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Evaluation of Real-Time Ethernet with Time Synchronization and Time-Aware Shaper Using OMNeT++

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Abstract—**Packet-switch Ethernet has been considered as a future communication standard for automotive and industrial applications because of its compatibility, scalability and high speed. However, many real-time systems in these domains need predictability which traditional packet-switch Ethernet does not support. Time-Sensitive Networking (TSN) is an upcoming set of standards aiming to provide deterministic services such as guaranteed packet transport with bounded low latency, low jitter, and low packet loss. In this paper, we present an OMNeT++ simulation model to simulate TSN time-based features. We provide a realistic clock-drift model and apply it to a distributed embedded system. Moreover, we utilize time synchronization and time-aware shaper to implement a high-accuracy scheduling. The simulation results show that the aforementioned protocols provide predictability for the system.**

Keywords-TSN; time synchronization; time-aware shaper; deterministic network; OMNeT++

I. INTRODUCTION

Packet-switch Ethernet has been widely deployed in civilian fields and will be used in future automotive and industrial domains as traditional fieldbuses like CAN or MOST cannot keep pace with the increasing bandwidth and the compatibility requirements of aforementioned domains. However, packet-switch Ethernet cannot provide reliable temporal performance boundary. Real-time extensions to Ethernet promise to overcome those obstacle [1].

TSN is the latest real-time Ethernet extension which is the successor of IEEE audio video bridging (AVB) [2][3]. AVB introduced credit-based shaper to make sure that specified traffic classes such as video and audio streams do not exceed predefined bandwidth boundary. AVB cannot solve problems caused by channel congestion, as a result, it is not able to fulfill the requirement of safety-critical (hard real-time) systems with strict timing constraints. TSN aims to focus on the uncovered areas in AVB, e.g., new traffic shaper for deterministic end-to-end latency and jitter, novel time synchronization mechanism for large-scale network with high-accuracy, seamless redundancy for security.

To evaluate the feasibility of the novel communication standard for next-generation automotive and industrial applications, it is necessary to make a detailed analysis and comparison between TSN and traditional packet-switch Ethernet. Discrete event simulator is a suitable tool for an essential evaluation. Furthermore, an initial approximate configuration of the network can be made according to the simulation result. The optimization of the network depends on the actual application environment.

The contribution of the paper is a network simulation model for TSN that implements time synchronization and time-aware shaper in the OMNeT++ [4]. The model that extends the traditional Ethernet controller to TSN Ethernet controller not only supports strict temporal requirements but also has a compatibility with traditional Ethernet.

The rest of this paper is organized as follows. In section II, related work is discussed. Section III introduces how time synchronization works. Section IV gives a brief overview of the time-aware shaper. Section V gives details about the implementation of the proposed model. Evaluation and analysis are placed in section VI. The last section concludes the paper.

II. RELATED WORK

To date, few simulation models have been developed for the evaluation of real-time network. Paper [1] presents a simulation model for TTEthernet [5]. TTE adopts different time synchronization mechanism and time-aware shaper from TSN. However, TSN is more comprehensive than TTE, for example, asynchronous communication in TTE is not optimized. TsimNet [6] implements frame preemption and partial redundancy mechanism which are sub-protocols of TSN. Instead, we pay more attention to time-based features. The authors in [7][8] evaluate time-aware shaper of TSN using discrete event simulator regardless of clock drift in reality. To our best knowledge, there is no simulation model focusing on the performance of TSN's time-based scheduler in reality.

III. TIME SYNCHRONIZATION

Critical tasks in hard real-time system have to be processed within a defined time interval by predetermined scheduler. A failed reception beyond the time boundary at the receiving end may cause serious accidents in reality. On the other hand, it will be extremely costly to equip each node in a distributed embedded system with a GPS or an atomic clock. Therefore, precise time synchronization mechanisms are developed for low-cost applications.

NTP [9] is a widely used protocol in the Internet because of its hierarchy structure and millisecond synchronization

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accuracy. However, it is not sufficient even for soft real-time systems. The principle of PTP [10] is similar to NTP, but it provides alternative hardware support to meet microsecond accuracy. IEEE 802.1AS [11] generalized Precision Time Protocol (gPTP) is an improved standard for TSN which achieves nanosecond accuracy because of its specialized implementation in the 802.3 (Ethernet) and 802.11 (Wi-Fi) standards based on PTP [12].

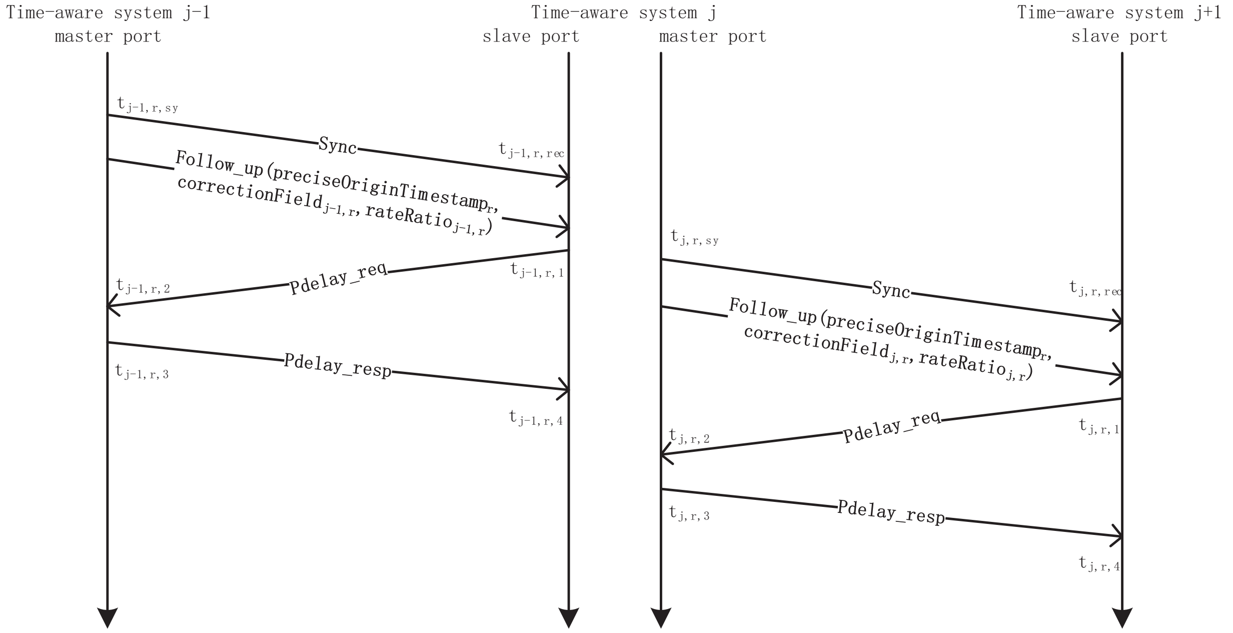

Figure 1. Transport of time-synchronization information.

A. *Architecture of a Time-Aware Bridged Local Area Network Based on gPTP*

A set of time-aware systems that are interconnected by gPTP-capable LANs is called a gPTP domain. There are three types of time-aware systems, as follows:

- A grandmaster which provides initial clock and sends synchronization messages periodically through its sole master port. Here, we adopt simplified gPTP without best master clock algorithm because we do not consider network link failure, therefore, the grandmaster is predetermined and fixed in a gPTP domain.
- Multiple slaves receiving synchronization messages through their respective slave ports.
- Several bridges that comprise sole slave port connected to the master port of another time-aware system and possibly other types of ports like master port, passive port or disabled port.

B. *Synchronization Procedure*

The time synchronization on a full-duplex, point-to-point link in the gPTP domain is the same as the synchronization in case of a PTP boundary clock that uses the peer delay mechanism [11]. Fig.1 shows three adjacent time-aware systems, indexed j–1, j, and j+1, in the synchronization cycle r. The whole gPTP domain is a cascaded system. Time-aware system j receives synchronization information from upper level, computes its own correctionField$_{j,r}$ using Eq.1, relays it to low levels with rateRatio$_{j,r}$ and preciseOriginTimestamp$_r$ which is the precise origin timestamp from grandmaster.

$$correctionField_{j,r} = correctionField_{j-1,r} + transmissionTime_{j-1,r} + propagationTime_{j-1,r} + resideTime_{j,r} \quad (1)$$

The transmissionTime is calculated using Eq.2:

$$transmissionTime_{j-1,r} = packetSize[bit] / dataRate[bps] \quad (2)$$

The resideTime is the sum of processing time and interval between Sync and Follow_up. The propagationTime$_{j-1,r}$ is computed by Pdelay_req and Pdelay_resp of the last synchronization cycle r-1 using Eq.3:

$$propagationTime_{j-1,r} = (\, t_{j-1,r-1,4} - t_{j-1,r-1,1}\,) \cdot rateRatio_{j,r} / 2 \; - \; (\, t_{j-1,r-1,3} - t_{j-1,r-1,2}\,) \cdot rateRatio_{j-1,r} / 2 \quad (3)$$

Because of respective frequency drifts of different time-aware systems, the time counted by different time-aware systems should be corrected on the basis of the frequency of grandmaster according to the ratio of cascaded multiplication and the periodicity of gPTP synchronization mechanism using Eq.4:

$$rateRatio_{j,r} = rateRatio_{j-1,r} \cdot (t_{j-1,r,sy} - t_{j-1,r-1,sy}) / (t_{j-1,r,rec} - t_{j-1,r-1,rec}) \quad (4)$$

Finally, the clock of time-aware system j is synchronized to the grandmaster using Eq.5:

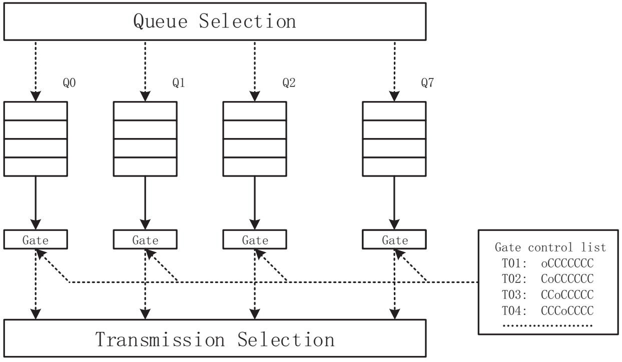

Figure 2. Transmission selection with gates.

$$TimeSynced_{j,r} = preciseOriginTimestamp_{r} + transmissionTime_{j\text{-}1,r} + correctionField_{j\text{-}1,r} + propagationTime_{j\text{-}1,r} \quad (5)$$

We can figure out the synchronization error by means of a subtraction of the $\text{TimeSynced}_{j,r}$ from the local time.

IV. Time-Aware Shaper

Hard real-time systems need a highly predictable data delivery in terms of time. For example, end-to-end latency and jitter must be bounded. Generally, safety-related control frames in automotive applications are dispatched on a repeating time scheduling. However, prioritization (QOS) introduced in IEEE 802.1Q [13] cannot guarantee that safety-related control frames can be received by listeners at the right time, because higher priority frame may be blocked by lower priority frame. Frame preemption can only reduce blocking time [14]. TSN's time-aware shaper [15] uses time-driven scheduler which sacrifices a part of bandwidth utilization for predictability to dispatch ingress traffic.

As the Fig.2 shows, Queue Selection unit places traffic classes into respective first-in first-out (FIFO) queues according to VLAN priority by default. The gate states change on the basis of time-based gate control list (GCL). They determine at each instant of time which queue can be scheduled by Transmission Selection unit. The gate control list makes it possible to transmit frames along the associated route with low latency by having the correct gate open alone which called protected window. To guarantee deterministic behavior, a guard band should be placed before the protected window. For the worst case, the guard band must cover the time that the maximum size frame transmission takes without frame preemption mechanism. The Transmission Selection unit pulls one frame each time form the non-empty queue with the highest priority in the open state.

V. Implementation Details

OMNeT++ is an extensible, modular, component-based network simulator. Our simulation model extends INET framework [16] which is an open-source OMNeT++ model suite for wired, wireless and mobile networks and introduces new time-based features on top of it. The main components are depicted in Fig.3.

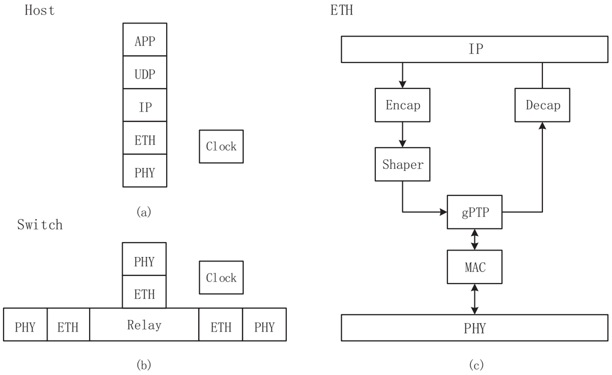

Figure 3. (a) The TSN host compound module, (b) The TSN switch compound module, (c) The TSN Ethernet controller compound module.

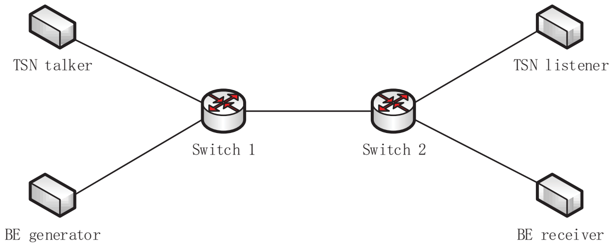

Figure 4. Topology of the TSN simulation model.

A. TSN Switch Module

The most significant difference between traditional Ethernet and TSN is explicit identification, policing and shape of individual streams in the Ethernet controller of switch. These streams are classified as three types: Time-Triggered (TT) traffic, AVB traffic and Best Effort (BE) traffic. The classification method can be based on either MAC address, VLAN, IP address or their logical operation. Our switch module identifies TT traffic according to VLAN priority and pushes it into pre-defined queue. Considering the synchronization error, the gate control list is initialized at the time of the reception of Follow_up frame. The bandwidth allocation is pre-defined in the gate control list and depends on actual application environment.

TABLE I. Network Configuration

Traffic	**Parameter**			
	Start time	***Line load***	***Packet length***	***Priority***
TT	0.001005s	0.01176	1400B	0
BE	0.0025s	0.998	500B	1

B. TSN Host Module

TSN host is similar to standard host. The only difference between them is the Encap and Decap module inside the Ethernet controller because of their different frame format.

C. Time Synchronization Module

In order to provide each node with different clock deviation property and evaluate the performance of gPTP, we adopt the module proposed by [17] as local clock. In accordance to the gPTP standard, timestamp is marked at the date link layer for minimum deviation. Therefore, we locate the time synchronization module between the shaper and the MAC controller of each Ethernet controller. Additional bandwidth for gPTP frames should be reserved.

VI. Simulation and Evaluation

In this section, we investigate the synchronization accuracy and the predictability of TT traffic under the influence of cross BE traffic using aforementioned model. We consider the topology depicted in Fig.4 which contains a TSN talker, a BE generator, their respective receivers and two TSN switches interconnected by full-duplex 1Gbps wired links with 250ns delay. The BE generator is not covered by gPTP domain and congests the network with high-load BE traffic for the worst-case scenario. The detailed network configuration is listed in Table I.

TABLE II. Bandwith Allocation

	One loop (1ms)			
	Sync	***Protected***	***Unprotected***	***Guard***
GCL	cccccccc	occccccc	cooooooo	cccccccc
Interval	5us	15us	965us	15us

TABLE III. Simulation Result

Scenario	**Simulation time (10s)**			
	End to end delay (TT)		***Synchronization deviation***	
	Maximum	***SD***	***Mean***	***Maximum***
TSN	3.57e-5s	0s	1.13e-10s	4.52e-9s
QOS	4.03e-5s	1.48e-6s	1.37e-6s	5.23e-6s
Non-QOS	0.046s	0.015s	1.79e-6s	2.12e-5s

To evaluate the proposed model, three scenarios are considered. TSN places time-aware shaper in Switch 1 and configures it with the content listed in Table II. QOS cancels the restriction of the gate control list while traditional Ethernet only have a single FIFO queue with finite length (Non-QOS). Also, we assume the maximum drift rate of the local clock is 100 ppm and the synchronization period of gPTP is 1ms.

The results are shown in Table III. The third scenario with no shaper shows that the BE traffic blocks the TT traffic and synchronization information frames severely which causes high latency of TT traffic and microsecond synchronization deviation. Once prioritization comes into effect, the transmission quality of TT traffic has been greatly improved. However, the jitter and the synchronization accuracy are still needed to be optimized. The time-aware shaper brings predictable transmission with high accuracy to time-critical traffic at the cost of partial bandwidth.

VII. Conclusions

In this paper, we proposed a TSN simulation model for OMNeT++ that implements gPTP and time-aware shaper. These protocols are seen as necessary elements for providing temporal features in TSN. The evaluation of results derived from different scenarios validates that the temporal features in TSN meet the strict timing requirement of safety-critical systems. In future work, we will investigate static schedule table generation algorithms for load balancing in specific applications.

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