Evaluation Of Time-Triggered Traffic In Time-Sensitive Networks Using The OPNET Simulation Framework

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***Abstract*—Highly reliable, scalable and deployable networks with strict temporal constraints are inevitable for future cyber physical systems. Due to widespread usage and success of Ethernet technologies, the Time Sensitive Networking task group introduces a series of protocol extensions to the IEEE 802.1 Ethernet standard. These standards provide real time capabilities and performance improvements. Simulation environments are intensively used to investigate correctness and applicability of new protocol suites. This paper presents an OPNET simulation framework for simulating TSN time-based features. Our framework implements ingress time-based policing and enhancements for scheduled traffic as an extensions of the Ethernet standard. We describe the implementation details of our simulation models which provide temporal properties. We also evaluate and compare our results with the expected behaviors of the aforementioned protocols.**

***Keywords*-Temporal Constraints; Cyber Physical Systems; Time Sensitive Networking; OPNET; Simulation Models**

I. INTRODUCTION

The Ethernet standard has been used extensively in a wide range of networks like LANs and WANs. The Ethernet technologies fulfill different needs of various stakeholders from the high demand for bandwidth to the seamless connectivity between the vendor-specific devices [1]. Ethernet is also considered to be a promising solution for the industrial and deterministic networks. Temporal properties play a key role in the development of emerging applications and improvements of current technologies (e.g. autonomous driving). However, the Ethernet standard is not designed to provide deterministic behaviors which is mandatory for safety-critical real-time applications [2]. In conventional Ethernet based networks, time is only used as a component for performance measurements, not as a correctness metric [3]. Therefore, several extensions of Ethernet were introduced to offer determinism such as bounded end-to-end delay and low jitter.

The most recent real time Ethernet extension is Time Sensitive Networking (TSN) [4]. The convergence of synchronous, asynchronous and best effort traffic on a single network is the key aspect of TSN. TSN standards are built on top of protocol suites called Audio Video Bridging (AVB) [5]. AVB is specified to provide guaranteed latency and fixed jitter for the audio and video transmission by reserving bandwidth throughout the path from a sender to a receiver. Despite success and widespread use of AVB in automotive networks, AVB is not able to fulfill the requirements of mission-critical applications like strict timing constraints [6].

The main goal of TSN is to focus on the uncovered areas in AVB sub standards. To achieve this, the TSN task group develops fault-tolerant synchronization mechanisms, a time-sensitive transport protocol and enhancement mechanisms for the Stream Reservation protocol. The task group also introduces a robust redundancy procedure to prevent traffic loss in case of any failure at the different network levels. Furthermore, TSN includes time aware scheduling and policing mechanisms. The aforementioned features lead TSN to be a real-time capable, reliable and interoperable standard, which is suitable for different industrial automation and control networks (e.g. railway, avionic).

It is essential to evaluate and validate the proposed solutions in TSN protocols. Simulation tools are cost and time efficient options for analyzing the temporal attributes of TSN. This evaluation can be performed by using various network performance metrics like end-to-end delay and jitter. Simulation models provide an opportunity to simulate the temporal behavior of TSN networks with high precision. This paper presents a simulation framework for TSN which is developed as an Ethernet-based network for mixed-critically traffic. Our simulation model implements a time-aware shaper and a policer in the OPNET framework. The TSN model uses the standard MAC unit for switching messages, however, it adds the necessary functionalities to support strict temporal requirements. The described implementation is modular and could be integrated to different vendor-specific network elements. The evaluation of the model is performed using several use cases and network configurations. The simulation results are compared to the temporal constraints of safety-critical applications.

The rest of paper is structured as follow: In section

II, related work is discussed. Section III gives a brief overview of the time aware shaping mechanism. Section IV describes the policing approach called time-based ingress policing. Section V presents the conceptual models used in our TSN simulation framework. In this section, our implementation work is also explained in more detail. Simulation results for an example system are evaluated in section VI. The last section concludes the paper.

II. RELATED WORK

For the evaluation of deterministic networks, a wide range of simulation frameworks has been developed. Steinbach et al. [7] implemented the simulation framework called INET-Framework for TTEthernet[8] in OMNeT++. The authors in [9] extend the INET-Framework with the AVB standards in order to evaluate the effect of co-existence of the time critical flows and the AVB stream classes on the shared physical infrastructure. This framework was extensively used to analyze the impact of AS6802 (TTEthernet) and AVB on the real-time applications in the automotive use cases. TsimNet [10] is the most recent TSN simulation framework which is implemented on top of the INET framework. This work addresses TSN sub-protocols which are not time-based such as frame preemption, frame replication and elimination and per-stream filtering. This framework is implemented to evaluate TSN standards for the domain of avionics, where no time synchronization mechanism is used till now due to the certification overheads.

In contrast to TsimNet, we implemented subsets of time-based mechanisms specified in the TSN protocol-suites. To our best knowledge, no network simulator addressing time-based features of TSN is developed yet. Our simulation framework considers synchronized networks in which a global time is used to police and schedule mixed-critically traffic.

III. SCHEDULED TRAFFIC IN TSN

The credit-based shaping (CBS) mechanism of AVB is non-preemptive, which means the lower priority traffic can interfere with TT flows which have strict timing requirements and block their transmission. Therefore, CBS is unable to offer deterministic end-to-end latency and tight jitter for the mission-critical traffic [11]. Time aware shaping (TAS) introduced in IEEE 802.1Qbv [12] is developed to resolve these problems of the AVB shaping mechanism. TAS is a preemptive scheduling method in which scheduled traffic always preempts lower priority traffic in order to meet its transmission schedule. In non-deterministic networks, delivery delay is estimated using analytical methods like network calculus [13] and the trajectory method [14]. However, schedules for TT traffic in TSN are computed offline by using the network topology and the TT stream characteristics [1].

The time aware shaper is defined on the basis of Gate Control List (GCL) concept. In this approach, all TT flows are enqueued into the queues dedicated to TT traffic and the schedule is applied to egress port queues unlike other TT protocols (e.g. TTEthernet) that place each TT flow in a separate buffer and apply a schedule to each buffer according to its requirements. This is the main reason that TAS requires knowledge of the device queue configuration in addition to requirements of TT streams. The GCL is specified for each device's egress port and defines at each instant of time which queue is eligible to transmit traffic. TSN extends the set of traffic types in AVB with an additional TT traffic type. This traffic type is specified for applications that have strict timing requirements and despite of AVB stream classes do not allow interference with less demanding applications. This traffic type is transmitted periodically. Therefore, each individual flow in TSN is assigned to one of the following types: TT traffic, AVB classes or Best Effort (BE) traffic. In time-sensitive networks, the traffic type assignment strictly depends on 802.1Qbv capable switch configurations that specify the characteristics of incoming TT streams [1].

IV. TIME BASED INGRESS POLICING

In fully deterministic and scheduled networks, switches must be aware of the arrival time of TT flows at incoming ports so that they can transmit them based on the predefined schedule tables. The TSN task group develops IEEE 802.1Qci [15] to achieve this goal. The aforementioned property is addressed with the time aware Access Control List (ACL) and ingress policing. The time-based ACL would grant the pass/fail, MTU size and target queue decision for each incoming TT frame at each instant of time. Same as GCL, the time aware ACL for a TSN switch is also defined off-line. The time-based ACL must be aligned with the switch's GCLs. The key benefit of time-based ingress policing is to protect a TSN switch from a wide range of network attacks like man-in-the-middle and babbling idiots attacks. This sub-protocol makes the switch more robust by blocking TT frames arriving outside their scheduled windows. Therefore, the possibility of sending TT frames in an arbitrary order can be completely eliminated. It also results in the optimized usage of network and switch resources like link bandwidth and memories [16].

V. TSN SYSTEM MODEL

Our TSN model is implemented in the OPNET simulator. OPNET [17] is a powerful tool for the modeling and performance evaluation of various network environments. This simulation platform is a discrete event-based simulator. OPNET evolves constantly to support a wider range of network protocols and technologies.

A. TSN Configuration Parameters

As explained in section III, a TSN switch needs the TT flow specifications and corresponding GCL to police and shape incoming TT frames at certain time instants. We define TT stream parameters and GCL in XML format using two separate configuration files and provide them as inputs to the switch model. Each TT flow is identified using the following parameters: 1) Source port: It specifies the port at which TT frames are arriving. 2) Phase: It defines a time instant at which the switch expects that a TT flow reception starts. This value is an offset in the range of [0, flow's period]. 3) Period: Each TT stream would receive and transmit periodically. This value defines the period time. 4) Transmission window: In TSN, a TT flow can be comprised of more than one Ethernet frame. Thus, this parameter specifies how long the arrival of TT frames could continue. 5) VLAN ID: It determines a VLAN identifier in IEEE802.1Q header. 6) Destination ports: For a TT flow, we need to know the route from a sender to the receiver in addition to the arrival time. Therefore, this parameter lists egress ports.

It is noteworthy that we follow the flow isolation constraint introduced in [18] to define TT flows. Based on this constraint, it is not feasible to have two TT streams forwarded from the same port with overlapping transmission times. We define our GCL off-line considering 802.1Qbv constraints such as link constraints and end-to-end constraints proposed in [1]. The GCL is specified for each egress port separately and contains the following parameters: 1) Queue mask: This attribute specifies the state of each queue's gate during the period between start and end time parameters. For instance, consider 10000000 as a queue mask while start and end time are set to 0 and 10 microseconds respectively. This means the queue number 7 (i.e. TT queue in our TSN switch) would be open and enabled to transmit traffic at any time between 0 and 10 microsecond. All other queues are closed in the defined period. Each port-specific GCL runs over a period that is assigned to the least common multiple of all the TT flow periods destined to that port. Furthermore, at all TSN switches the GCL begins simultaneously. To make this possible, all switches must be synchronized to the global time. All time parameters mentioned in the above configuration files are relative to the start of the simulation time.

B. TSN Switch

As TSN aims to incorporate TAS and time-based ingress policing to the existing queuing and scheduling scheme of the regular switch, we extends the standard bridge's dispatch and relay processes to implement a 802.1Qbv and 802.1Qci-capable switch. TAS must be applied to egress port queues. In our simulation framework the local clocks of all nodes including switches and end systems are synchronizing to the global clock (i.e. simulation time) on the predefined rate. In addition, each switch's clock has own constant clock drift. In our implementation, the MAC-relay unit calls the time-aware-ingress-filtering function before enqueuing messages to the correct egress queue. This function first specifies the message type with the help of packet information such as the incoming port, VLAN ID and outgoing ports. Then, if the traffic type is TT, it makes a decision about the message transmission. If the frame belongs to a TT flow that is expected to arrive at the current local time (i.e. local simulation time), the function enqueues the message to the corresponding TT queue. The TSN switch model starts dequeuing TT frames right after enqueuing. In the counter case, if a TT frame arrives outside its transmission window, the filtering function would drop the TT frame. Consequently, this function protects the switch from the faulty devices that are trying to manipulate TT frames or flood the network with unexpected TT flows.

Another key component of the TSN switch is the time-aware shaping function. In the MAC-relay unit, the dequeuing module specifies which queue is eligible to transmit the next packet. This selection is done based on the switch's queuing policy. In our TSN switch, each egress port has 8 queues. There is a strict priority scheme between a TT queue (i.e. queue number 7) and the remaining queues. As a following step, the time-aware shaping function checks whether the gate of the selected queue is enabled. If the queue's gate is open according to the predefined GCL, the required time for the packet transmission is checked against the period of the corresponding gate. If the time is sufficient for transmission, the packet would be dequeued and sent out immediately. This check is performed to prevent initiating a non-TT frame transmission in its own time slot and continuing it over a TT time slot. To guarantee deterministic behavior of the TSN switch, a fixed time slot called guard band is reserved before each TT time slot. The guard band is usually set to the required time for forwarding the Ethernet frame with the maximum length (i.e. 1526 bytes). This approach is not optimized in terms of the bandwidth usage. Therefore, we use the dynamic guard band (i.e. checking required time for non-TT message transmission against GCL) instead of a static one to improve the link bandwidth utilization. When either a gate is disabled or time is not sufficient, the packet would not be dequeued.

In our switch model, we did not make any changes to the switch's enqueuing and dequeueing functions which are considered as core modules in the mac-relay unit. All necessary functionalities are developed in separate modules and invoked at the appropriate stages in the packet processing and forwarding pipeline. This is the most important reason we believe that our implementation could serve as an optimized and efficient base line for the development of real TSN switches.

C. End System Model

We use the regular Ethernet workstation as an end system. A TSN end system does not require any extra functionality and it just needs to transmit TT messages in a cyclic period according to the static schedule. This is implemented by means of traffic profile definitions.

VI. SIMULATION AND EVALUATION

Our proof-of-concept focuses on multi-hop switched Ethernet network in which all nodes are interconnected with full-duplex 10 Gbps links. Our simulation runs on PC hardware with two cores of 2.4 GHz and 32GB memory.

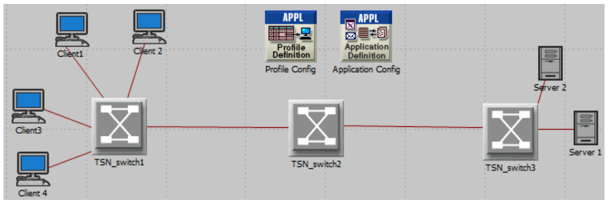
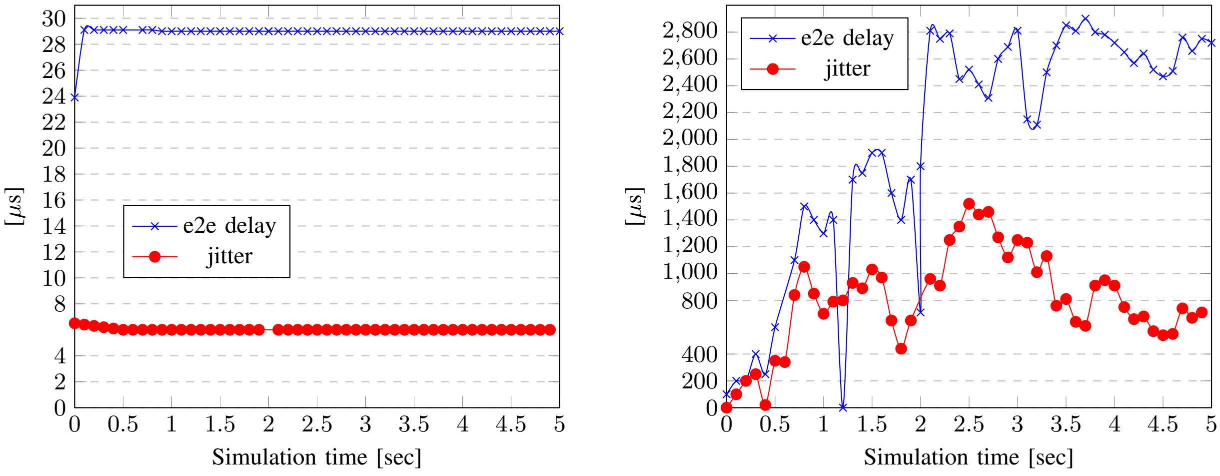


Figure 1: Network with three TSN switches

To evaluate our TSN simulation framework, we define different network topologies and configurations and analyze the data gathered from each simulation run. Since a TSN switch transmits AVB streams and BE traffic when there is a sufficient bandwidth on the outgoing link, without loss of generality, we consider all frames in our framework to be either TT messages or BE traffic.

TAS is developed to provide temporal isolation for safety-critical application regardless of other TT flows and BE traffic load which share the same physical infrastructure. We verified the expected behaviors with help of the following use cases. For these use cases as shown in figure 1, we define a network in which 3 TSN switches are interconnected linearly and form a VLAN-aware network.

In the first scenario, we send a TT flow from client1 to server1 while one BE stream (with 40 % load of link bandwidth) is transmitted from client2 to server2. The TT frames schedule for every 100 milliseconds but the transmission window is only 200 microseconds. We set clock drifts of 100, 200 and 300 PPM for TSN switch1, TSN switch2 and TSN switch3 respectively. The local clock of each switch is synchronized to the simulation time every 100 milliseconds. We run the simulation with and without our time-aware shaper module to evaluate the impact of TAS on the end-to-end delay and jitter of TT flows. As the graphs in figure 2 depict, with the TAS module the delay of the TT flow transmission decreases dramatically (from a maximum of 2850 microseconds to 29 microseconds) and remains fixed. In a similar way, the jitter of scheduled traffic was reduced considerably (from a maximum of 1500 microseconds to 6.5 microseconds) and stabilized using TAS. We repeat the simulation with different loads of BE traffic and compare the results with each other in figure 3. As expected, the maximum end-to-end delay and delivery variation for the TT stream is constant and



(a) delay and jitter of TT traffic in presence of TAS

(b) delay and jitter of TT traffic in absence of TAS

Figure 2: Effect of time-aware shaper on scheduled traffic transmission

is not affected by the BE traffic load.

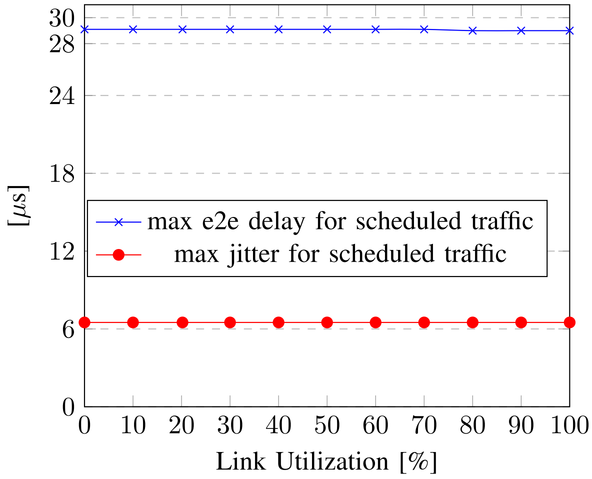


Figure 3: Effect of different BE loads on TT traffic

In the second use case, we define two more TT streams dispatched from client3 and client4 with a schedule of 100 and 200 milliseconds. The transmission windows of these three TT streams do not overlap and follow the flow isolation constraints. Therefore, the egress interleaving in the TT queue of switch1 is eliminated. The results show the new TT flows do not affect the end-to-end delay and jitter of the existing TT stream.

VII. CONCLUSION

This paper presented the simulation framework for IEEE 802.1Qbv and 802.1Qci capable networks. These protocols are seen as necessary elements for providing temporal isolation in TSN. Since TSN is proposed as a comprehensive standard to support a wide range of existing and future industrial control networks (e.g. automotive networks) and there are no real TSN switches available in the market, we developed our switch model to evaluate and verify behaviors of TAS and ingress time-based filtering. The evaluation of results derived from different network setups and TT communication configurations validate that the aforementioned protocols provide the strict timing requirements for mission-critical applications.

We also specified the necessary parameters for ingress time-aware policing and TAS in XML based configuration files. This configuration approach provides us with an effective way to define different network configurations. In this work, we established the IEEE 802.1Qbv and 802.1Qci-capable switch model with minimal modifications to standard Ethernet switch models. We introduced our implementation of TAS and time-based filtering in the separate modules and added them in appropriate phases in the packet processing and forwarding pipeline of the switch. Therefore, this approach can be easily used in different vendor-specific switches to cover time-based features of TSN.

VIII. ACKNOWLEDGMENT

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