling are exploited to analyze the WCD of AVB. In the work by Ojewale et al. (2021), a CPA approach is provided for the WCD analysis in TSN with multilevel preemption. Multilevel preemption overcomes the limitations of 1-level preemption specified by the 802.1Qbu standard, where the transmission of a preemptable frame can be suspended by a time-critical frame to meet the stringent temporal requirements of critical traffic, but any other time-sensitive preemptable frame cannot be transmitted before the completion of the already preempted one. In case of 1-level preemption, the performance of preemptable frames with time-sensitive requirements is significantly degraded, especially in scenarios with a high number of highest-priority express frames. Experimental results obtained in a realistic automotive scenario show that multilevel preemption achieves a significant improvement for the delay characteristic of time-sensitive preemptable frames.

2.1.4. Other

In the study by Maxim and Song (2017), a delay analysis of AVB frames is performed in the presence of both CBS and TAS, and the proposed analysis approach is applied to an automotive use case. The impact of TAS on the latency of AVB traffic are taken into account while analyzing the worst-case scenarios for lower-priority AVB streams. In their approach, the so-called *eligible interval*-based analysis is extended to make it applicable to the TSN model. An eligible interval is an interval in which a stream has a pending traffic load and a positive credit so that the traffic can be forwarded as long as the corresponding egress port is not busy transmitting other traffic. In the work by Cao et al. (2016), the worst-case response time of AVB traffic resulting from the use of CBS is evaluated by providing a tighter delay bound compared to the previous work. The proposed analysis method relies on eligible intervals, which takes into account both pending traffic load in a transmission queue and credit available to a shaper located in front of the queue, in contrast to the busy-period approaches, which are more pessimistic due to the lack of any consideration of the available bandwidth. In the research by Cao et. al (2018), relying on eligible intervals, the worst-case response time of AVB frames is analyzed under CBS by applying the proposed method to the case where there are multiple higher and lower interfering priority classes. The proposed analysis approach does not require a detailed model of the inter-arrival patterns of the interfering traffic so that the analysis process is significantly simplified in contrast to the related work. In the study by Xu and Kong (2025), the traditional CBS algorithm is improved by introducing a frame preemption mechanism to support critical traffic streams with extremely low latency and jitter requirements. Relying on the eligible interval method, WCD analysis of the proposed scheme is also performed through a vehicular communication scenario, which shows that the timing properties of the critical traffic is significantly enhanced, thanks to the extended CBS.

In the study by Bordoloi (2014), equations to perform WCD analysis on AVB switches are derived by considering the CBS algorithm, and different approaches are proposed to reduce the pessimism in the analysis. Their approach addresses several challenges regarding the delay analysis of AVB traffic, that were not previously considered by the *busy-period* analysis originally defined by Diemer et al. (2012). In their analysis, the blocking effect of CBS is taken into account, while the busy-period approach only considers the interference of the lower-priority traffic. In the work by Smirnov et al. (2017), a computationally efficient formal method taking into account the impact of the scheduled traffic is proposed for the delay analysis of the non-scheduled hard real-time traffic without making any assumptions about the underlying scheduling mechanism. Their approach relies on the busy-period technique for the timing analysis of the critical non-scheduled traffic with hard deadlines. In the research by Axer et al. (2014), favoring the deployment of AVB in automotive communication networks and experimenting on a line topology, an improved AVB delay analysis approach with significantly tighter delay bounds is proposed to extend the busy-period approach. It differs from the related work in that it takes into consideration the impact of CBS on the traffic load of downstream switches along a transmission route. In the study by Yuan et al. (2022), a busy-period-based response-time analysis method is proposed to predict the upper bound of the latency experienced by TT streams under IEEE 802.1Qbv scheduling. Based on the analysis results, a deadline-sensitive scheduling algorithm with adaptive priority adjustment is developed to divide the priority into more levels to optimize the transmission order of frames within the egress ports of switches. The experimental results show that the proposed scheduling scheme both improves the scheduling success rate and reduces the network delay for TT streams.

The work presented by Lv et al. (2020), is the first study on the formal analysis of TSN scheduling mechanisms, where the UPPAAL model checker is used to formally model CBS and *First-In First-Out* (FIFO), and analyze the corresponding transmission latencies of AVB streams. Verifying the deadlock-free, safety, and starvation-free properties of the proposed model, the performance of CBS and FIFO mechanisms are compared. Please note that Uppaal is an integrated environment for modeling, validation, and verification of real-time systems using timed automata. In the research by Li and George (2017), WCD analysis for aperiodic AVB flows is performed by extending *Trajectory Approach* (TA), which was first proposed for FIFO scheduling in the study by Martin and Minet (2006). TA defines the worst-case scenario delaying an AVB flow most by considering the entire transmission path instead of determining an individual scenario for each traversed node, and summing up these individual worst-case delays to compute the end-to-end delay of a frame. Taking into consideration the CBS characteristics, the performance of the proposed approach is illustrated on different automotive use cases. Underlining that NC is poorly applicable in traffic scenarios of dynamic networking conditions, the work by Torres-Macias et al. (2024) provides a preliminary research effort by deriving a *Timed Petri Net* model for TSN with changing conditions, which is a mathematical and graphical tool for modeling and analyzing discrete event systems. The authors claim that their model can also be used to design an online control tool for TSN to open and close the gates in egress switch ports to satisfy temporal requirements of traffic streams.

2.2. Network Simulation

In the study by Hellmans et al. (2020), a simulative delay analysis of stream-based TAS, class-based TAS, and frame preemption is presented using the Omnet++ network simulation tool presented by Falk et al. (2019) to assist network designers in selecting and applying suitable mechanisms for their own needs. Class-based scheduling is a way to use TAS with less computational effort, which schedules streams with similar jitter and deadline requirements as a group. In the work by Fang et al. (2020), the WCD performance of CBS and ATS mechanisms of TSN, which provide per-class and per-flow scheduling strategies, respectively, is compared through Omnet++ simulations under varying traffic loads. The experimental results show that ATS can achieve better performance especially in heavy traffic. In the research by Luo et al. (2022), a methodology for the design of TSN-supported automotive platforms is proposed to build a communication infrastructure that satisfies the deadline constraints of in-vehicle traffic. The performance of their proposal is evaluated through Omnet++ simulation models using a real TSN-supported automotive scenario with a zonal architecture. The functionalities conventionally offered by different domain-specific *Electronic Control Units* are combined into a smaller number of components in a zonal architecture, each with a high performance computing capability. In the study by Arestova et al. (2021), relying on Omnet++ simulation models, TAS and frame preemption mechanisms of TSN are compared to strict priority scheduling in terms of latency, jitter, and the amount of interference of low-priority traffic. The evaluation results show that TAS achieves the best schedulability at a cost of high configuration overhead. In the work by Ashjaei et al. (2017), a schedulability analysis is performed for AVB traffic taking into account the impact of the scheduled TT traffic shaped by 802.1Qbv. The performance results are compared to the ones achieved by Omnet++ simulations using industrial use cases. Furthermore, it is formally shown that the tight bandwidth allocation requirements specified by the AVB standard may cause unschedulable results to arise in most of the cases, even if these cases are schedulable in reality. In the research by Bello et al. (2020), a response time analysis method for TSN networks is provided by considering the scheduled traffic and preemption support specified in 802.1Qbv and 802.1Qbu, respectively. A performance comparison between the response times achieved by the proposed method and Omnet++ simulations is realized based on a realistic in-vehicle use case. The proposed analysis method differs from the previous work in that it takes into account the case where both preemptive and non-preemptive transmissions coexist. In the study by Luo et al. (2024), a new analysis tool based on CPA is developed to obtain the theoretical worst-case bounds in TSN with a combination of *Cyclic Queuing and Forwarding* (CQF) and frame preemption mechanisms. CQF alternately stores incoming frames in different queues of a switch based on the type of current cycle, namely odd or even, and cyclically forwards them. The authors performed Omnet++ simulations to compare simulation and theoretical results, providing significant guidelines for network designers to determine the right CQF configuration.

Underlining that time-critical applications require fault-tolerance and deterministic latency, the work by Silva et al. (2025) develops a fault-tolerant scheduling methodology for TAS. The authors extend the existing Omnet++-based *NeSTiNg* simulation model for TSN with an advanced fault injection capability to perform reliability experiments under different types of network failures and evaluate the impact of these failures on network latency. Experimental results show that the proposed fault-tolerant scheduling approach achieves low-latency schedules regardless of the network failures. In the study by Liu et al. (2024), the accuracy of the OMNeT++ INET simulator for TSN is evaluated by comparing INET simulations with performance measurements of two commercial TSN switches, in terms of time synchronization achieved via the *generalized Precision Time Protocol* (gPTP) and forwarding latency resulting from TAS. Based on their experiments showing that INET simulations yield different results compared to the hardware-based observations, the existing INET simulation modules are modified in accordance with the behavior of hardware switches. In the study by Anjum et al. (2024), deterministic data delivery requirement of content-centric and real-time *Internet of Things* (IoT) applications with TSN support is addressed by proposing a deadline-aware scheduling algorithm, which prioritizes the transmission of time-sensitive data over best-effort traffic. The performance of the proposed approach is analyzed through Omnet++ simulations, which show that it ensures the effective delivery of time-sensitive IoT data by achieving deterministic low-latency.

In the work by Kim et al. (2023), in contrast to the existing work that focuses on WCD analysis, the average time delay in an in-vehicle network is attempted to be estimated through queueing analysis for TSN and CAN. In case of TSN, the performance of AVB streams is analyzed with frame preemption in mind and the proposed queueing model is evaluated through network simulations. In the research by Zhou (2018), the WCD analysis of two different ATS approaches including *Urgency-Based Scheduler* and *Paternoster* is performed using the Riverbed modeller, which provides a comprehensive development environment to simulate communication networks. Performance evaluation shows that ATS has an effective traffic shaping capability without synchronous mechanisms.

Table 2 summarizes the recent literature on simulative delay analysis of TSN.

Table 2. Summary of the recent literature on simulative and ML-based analysis of TSN

Reference(s)	Classification	Method(s) / Simulator	Traffic Type	Experimental Domain
[Luo et al., 2024]	Network Simulation	Omnet++	CQF	Automotive
[Silva et al., 2025] [Liu et al., 2024]	Network Simulation	Omnet++	TT	Generic
[Anjum et al., 2024]	Network Simulation	Omnet++	TT	Automotive
[Kim et al., 2023]	Network Simulation	Omnet++	AVB	Automotive
[Luo et al., 2022]	Network Simulation	Omnet++	TT & AVB	Automotive
[Arestova et al., 2021] [Hellmanns et al., 2020]	Network Simulation	Omnet++	TT	Industrial Automation
[Bello et al., 2020]	Network Simulation	Omnet++	TT & AVB	Automotive & Industrial Automation
[Fang et al., 2020]	Network Simulation	Omnet++	AVB & ATS	Generic

Table 2 (continued). Summary of the recent literature on simulative and ML-based analysis of TSN

Reference(s)	Classification	Method(s) / Simulator	Traffic Type	Experimental Domain
[Zhou et al., 2018]	Network Simulation	Riverbed	ATS	Generic
[Ashjaei et al., 2017]	Network Simulation	Omnet++	AVB	Automotive & Industrial Automation
[Wang et al., 2024]	Machine Learning	BPNN	Generic	Automotive
[Mai & Navet, 2021]	Machine Learning	GNN	Generic	Automotive
[Navet et al., 2019]	Machine Learning	k-NN, K-Means	Generic	Automotive
[Mai et al., 2019a] [Mai et al., 2019b]	Machine Learning	k-NN	Generic	Automotive

2.3. Machine Learning

In the study by Mai et al. (2019a), the work by Navet et al. (2019) is extended through a hybrid approach combining machine learning (ML) and conventional schedulability analysis to decrease the number of false positives. In contrast, in the work by Navet et al. (2019) estimate the schedulability of a TSN network using only ML, without integrating any conventional analysis. Experimental results show that the proposed hybrid approach yields a prediction accuracy of 99% and has a much higher computational efficiency compared to the related work. In the research by Mai et al. (2019b), schedulability analysis of a TSN network is performed by applying a supervised ML method, that is, *k-nearest neighbors* (k-NN), to the delay analysis problem and comparing the accuracy and execution time of k-NN against conventional NC-based analysis. Experimenting on an automotive network topology, k-NN is observed to achieve up to 95% accuracy with a very high speedup in computational time in contrast to the NC-based analysis. In the work by Mai and Navet (2021), targets to overcome the difficulties of existing ML-based schedulability prediction techniques for TSN. These difficulties include the requirement of an in-depth domain expertise to determine the feature set as well as the poor performance in the case that the traffic patterns covered by the test data significantly differ from the ones in the training data. For this purpose, a deep learning model with a *Graph Neural Network* (GNN) is firstly proposed in the literature for the schedulability analysis of a TSN network with an automated feature selection process. Experimental results obtained on a realistic automotive network show that the proposed model achieves an accuracy of up to 90% as well as a much lower execution time compared to the existing conventional ML work. In the work by Wang et al. (2024), the schedulability analysis of TSN is performed by using *Backpropagation Neural Networks* (BPNN), which is combined with *Particle Swarm Optimization*. The MATLAB simulation results show that the proposed approach achieves an accuracy of above 97%, while yielding short training and test times.

Table 2 summarizes the recent literature on ML-based analysis of TSN.

3. IEEE 802.1BA Audio Video Bridging

IEEE 802.1 Working Group on AVB previously provided the CBS standard specified by 802.1Qav, which is leveraged by TSN. Each egress queue allocated to AVB traffic exploits an instance of CBS mechanism, which shapes AVB streams based on a credit value to prevent traffic bursts and hence avoid the starvation of lower-priority messages. CBS can be used in combination with TAS specified by 802.1Qbv to provide real-time guarantees for AVB and TT traffic types, which may have different temporal requirements. TAS relies on a pre-computed GCL per each egress port to guarantee timely transmission of the most critical TT traffic.

3.1. Credit-Based Shaper

CBS mechanism relies on a credit value for each egress AVB queue, which is initialized to zero. It allows transmission of an AVB frame whenever the credit is positive or zero, and blocks its forwarding otherwise. If a queue storing AVB class *i* frames is not empty, the corresponding credit is decreased during transmission at a rate determined by the *send-slope* (ssl_i) configuration parameter. On the other hand, it is increased at a rate defined by the *idle-slope* (isl_i) parameter, when either credit is negative, or when AVB frames in the queue can not be forwarded since the traffic in another queue is already in transmit (Lv et al., 2020). If an AVB queue is empty and its credit is positive, the credit is set to zero, whereas it is increased with respect to isl otherwise (Zhao et al, 2018b).

Fig. 1 shows an operational example for CBS based on a simple traffic scenario, where four different frames belonging to AVB Class 1 and Class 2 with a decreasing priority arrive at an egress port at different times to get forwarded on the corresponding link. Colored rectangles on the first timeline represent the transmission of AVB frames on the respective link, while the down arrows above the frame transmissions indicate the arrival times of frames. As shown in the figure, at t=0, the frames $f^1_{AVB_{C1}}$ and $f^1_{AVB_{C2}}$ arrive at AVB Class 1 and Class 2 egress queues, respectively, where $f^1_{AVB_{C1}}$ is eligible to transmit first, since Class 1 has a higher priority. During the transmission of $f^1_{AVB_{C1}}$, the credit is decreased and increased for Class 1 and Class 2 according to ssl_{C1} and ssl_{C2}, respectively. During the transmission of $f^2_{AVB_{C1}}$, the credit of Class 2 is increased until zero and remains zero until the arrival of $f^2_{AVB_{C2}}$. Gray-colored rectangles in Fig. 1 indicate the time windows, when both Class 1 and Class 2 queues are empty, in which case the currently positive credit of Class 1 is set to zero, while the credit of Class 2 is increased with respect to isl_{C2} until zero.

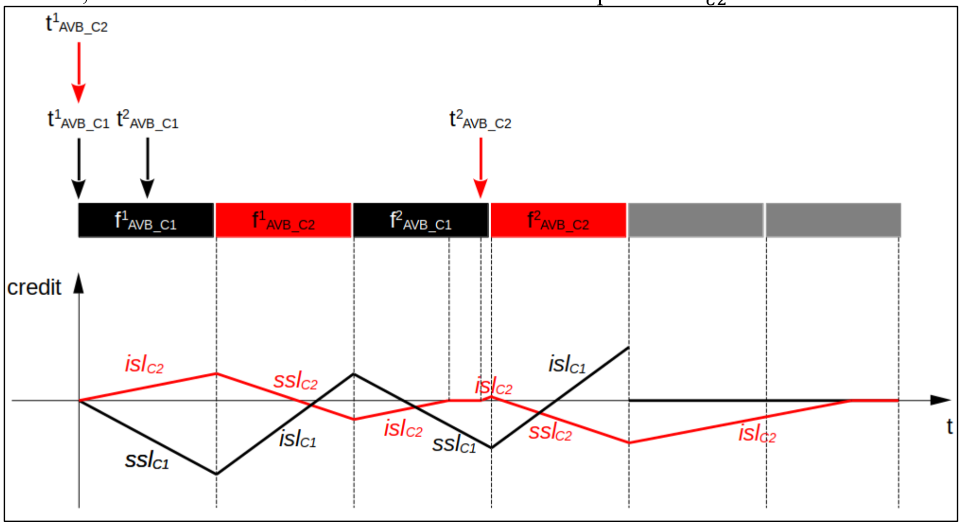


Figure 1. Operational example for CBS

3.2. Combined Usage with TAS

Fig. 2 shows the structure of a TSN switch for a single egress port, which features the combined usage of CBS and TAS. As shown in the figure, a newly arrived data frame is dispatched by the *Switching Logic* to the appropriate egress queue based on its priority encoded by the *Priority Code Point* field within its frame header. TSN switch provides a maximum of eight queues with varying priorities for each egress port to store TT, AVB, and BE frames awaiting to be transmitted on the corresponding link (Demir and Cevher, 2023). Accordingly, one or more egress queues are allocated for TT traffic, whose exact number is decided based on the outcome of an optimization process (Craciunas et al., 2016). On the other hand, two or more queues are used for different classes of AVB traffic, while the remaining queues are assigned to the lowest-priority BE traffic (Zhao et al., 2020a). TAS prioritizes the forwarding of TT traffic relying on a pre-computed and globally-synchronized GCL per each egress port, which encodes the timings of opening and closing events of gates located at the front of each egress queue. Frames awaiting in each egress queue are eligible for transmission only if the corresponding gate is open. In case of AVB traffic, an enqueued frame is forwarded only if *i)* the associated CBS permits it, *ii)* the corresponding gate is open, and *iii)* no other higher-priority traffic is eligible for transmission. When the gate for an AVB queue is open, the credit behavior of CBS is the same as the one described in the previous section, while the credit is assumed to be frozen in the case that the gate is closed (Zhao et al., 2018b). *Transmission Selection Logic* shown in Fig. 2 selects messages for transmission from the highest-priority queue, whose gate is open, as long as CBS if present enables it.

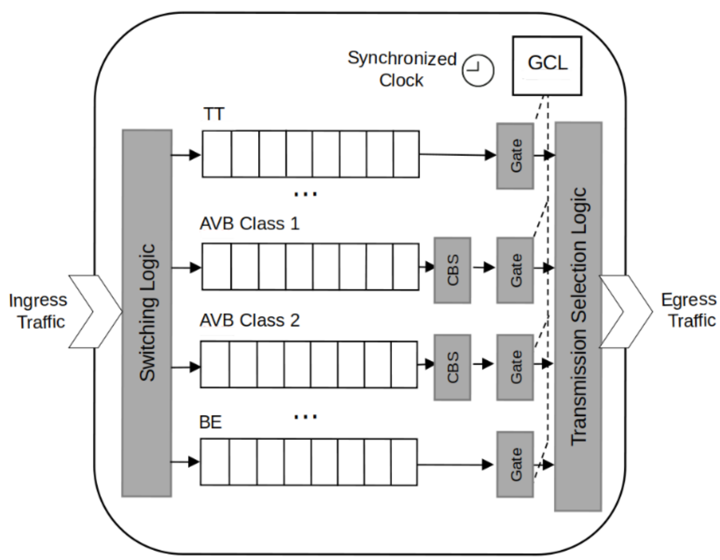


Figure 2. Architecture of a TSN switch with CBS and TAS support

4. Omnet++ Simulation of 802.1BA AVB Networks

In our work, we use the Omnet++ simulation model for each TSN switch in the experimented networks, which is provided by the INET framework (INET Framework, 2024). The AVB egress queue implementation in our switch model incorporates the CBS algorithm, which is used in combination with TAS as explained in Section 3.2. We also use the simulation model provided by INET for each TSN end-system (ES) hosting the user applications, which differs from the switch model only in that it does not implement the CBS mechanism and hence does not perform any traffic shaping. Due to this subtle difference between the switch and ES simulation models, only the switch model is explained in this section.

Fig. 3 demonstrates the structure of a simulated TSN switch with two egress ports in a hierarchical manner. The depicted model supports the transmission of only AVB streams with the same AVB class, namely *A*, and hence features a single AVB egress queue at each egress port to enqueue AVB frames with the same priority. *Block 1* demonstrates the general structure of the switch model, which implements its basic functionality in network, link, and MAC layers as represented by *bridging* submodule, the set of *ethernet*, *ieee8021q*, and *ieee8021r* submodules, and *eth[0]/eth[1]* submodules, respectively. The *bridging* component in Fig. 3 provides various services such as packet forwarding, while *ethernet*, *ieee8021q*, and *ieee8021r* perform Ethernet, IEEE 802.1Q, and IEEE 802.1r encapsulation/decapsulation, respectively. Each pair of successive layers used in the layered architecture of *Block 1* in Fig. 3 is connected by a *Message Dispatcher* module represented by a blue-colored line, which automatically dispatches messages between these layers.

Block 2 represents an Ethernet network interface, which is comprised of MAC and physical layers. The structure of MAC layer is demonstrated by *Block 3*, which contains the *queue*, *server*, and *outboundEmitter* components on the sending side, and the submodules of *inboundEmitter* and *fcsChecker* on the receiving side. The *server* and *outboundEmitter* of *Block 3* are placed by INET by default to pull packets from *queue* when available and push them into the transmission line. On the other hand, *inboundEmitter* receives the frames from the transmission line, while *fcsChecker* verifies the reliability of each received frame. Finally, *Block 4* presents the structure of *queue* component, which is comprised of a queue buffer, CBS mechanism, and a gate located at the front of the CBS as shown in Fig. 3, whose functionalities are explained in Section 3.

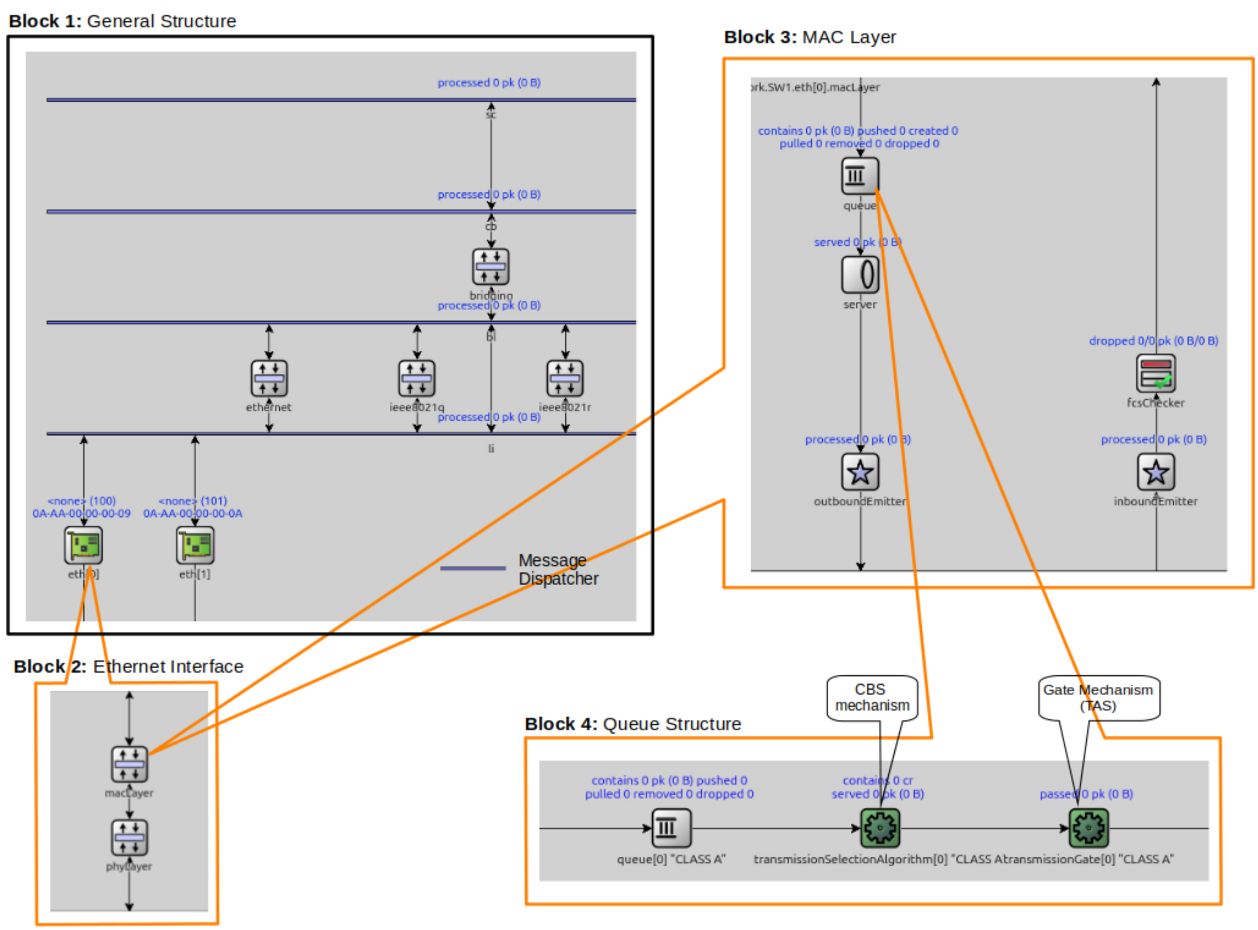
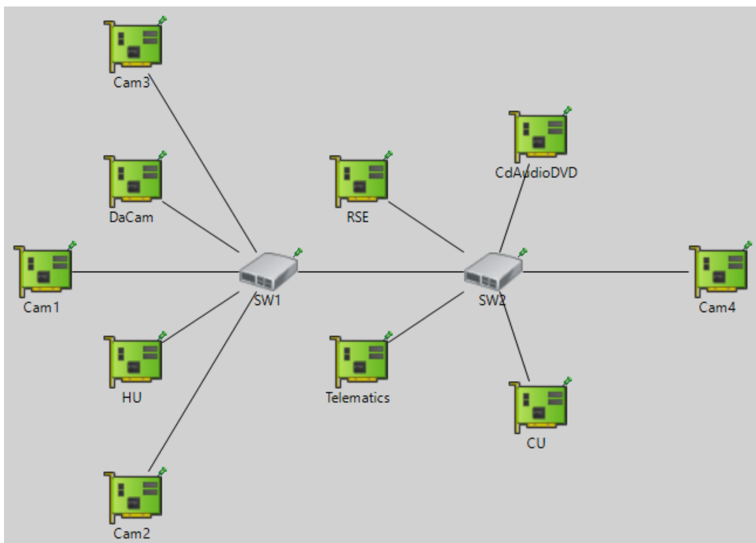


Figure 3. Simulation model for TSN switch

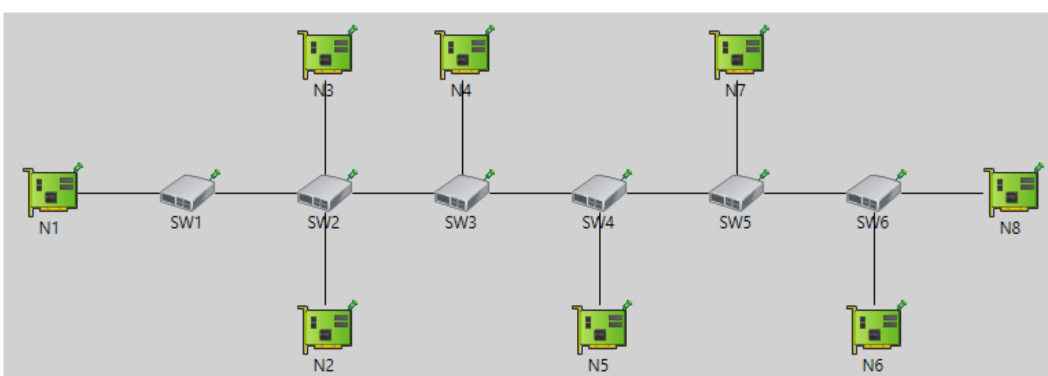
5. Simulation Results

In this section, using the Omnet++ simulation models described in Section 4, we simulate the operation of realistic in-vehicle and industrial automation networks shown in Fig. 4a and Fig. 4b, respectively, to analyze their temporal behavior under realistic traffic scenarios. The experimented in-vehicle network is taken from in the research by Bello et al. (2020), while the industrial automation use case is from in the work by Ashjaei et al. (2017). The in-vehicle use case contains two switches and 10 ESs and is composed of two functional domains, namely *Advanced Driver Assistance Systems* (ADAS) and *Multimedia/Infotainment*. Four cameras, namely *Cam1* to *Cam4*, a *Head Unit* (HU), and two *Electronic Control Units* (ECUs), namely *Control Unit* (CU) and *DaCam*, constitute ADAS. The environmental visual data from *Cam1* to *Cam4* is delivered to *DaCam* to create a bird-eye view and navigation notifications. *HU* provides visual assistance on a display while *CU* produces real-time control messages. *CdAudioDVD* component of *Multimedia/Infotainment* system provides multimedia content to passengers by streaming audio/video data to the rear seat entertainment system (RSE). *Telematics* transmits non-critical real-time data, such as GPS information, to *HU* and *RSE*. On the other hand, the industrial automation use case shown in Fig. 4b consists of 6 switches connected in a line topology and 8 ESs, seven of which are talkers (*N1* to *N7*) and one is a listener (*N8*). This results in a high traffic load for *N8* leading to traffic congestion on network links. Both of the experimented topologies shown in Fig. 4 conform with the 7-hop limit requirement specified by the AVB standard, which restricts the length of a transmission path used between any two nodes to a maximum of 7 hops (Ashjaei et al., 2017). Please note that the AVB standard is able to provide performance guarantees for a network only if the network satisfies this hop limit requirement.

We perform experiments by setting various *idle-slope* values, that is, isl, for CBS operating within the switches to quantify the impact of isl on End-to-End (E2E) latency of the transmitted streams. In our experiments, the total simulation time is selected to be 15 seconds for each experiment, while the specific amount of time it takes for an Ethernet packet to travel through a network switch is assumed to be 5.12 microseconds, similarly to in the study by Laursen et al. (2016), with the propagation delay for network links being set to 0. Our simulations are conducted on a machine equipped with an Intel Core i9-14900KF processor and 32 GB of memory.



a) In-vehicle use case



b) Industrial automation use case

Figure 4. Experimented network topologies

In this section, the worst-case performance of the experimented networks is also theoretically evaluated through the AVB-LM tool as implemented in the work by Laursen et al. (2016). The reason why AVB-LM is selected for theoretical latency analysis in our experiments is that it is computationally efficient. Taking into account link speed, MAC delay, switch delay, stream period, and maximum frame size, AVB-LM defines standardized WCD equations for AVB talkers and switches. To determine the WCD value for an AVB stream, it calculates the worst case latency for each hop on the transmission route of the stream and reports the aggregated sum of these latency values. Please refer to the work by Pannell (2010), for the details of the delay equations defined by AVB-LM.

5.1. Traffic Scenarios

Table 3a lists the properties of traffic streams transmitted within the experimented in-vehicle network shown in Fig. 4a, which are largely taken from in the study by Bello et al. (2020). As shown in the table, a total of 31 AVB streams, namely S_1 to S_{31}, are transmitted in the network. The priority class of all AVB streams are assumed to be identical, namely A, since the implementation of AVB-LM tool from in the study by Laursen et al. (2016) does not allow the evaluation of more complex scenarios with multiple AVB traffic classes. The streams S_1 to S_{22} handle small-sized network control messages specific to ADAS functions, whereas S_{23} to S_{27} and S_{28} to S_{31} are designated for video traffic, and associated with *CdAudioDVD* and *Telematics* units, respectively. Since the combined usage of CBS with TAS is the default behavior of INET as described in Section 3.2., a gate is located at the front of the queue storing class A AVB frames in our simulation model for a network switch as shown in Fig. 3. The status of this gate is selected to be "*open*" at all times throughout our simulations, which has no negative impact on network performance, since there is no other queue storing a different class of traffic. Finally, Table 3b lists the properties of traffic streams transmitted within the experimented industrial automation network shown in Fig. 4b. Apart from the traffic class, all other stream attributes in Table 3b are selected to be the same as in the work by Ashjaei et al. (2017). Shortest paths are used as the transmission routes of all streams listed in Tables 3a and 3b, while the capacity of each network link in our experimented topologies is assumed to be 1 Gbps.

Table 3. Stream properties for the experimented networks

a) In-vehicle use case

Stream	Source	Destination	Period (ms)	Payload (Byte)	#Frames	Class
S_1	DaCam	HU	1000	46	1	A
S_2	DaCam	HU	200			
S_3	DaCam	CU	1000			
S_4	DaCam	CU	200			
S_5	HU	CU	5			
S_6	HU	CU	50			
S_7-S_8	HU	CU	100			
S_9	HU	CU	200			
S_{10}	HU	CU	500			
S_{11}-S_{12}	HU	CU	1000			
S_{13}	HU	DaCam	100			
S_{14}- S_{15}	HU	DaCam	200			
S_{16}	CU	HU	100			
S_{17}	CU	HU	200			
S_{18}- S_{19}	CU	HU	500			
S_{20}	CU	HU	1000			
S_{21}	CU	DaCam	10			
S_{22}	CU	DaCam	1000			
S_{23}- S_{26}	Cam[1-4]	DaCam	0.26	678		
S_{27}	DaCam	HU	0.26			
S_{28}	Telematics	RSE	0.125	120		
S_{29}	Telematics	HU	0.625	50		
S_{30}	CdAudioDVD	RSE	0.256	334		
S_{31}	CdAudioDVD	RSE	0.25	80		

b) Industrial automation use case

Stream	Source	Destination	Period (ms)	Payload (Byte)	#Frames	Class
S_1	N1	N8	2875	500	1	A
S_2	N2		3500	500		
S_3	N2		4000	46		
S_4	N3		4000	46		
S_5	N4		1875	500		
S_6	N5		1500	500		
S_7	N6		3000	500		
S_8	N7		1250	200		

5.2. Performance Evaluation

Using the in-vehicle and industrial automation use cases shown in Fig. 4, Table 4 presents the E2E latency values achieved by our simulations in Omnet++ and theoretical analysis via AVB-LM, where $isl = 0.75$, indicating a credit increase rate of 1 Gbps 0.75 =

750 Mbps. Please note that E2E latency values reported for AVB-LM correspond to a worst-case upper bound, that is, WCD, while the results for Omnet++ reflect the average case denoting a lower bound. As shown in both tables, E2E latency values for the average case achieved by Omnet++ are significantly far smaller in all the cases compared to the worst-case results from AVB-LM. For example, in case of the stream S_{20} of the in-vehicle use case, Omnet++ yields the E2E latency value of $3.499\mu s$, while AVM-LM reports the value of $55799.803\mu s$ for the same case. Even though these huge differences between lower and upper bounds on the network performance may indicate that AVB-LM is too pessimistic, such a concluding remark based on the simulation results would not be reliable. This is due to the fact that it is not likely to imitate the worst case taken into account by AVB-LM for a given traffic scenario in a simulation environment and examine the resulting E2E latency values (Thiele et al., 2015). Table 4a also reveals that none of the latency values reported by Omnet++ for the average case exceeds the 2 ms deadline requirement specified by the AVB standard for time-critical streams, while the WCD values reported by AVB-LM for 13 streams out of 31 violate this deadline requirement (Ashjaei et al., 2017). For example, Omnet++ yields the latency value of $4.197\mu s$ for S_{17}, while AVB-LM computes a latency of $11189.989\mu s \approx 11.189ms$, which is considerably higher than 2 ms. On the contrary, in the case of the industrial automation use case, all of the latency values reported by Omnet++ and AVB-LM are in accordance with the 2 ms deadline requirement.

Table 4. E2E latency values (μs) for the experimented networks ($isl = 0.75$)

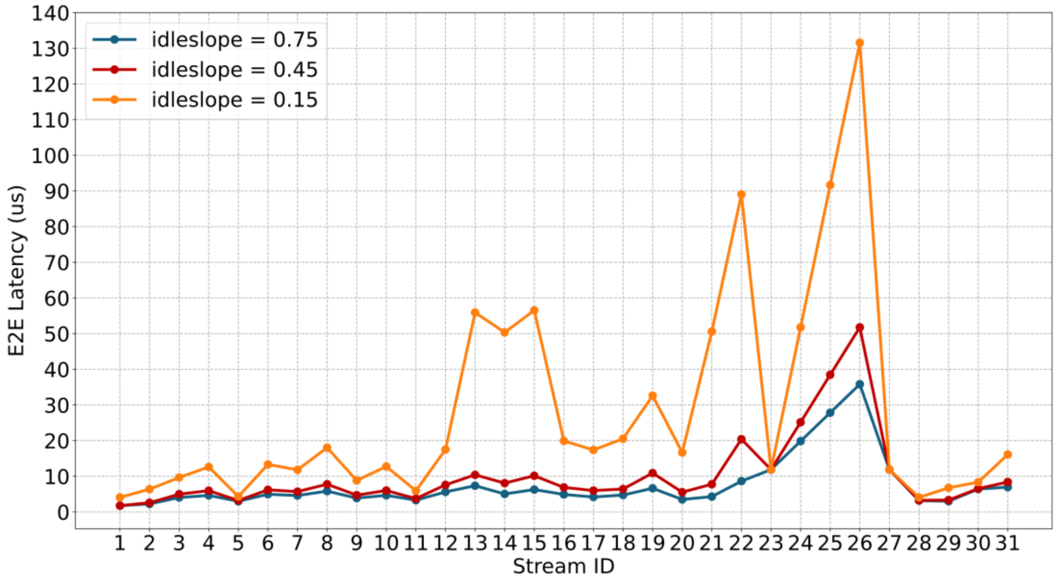
(a) In-vehicle use case

$\text{Stream}_{\text{ID}}$	Omnet++	AVB-LM	$\text{Stream}_{\text{ID}}$	Omnet++	AVB-LM
S_1	1.764	55674.438	S_{17}	4.197	11189.989
S_2	2.258	11154.906	S_{18}	4.742	27918.669
S_3	4.048	28962.381	S_{19}	6.635	27918.669
S_4	4.642	5822.505	S_{20}	3.499	55799.803
S_5	3.001	43.713	S_{21}	4.301	1430.086
S_6	4.968	99.314	S_{22}	8.636	139292.571
S_7	4.600	161.092	S_{23}	11.876	57.828
S_8	5.846	161.092	S_{24}	19.854	57.828
S_9	3.883	284.648	S_{25}	27.833	57.828
S_{10}	4.666	655.317	S_{26}	35.812	75.902
S_{11}	3.305	1273.098	S_{27}	11.876	36.122
S_{12}	5.615	1273.098	S_{28}	3.179	29.462
S_{13}	7.352	11170.313	S_{29}	3.013	32.547
S_{14}	5.041	22315.603	S_{30}	6.413	34.982
S_{15}	6.279	22315.603	S_{31}	6.956	36.067
S_{16}	4.906	5613.762			

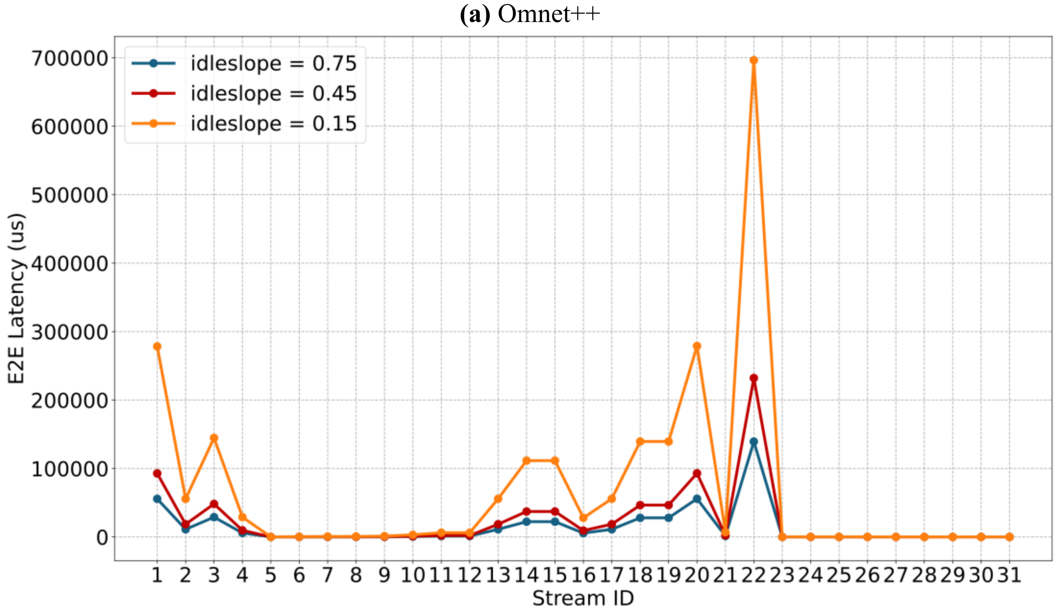
(b) Industrial automation use case

$\text{Stream}_{\text{ID}}$	Omnet++	AVB-LM	$\text{Stream}_{\text{ID}}$	Omnet++	AVB-LM
S_1	31.667	248.798	S_5	23.027	113.527
S_2	27.418	267.163	S_6	18.169	114.634
S_3	6.65	302.906	S_7	9.773	75.928
S_4	8.686	296.811	S_8	6.342	76.208

Fig. 5 shows the impact of various isl values on the latency of the traffic streams transmitted over the in-vehicle network shown in Fig. 4a, where the horizontal axis of each subfigure corresponds to the IDs of the transmitted streams, namely S_1 to S_{31} as listed in Table 3a. As shown in the figure, in case of Omnet++ (Fig. 5a), the latency decreases with respect to isl in almost all the cases. For example, in case of S_{26}, the latency varies as 131.56, 51.77, and 35.81 μs for isl being equal to 0.15, 0.45, and 0.75, respectively. The apparent decline in the latency of the transmitted streams with respect to isl is due to the fact that, in case of a larger isl, AVB frames are more likely to be forwarded immediately by a switch without waiting in the respective AVB queue, since a larger isl leads to a larger rate at which the credit for the respective AVB class is increased, resulting in a reduced latency. In case of AVB-LM (Fig. 5b), similarly to Fig. 5a, the worst-case latency is observed to decrease with respect to isl in almost all the cases. However, this decrease is not apparent for certain streams including S_5 to S_9 and S_{23} to S_{31}, since the very large latency value reported for S_{22} in Fig. 5b dominates the whole plot. For example, the latency of S_5 varies as 59.97, 46.42, and 43.71 μs with respect to isl ranging from 0.15 to 0.75, while the latency for S_{22} varies as 696304.26, 232127.85, and 139292.57 μs. Finally, Fig. 6 shows the impact of various isl values on the performance of the industrial network shown in Fig. 4b. Similarly to Fig. 5, the latency values reported by Omnet++ and AVB-LM decrease with respect to isl in all the cases except S_8 in the average case. In case of Omnet++, the latency of S_8 is measured as 6.342 regardless of isl (Fig. 6a), while it decreases with respect to isl in the worst-case (Fig. 6b).

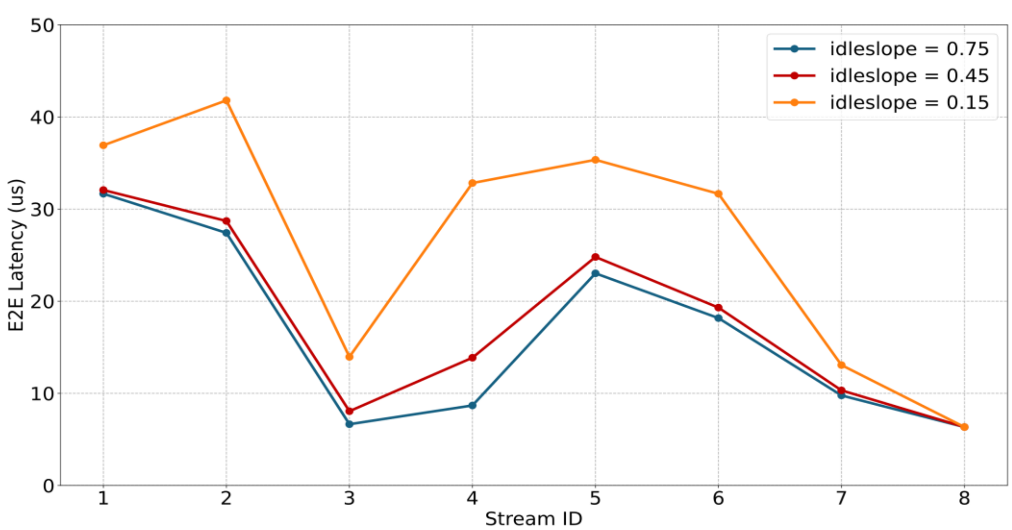


(a) Omnet++

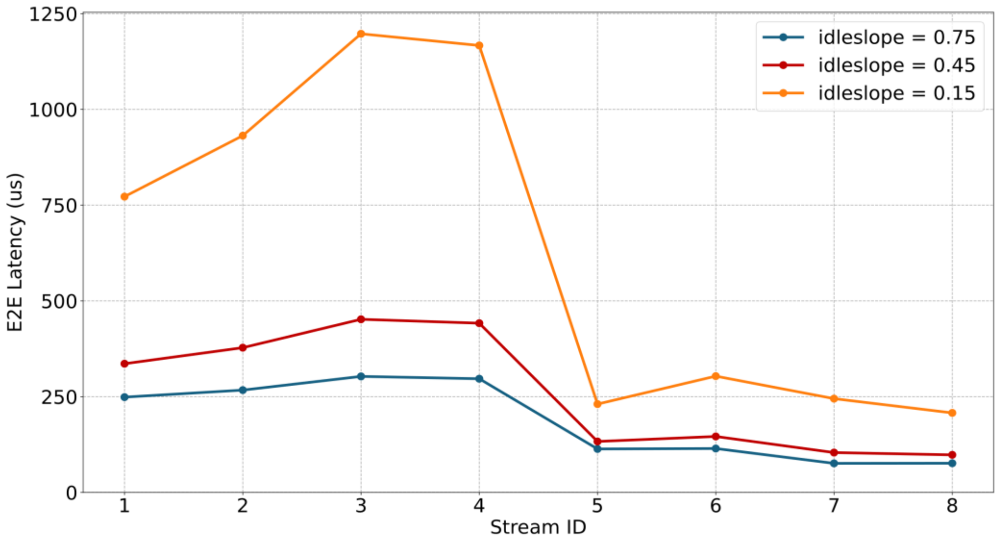


(b) AVB-LM

Figure 5. E2E latency for different isl values over in-vehicle network



(a) Omnet++



(b) AVB-LM

Figure 6. E2E latency for different isl values over industrial automation network

6. Conclusions

Real-time variants of IEEE 802.3 Ethernet are strongly anticipated to be a key solution to provide timing guarantees to time-sensitive traffic in future industrial platforms to achieve their effective computer-based control. IEEE 802.1 *Time-Sensitive Networking* (TSN) task group is the leading organization that aims to standardize Ethernet-based deterministic communication technologies, which build upon *Audio Video Bridging* (AVB) technology. In this paper, an in-depth review of the recent research work on the delay analysis of TSN is provided by categorizing the existing efforts into theoretical, simulation, and machine learning based approaches. The operation of realistic TSN-enabled in-vehicle and industrial automation use cases under traffic scenarios transmitting AVB streams with varying properties is simulated via Omnet++ and their worst-case performance is theoretically analyzed using AVB-LM. Our experimental results show that the average latency values achieved by Omnet++ are significantly far smaller in all the cases compared to the worst-case results from AVB-LM. We also perform experiments by setting various *idle-slope* (*isl*) values to configure CBS operating within the switches to quantify its impact on the latency of the transmitted streams. Our experiments reveal that the latency decreases with respect to *isl* in almost all the cases. This due to the fact that, in case of a larger *isl*, AVB frames are more likely to be forwarded immediately by a switch without waiting in the respective AVB queue, since a larger *isl* leads to a larger rate at which the credit for the respective AVB class is increased, resulting in a reduced latency. As our future work, we plan to use other theoretical tools such as *Network Calculus* and machine learning in our experiments to analyze different use cases under realistic traffic scenarios, since they are known to provide tighter bounds compared to AVB-LM. Furthermore, the performance analysis of traditional bus-based technologies such as CAN and FlexRay including the comparison of their performance with TSN is left as a future work, which requires the adoption of proper simulation models and theoretical delay analysis tools.

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