QoS Estimation of In-vehicle Ethernet with CBS and TAS by Multiple Regression Analysis

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***Abstract*—This paper evaluates the QoS of an in-vehicle network with CBS and TAS, one of the QoS controls defined in IEEE 802.1TSN standards, by experiment. The next-generation in-vehicle network uses Ethernet, which can provide high-speed transmission, and adopts IEEE 802.1TSN to support time-sensitive data transmission over Ethernet. In Ethernet-based in-vehicle networks, many devices are integrated, and then various data are transmitted over the network. Consequently, the design of an Ethernet-based in-vehicle network is not easy. Thus, QoS estimation of an Ethernet-based in-vehicle network is required. This study targets QoS estimation by multiple regression analysis for Ethernet-based in-vehicle networks with CBS and TAS, which are major QoS controls among controls of IEEE 802.1TSN. From the results of experiments by simulation, the authors show that QoS can be estimated accurately by the obtained estimation equations.**

***Index Terms*—QoS, in-vehicle network, TSN, CBS, TAS**

I. INTRODUCTION

Next-generation in-vehicle networks will utilize Ethernet, which can process vast amounts of data at high speed. Furthermore, since it is necessary to guarantee QoS for time-constrained data, the introduction of IEEE 802.1TSN[1], which emphasizes real-time performance over Ethernet, will also be used.

IEEE 802.1TSN standards have a variety of QoS controls, and the QoS provided by each control depends on the network environment. This makes it challenging to design an appropriate in-vehicle network. Therefore, it is necessary to evaluate the QoS of the in-vehicle network easily. Especially among IEEE 802.1 standards, the combination of CBS and TAS is considered a major control; evaluating QoS over in-vehicle Ethernet combined CBS and TAS is strongly required.

As the QoS mentioned above estimation, [2] proposes an estimation method to estimate QoS using multiple regression analysis, which can be adopted regardless of the network environment. By the method, [3] evaluates the QoS of TAS, [4] evaluates the QoS of FP. However, the method's effectiveness has yet to be inspected for in-vehicle Ethernet with the combination of CBS and TAS.

This paper confirms the effectiveness of the QoS estimation method by multiple regression analysis proposed in [2] for an in-vehicle network with the combination of CBS and TAS by experiment. This experiment is performed using simulation.

This paper is organized as follows. Sections II introduces CBS and TAS, respectively. We show our experiments in Sect.IV, and discuss the results in Sect.V. Finally, we conclude our paper in Section VI.

II. CREDIT-BASED SHAPER AND TIME-AWARE SHAPE

CBS performs priority control based on a variable called $Credit$. The rate of $Credit$ increase is defined as $idleSlope$, while that $Credit$ decrease is defined as $sendSlope$. When the $Credit$ in the queue is greater than or equal to 0, the $Credit$ value is decreased according to $sendSlpoe$ as soon as the stored frame is sent. When the $Credit$ value is less than 0, it waits until the $Credit$ value is equal to or greater than 0, according to $idleSlope$. When all stored frames are sent from the queue, that is, the queue becomes empty, the $Credit$ value is 0.

TAS acts as a gate for a queue and opens or closes this gate to enable or disable output from the queue. The gates of the TAS control their state based on a list called the Gate Control List. The GCL specifies the opening time of each gate, which opens at the time indicated by "o" and closes during the time displayed by "C". The time required to execute one round of GCL is called a gating cycle.

III. QOS ESTIMATION WITH MULTIPLE REGRESSION ANALYSIS

In the QoS estimation proposed in [2], the estimation equation is derived using configurable parameters such as traffic frame length as independent variables and the target QoS parameters as a dependent variable. Let us show an example of the estimation equation in Eq.1

$$\tilde{L} = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \cdots + \alpha_n x_n \tag{1}$$

where $x_k (0 < k < n + 1)$ is an independent variable,$\tilde{L}$ is QoS, α_0 is an intercept, and α_k is the k-th multiple regression coefficient. This estimation applies to any network since it does not take the configuration of the in-vehicle network as information.

IV. EXPERIMENTS

A. Experimental Environment

To use QoS estimation in [2], we must first decide on QoS parameters as independent variables. At this time, since we can remove insignificant parameters later, we can adopt as many QoS parameters as possible. Firstly, the frame size of traffic is considered to have a significant effect on QoS. Therefore, we adopt the mean frame size(bit), the minimum frame size(bit), the maximum frame size(bit), and the variance of frame size(bit^2) as independent variables. Secondly, since a general in-vehicle, Ethernet has many switches, we consider the number of hops and the number of TAS controls.

Next, we must also define a dependent variable, a QoS parameter to be estimated. Since real-timeness is important in time-sensitive in-vehicle networks, we consider the delay as a dependent variable. This paper treats the mean delay and the maximum delay. As a result, Eq. (2) and Eq. (3) show the QoS estimation equations for the mean delay $\tilde{L}_{mean}$ and that for the maximum delay $\tilde{L}_{max}$, respectively.

$$\begin{aligned}\tilde{L}_{mean} =&\alpha_0 + \alpha_1 l_ave + \alpha_2 l_max + \alpha_3 l_min \\ &+ \alpha_4 k + \alpha_5 h + \alpha_6 \sigma^2\end{aligned} \tag{2}$$

$$\begin{aligned}\tilde{L}_{max} =&\alpha_0 + \alpha_1 l_ave + \alpha_2 l_max + \alpha_3 l_min \\ &+ \alpha_4 k + \alpha_5 h + \alpha_6 \sigma^2\end{aligned} \tag{3}$$

Here, the variables used in Eq. (2) and Eq. (3) are listed in Table I.

TABLE I
PARAMETERS IN EQUATIONS

$\tilde{L}_{mean}$	Estimated mean delay
$\tilde{L}_{max}$	Estimated max delay
k	Number of TAS
l_ave	Mean frame size of the traffic for evaluation(bit)
l_min	Minimum frame size of the traffic for evaluation(bit)
l_max	Maximum frame size(bit)
h	Number of hops
σ^2	Variance of framesize(bit^2)

B. Environment

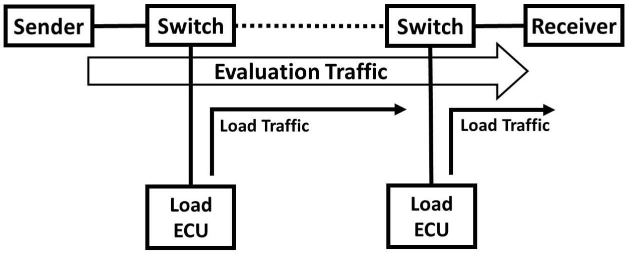

Fig. 1. Experimental Network

This experiment treats a multi-hop in-vehicle network based on a use case in IEEE P802.1DG[5], standardizing automotive network profiles. The network is shown in Fig. 1. The network consists of three types of ECUs(sender, receiver, and load ECUs) and multiple switches. Each switch performs priority control by CBS and TAS on its egress port. Here, we change the number of controls by TAS depending on the environment. This experiments use two types of traffic, traffic for evaluation and traffic for load. The sender generates traffic for evaluation, which has high priority, and the load ECU generates traffic for load, which has low priority. Under all experimental environments, the traffic for evaluation has a priority of 7, 6, and 5, while the traffic for load has a priority of 2, 1, and 0. The delay is measured while varying the transmission rate and frame size both of the traffic for evaluation and the traffic for load. The ECUs and switches are connected via 100BASE-T1, one of the Ethernet standards for in-vehicle networks. This experiment consists of the following two experiments: Experiment A and Experiment B. The experimenter evaluates QoS of traffic for evaluation while transmitting traffic for load. In Experiment A, estimation equations for the mean and maximum delays are obtained using traffic with fixed frame size and fixed transmission rates. Here, we would like to explain why we use traffic with fixed frame length and fixed frame interval in Experiment A. We recognize that QoS depends on the distribution of frame length and frame interval. Although challenging, we can perform our QoS estimation at a low cost if we get QoS estimation with fixed traffic. On the other hand, in Experiment B, traffic with random frame size, random transmission rate, and random transmission interval is used to evaluate the obtained equations in Experiment A. In IEEE P802.1DG, up to a hop count of 7 for multi-hop networks is considered. Thus, this study treats experimental networks with hop counts of 3, 5, and 7.

V. EXPERIENTAL RESULTS

A. Experiment A

From the results of Experiments A and B, we got an estimation for the mean and maximum delays shown in Eq. (4) and Eq. (5), respectively

$$\begin{aligned}\tilde{L} =&(7.21 \times 10^2 + 5.41 \times 10^2 \times h) \\ &+ (-3.31 \times 10^2 - 2.84 \times 10^2 \times h)k \\ &+ (-3.20 \times 10^{-1} + 2.19 \times 10^{-1} \times h)l_ave \\ &+ (-5.12 \times 10^{-3} + 7.78 \times 10^{-4} \times h)l_min \\ &+ (1.43 \times 10^{-1} + 1.31 \times 10^{-1} \times h)l_max \\ &+ (1.50 \times 10^{-5} + 1.36 \times 10^{-5} \times h)\sigma^2\end{aligned} \tag{4}$$

In the same way, Eq.(5) was obtained as the expression for the maximum delay L_{max}.

$$\begin{aligned}\tilde{L} =&(1.07 \times 10^3 - 3.01 \times 10^{-2} \times h) \\ &+ (-4.59 \times 10^{-2} + 7.08 \times 10^{-1} \times h)k \\ &+ (-6.10 \times 10^{-1} + 1.77 \times 10^{-1} \times h)l_ave \\ &+ (-1.37 \times 10^{-1} + 2.21 \times 10^{-2} \times h)l_min \\ &+ (2.29 \times 10^{-1} + 1.85 \times 10^{-2} \times h)l_max \\ &+ (1.93 \times 10^{-6} + 2.67 \times 10^{-6} \times h)\sigma^2\end{aligned} \tag{5}$$

The coefficients of k in Eq. (4) and Eq. (5) quantitatively mean the effect of the number of TAS. The estimated values obtained by Eq. (4) and Eq. (5) are shown in Fig. (2) and Fig. (3), respectively. In the figures, the abscissa indicates the measured value while the ordinates the estimated one. The adjusted degree of freedom of multiple correlation coefficients between the measured and estimated values are 0.847 and 0.844. This indicates that the estimation is effective. To valuate of the estimation the effectiveness quantitatively, we compared the delay between the actual measurements obtained in the Experiment B environment and the estimates obtained by the equation.

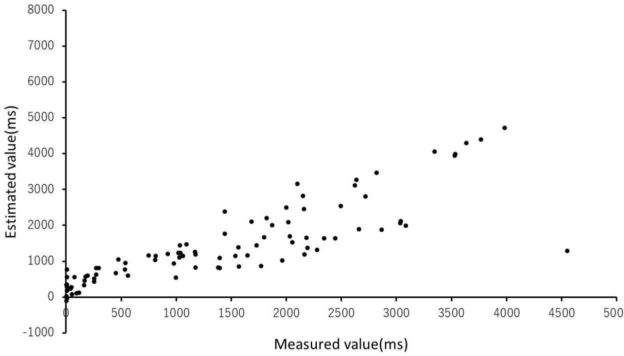

Fig. 2. Estimated value vs measured value(mean)

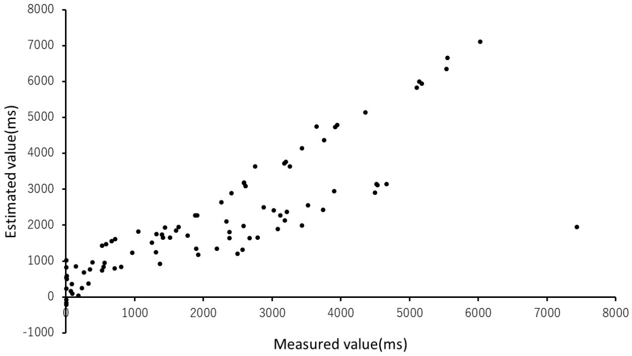

Fig. 3. Estimated value vs measured value(max)

B. Experiment B

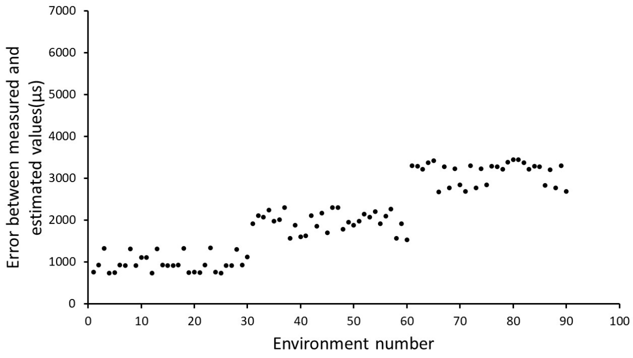

Fig. 4. Difference between measured and inferred values (mean)

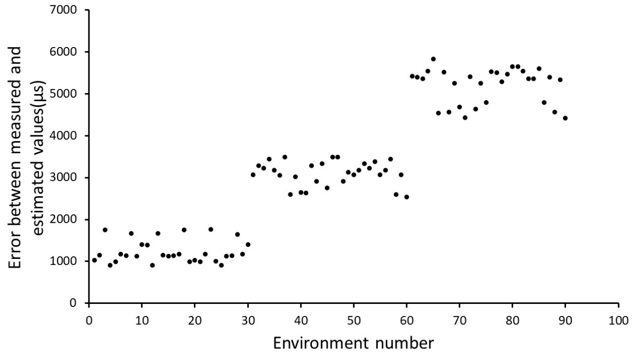

Fig. 5. Difference between measured and estimated values (max)

Figures 4 and 5 display the results of Experiment B. Figures 4 and 5 show the results from obtained Eq. (4) and Eq. (5), respectively. In these figures, the abscissa indicates the experimental environment, and the ordinate means the difference between the estimated value and the corresponding obtained one. The following table shows the environment number on the horizontal axis, the number of hops, and the variance of the error. Table II shows the label of environments. In addition to Figs. 4 and 5, Table II shows that the larger the hop count, the more significant the difference between the estimated and measured values. This means that the delay is highly dependent on the number of hops. We also see that the variance of the difference between the estimated and measured values becomes more significant for the maximum delay than for the mean delay. That is, the maximum delay is more difficult to estimate. Furthermore, Table II indicates that the variance with the same hop count is smaller than the total variance. This means the difference varies greatly depending on the number of hops. Therefore, a more accurate estimation can be achieved using a separate equation for each hop number.

TABLE II
EXPERIMENTAL ENVIRONMENTS

environment	the number of hops	the variance(mean)	the variance(max)
from 1 to 90	3 and 5 and 7	6.1×10^3	2.3×10^5
from 1 to 30	3	4.5×10^3	7.4×10^4
from 31 to 60	5	4.8×10^3	8.9×10^4
from 61 to 90	7	3.7×10^3	1.8×10^4

VI. CONCLUSIONS

This paper studied QoS estimation by multiple regression analysis for a multistage in-vehicle network when CBS and TAS are used. The proposed estimation equation is significant with a degree of freedom adjusted multiple correlation coefficient of more than 0.83. The estimation equation quantitatively shows the effect of TAS on latency. Furthermore, the estimation equation was able to confirm the versatility of the estimation equation because the multiple correlation coefficient was estimated to be high even in an environment using real data. Our future works include evaluation using more traffic, evaluation with an increased number of switches to which TAS is applied, and evaluation in actual in-vehicle networks.

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