Worst Case Communication Delay of Real-Time Industrial Switched Ethernet With Multiple Levels

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***Abstract*—The industrial network, often referred to as fieldbus, becomes an indispensable component for intelligent manufacturing systems. Thus, in order to satisfy the real-time requirements of field devices such as sensros, actuators, and controllers, numerous fieldbus protocols have been developed. But, the application of fieldbus has been limited due to the high cost of hardware and the difficulty in interfacing with multivendor products. As an alternative to fieldbus, the Ethernet (IEEE 802.3) technology is being adapted to the industrial environment. However, the crucial technical obstacle of Ethernet is its nondeterministic behavior that cannot satisfy the real-time requirements. Recently, the switched Ethernet becomes a very promising alternative for real-time industrial application due to the elimination of uncertainties in Ethernet. This paper focuses on the application of the switched Ethernet with multiple levels (that is, cascade structure with multiple switching hubs) for real-time industrial networking. More specifically, this paper presents an analytical performance evaluation of the switched Ethernet with multiple levels from timing diagram analysis, and experimental evaluation from an experimental testbed of networked control system.**

***Index Terms*—Fieldbus, industrial network, network delay, networked control system (NCS), real-time requirements, switched Ethernet.**

I. Introduction

RECENTLY, the real-time industrial network has become an important element for intelligent manufacturing systems. Especially, as the systems are required to be more intelligent and flexible, the systems should have more field devices such as sensors, actuators, and controllers. As the number of field devices in manufacturing systems grows and the functions of the system need to be more intelligent, these devices need to exchange the rapidly increasing amount of data among them. Conventionally, these devices are connected with point-to-point or direct connections where each pair of devices requires at least one electrical cable. This approach is not suitable any more for the system composed of many devices because the number of cables is proportional to the square of the number of devices. As an alternative to the point-to-point connections, an industrial network has been adopted where various data can be exchanged via a shared transmission medium. Because the industrial network has more advantages than the direct connection such as reduction of wiring and ease of maintenance, its application areas have grown to include various applications such as process automation system, automated manufacturing system, and automated material handling system [1], [2].

On many industrial networks, various data types, that are real-time and nonreal-time data, are sharing a single network even though they have different real-time requirements. That is, the nonreal-time data need assurance of delivery without error and duplication while the real-time data are concerned mostly on the time taken to reach the destination. Therefore, when building an industrial network, the designer must configure the network to satisfy these requirements.

In order to satisfy the real-time requirements, many industrial networks, often referred to as fieldbus, have been developed by various standard organizations since the late 1980s. Recently, the IEC 61158 fieldbus standard with several protocols including Profibus, Fieldbus Foundation, and WorldFIP was announced as an international standard in the late 1990s [3]. Although the fieldbuses are able to satisfy the real-time requirements of field devices, they suffer from their high hardware and software cost and uncertain interoperability of multiple-vendor systems. These shortfalls are hindering the adoption of fieldbuses in numerous application areas [4].

As an alternative to the fieldbus, Ethernet has attracted some attention because of its simplicity and wide acceptance. However, it has been known that Ethernet is not suitable for industrial networking because the medium access control method of Ethernet, contention-based carrier sensing multiple access/collision detection, exhibits unstable performance under heavy traffic and unbounded delay distribution [5]. Recently, the switched Ethernet shows a very promising prospect for real-time industrial networking because the switching technology using full duplex [6] can eliminate frame collisions. Because the Ethernet without collisions is no longer unstable under heavy traffic and its delay can be drastically reduced, the adoption of switched Ethernet as the real-time industrial network is seriously considered along with the appearance of inexpensive switches [7].

Currently, the switched Ethernet is being adopted as backbone networks for manufacturing systems, as shown in Fig. 1. In the figure, the fieldbus is chosen for exchanging real-time data among sensors and actuators at the device level, while the switched Ethernet is chosen for exchanging nonreal-time data among programmable logic controllers (PLCs) and robots at the cell level, or among industrial computers and database systems at the plant level. In addition, a gateway is used to interconnect

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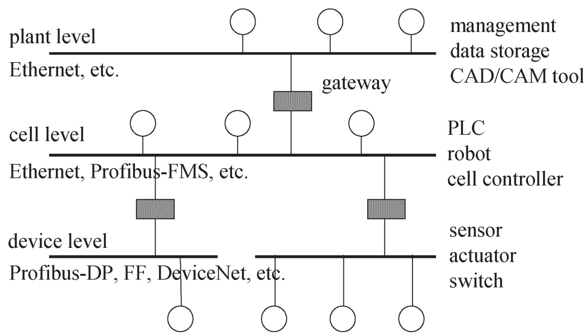

Fig. 1. Layer architecture of industrial network.

the fieldbus and switched Ethernet. In this configuration, the real-time requirements may not be satisfied owing to nonreal-time features of the gateway. The delay created at the gateway may be too large to satisfy the real-time requirement. However, the transmission rate of the switched Ethernet is higher than that of the fieldbus, and development of its nodes is easier due to the Ethernet's mature, low cost, and widely accepted technology. Therefore, if the switched Ethernet is adopted at the lower level, the upper and lower levels can be integrated without a gateway, and the real-time requirements can be satisfied.

To verify that the switched Ethernet can satisfy the real-time requirements at the device level, this paper evaluates the performance of the switched Ethernet with multiple switching hubs. This paper derives the worst case communication delay of the switched Ethernet with multiple levels, and demonstrates the efficacy of the switched Ethernet by examining the performance of a networked control system (NCS) [8], [9].

This paper is organized into five sections including this introduction. Section II gives a brief overview of the switched Ethernet, and Section III presents an analysis of the theoretical worst case communication delay of the switched Ethernet with multiple levels. An NCS with a servomotor is implemented via the switched Ethernet and its control performance is evaluated in Section IV. Finally, the summary and conclusions are presented in Section V.

II. Overview of the Switched Ethernet

IEEE 802.3 [10], often referred to as Ethernet, is developed for data communication among computers in the early 1970s by Institute of Electrical and Electronics Engineers (IEEE), and is the basis of physical and data link layers of the Internet for office communications. In the traditional Ethernet, the hub is a passive device that broadcasts whatever received from source to other stations, which operates as shown in Fig. 2(a). On the other hand, the hub of the switched Ethernet is an active device that identifies the destination ports and relays the frame only to those as shown in Fig. 2(b). This means that if multiple stations are transmitting simultaneously, frames can be delivered without collision as long as their destinations are different from each other. Also, the traditional Ethernet uses half-duplex method while the switched Ethernet uses full-duplex method as the connection method between a station and the hub [6]. This allows a station to transmit and receive frames simultaneously.

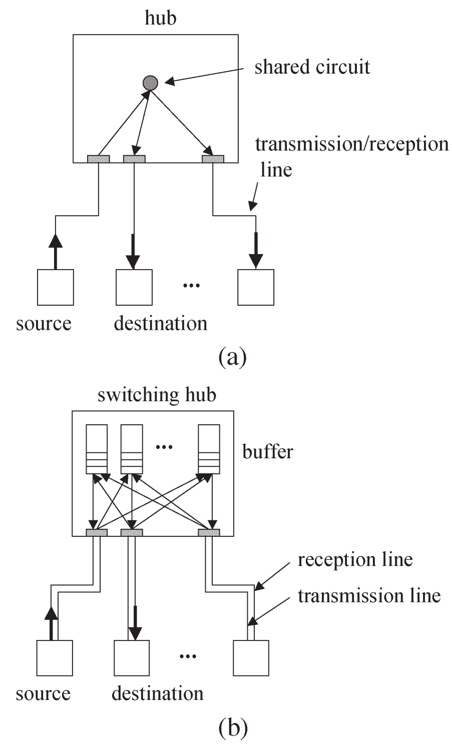

Fig. 2. Comparison of transmission methods of traditional Ethernet and switched Ethernet.

These differences make the switched Ethernet free of frame collisions.

A typical method of switching technology is the store and forward method [11] as shown in Fig. 2(b). In the figure, the switch receives a frame through transmission line from a source station, and then checks if the reception line of a destination station is idle. If the reception line is idle, the switch transmits the frame. Otherwise, the switch stores the frame into its buffer and waits until the reception line becomes idle. In addition, if several frames with the same destination address are received at the switch simultaneously, the switch stores frames to the buffer and then sends frames to the destination one by one.

III. Worst Case Communication Delay of the Switched Ethernet

This paper presents the level architecture of the switched Ethernet with multiple levels, which integrates the upper and lower levels of an automation system and satisfies the real-time requirements, as shown in Fig. 3. In the figure, the switched Ethernet is used as a subnetwork for exchanging data among the sensors, actuators, PLCs, robots, and industrial PCs located in each level of an automation system. In addition, switching hubs are used to interconnect subnetworks in the upper and lower levels.

In order to guarantee the applicability of the switched Ethernet for real-time control, it should be verified whether the worst case communication delay remains below the maximum allowable delay, that is, real-time requirements, under two configurations. The first configuration is two stations exchanging data via one switching hub in a single subnetwork

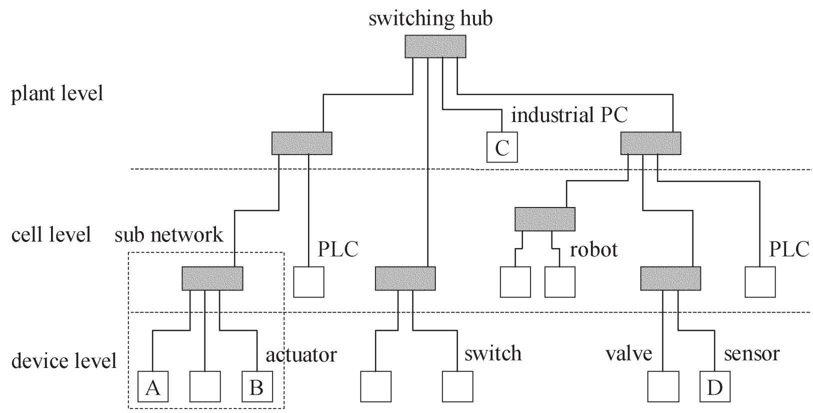

Fig. 3. Layer architecture of industrial switched Ethernet.

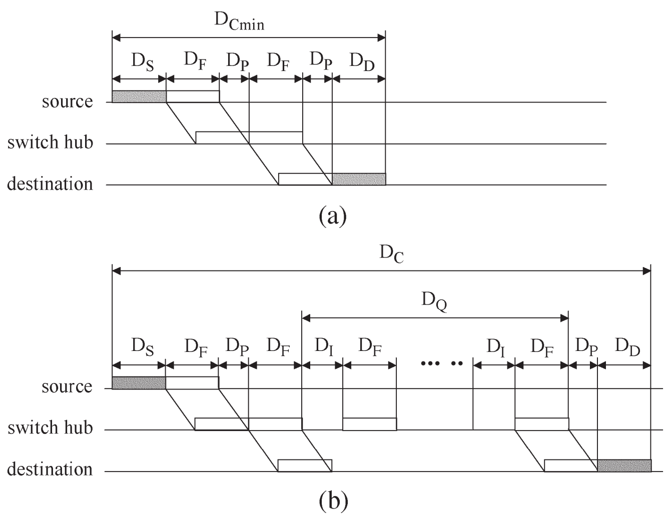

Fig. 4. Communication delay of switched Ethernet with one switching hub.

(e.g., stations A and B in Fig. 3). The second configuration is two stations belonging to two different subnetworks (e.g., station A at the device level and station C at the plant level, or station A and station D in different subnetworks at the device level in Fig. 3).

A. Worst Case Communication Delay of the Switched Ethernet With Single-Switching Hub

First, the worst case communication delay of the switched Ethernet with single-switching hub can be calculated from a timing diagram, as shown in Fig. 4.

In the figure, if a frame is transmitted from the source to the destination directly without being stored in the buffer, the minimum communication delay (D_{Cmin}) can be defined as follows:

$$D_{\mathrm{Cmin}} = D_{\mathrm{S}} + 2(D_{\mathrm{F}} + D_{\mathrm{P}}) + D_{\mathrm{D}} \tag{1}$$

where D_{S} is the processing delay for transmission at the source; D_{D} is the processing delay for reception at the destination; D_{F} is the frame transmission delay, which is defined as the number of bits in the frame divided by the data rate; and D_{P} is the propagation delay as the electrical signal is propagated from the source to the switching hub, which is proportional to the length of the cable connecting the station and switching hub. For example, for a 20-m cable, the propagation delay is about $0.1\ \mu$s at the propagation speed of 2.0×10^8 m/s. In (1), we simply use twice the propagation delay from a station to the hub assuming that the cable lengths are identical for all the stations [6].

Based on our preliminary experiments, D_{Cmin} is dominated by station performance. In a simple experiment with two computers [Pentium 500 MHz with Windows 2000 operating system (OS)] that exchanged the frames with 576 bits (minimum Ethernet length including overhead of 432 bits) on a 10BASE-T Ethernet network, D_{Cmin} was measured to be about 200 μs.

If the frame is stored at the switch, the communication delay (D_{C}) is the sum of D_{Cmin} and its queuing delay (D_{Q}), i.e.,

$$D_{\mathrm{C}} = D_{\mathrm{Cmin}} + D_{\mathrm{Q}}. \tag{2}$$

Here, if the buffer contains N_{Q} frames, D_{Q} can be defined as follows:

$$D_{\mathrm{Q}} = \sum_{k=1}^{N_q} D_{\mathrm{I}} + \max(L_k + L_h, 576) \times t_{\mathrm{b}} \tag{3}$$

where D_{I} is the interframe delay when the source waits between two successive frame transmissions, which is defined as 96 bit times in the 10BASE-T Ethernet standard. L_h is the overhead of a frame, and L_k is the length of data in the kth frame. Here, L_h is defined as 432 bits, while L_k is larger than 144 bits in the 10BASE-T Ethernet standard [10]. Also, t_{b} denotes the bit time, which is defined as 0.1 μs in the 10BASE-T Ethernet standard.

The theoretical worst case communication delay (D_{Cmax}) of the switched Ethernet with one switching hub occurs when the number of frames (N_{Q}) is the greatest. Here, the maximum N_{Q} is when the maximum number of frames is sent to only one destination simultaneously. For a given amount of data, the worst case is when the data are sent in the shortest frame, because the frame overhead including the interframe delay will be the maximum (144-bit data resulting in a 576-bit frame).

The maximum value of N_{Q} is "the number of stations $(N_{\mathrm{N}}) - 1$," because the worst case occurs when all the stations except the destination transmit to that station simultaneously, and all the frames are stored in the buffer of the switching hub.

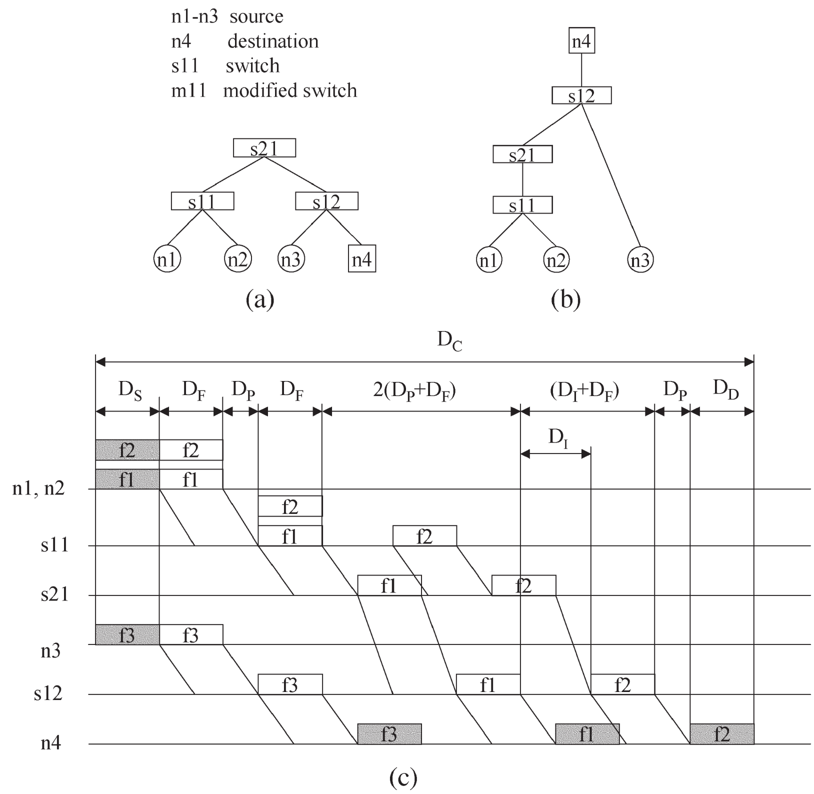

Fig. 5. Communication delay of switched Ethernet with multiple layers.

For example, when 24 stations are connected to one switching hub and the average message generation period is larger than D_{Cmax}, the maximum value of N_{Q} is 23. However, if the average message generation period is smaller than D_{Cmax}, the real-time requirements cannot be satisfied because the network becomes unstable with the increasing number of messages in the buffer. From this reasoning, the worst case communication delay can be calculated as shown in (4), when the frame length is 144 bits and switching hub connects 24 stations

$$\begin{aligned} D_{\mathrm{Cmax}} &= D_{\mathrm{Cmin}} + D_{\mathrm{Q}} \\ &= D_{\mathrm{Cmin}} + N_{\mathrm{Q}}\left(96 + \max(L_k + 432, 576)\right) t_{\mathrm{b}} \\ &\approx 200 + 23 \times 672 \times 0.1 = 1745.6\ \mu\mathrm{s}. \end{aligned} \tag{4}$$

From this calculation, we know that D_{Cmax} is about 1.745 ms, which is very low compared to the speed of many control systems. Since the message generation period of the real-time data in a typical automation system is in the order of 10 ms [12], we can see that the network delay does not affect the control performance significantly. As a comparison to a fieldubs, we can consider controller area network (CAN) that is widely used in many industrial and automotive applications. Tindell derived the formula to calculate the worst case communication delay shown below [13]–[15].

$$C_{\mathrm{m}} = \left(\left\lfloor \frac{54 + 8s_{\mathrm{m}}}{4} \right\rfloor + 67 + 8s_{\mathrm{m}} \right) \tau_{\mathrm{bit}} \ \text{ and } \ D_{\mathrm{Cmax}} = \sum_{i=1}^{N} C_{\mathrm{m}} \tag{5}$$

where C_{m} is the worst case transmission time of one frame, τ_{bit} is the bit time, s_{m} is the byte length of the CAN message, and N is the number of stations.

If we substitute the values for a network with 24 stations that send packets containing 8 B of data (the maximum payload that CAN allows) at the transmission speed of 1 Mb/s into (5), we can obtain the worst case communication delay of 3.582 ms. With these results, we cannot make a direct comparison because the switched Ethernet transmits more data (144 bits versus 64 bits) and the delay of switched Ethernet includes hardware-dependent processing delay (D_{Cmin}) while the transmission speed of switched Ethernet is faster than that of CAN. However, it can be said that the switched Ethernet can perform as well as CAN does.

Therefore, if the switched Ethernet with one switching hub is applied at the device level in manufacturing systems, we can expect that the switched Ethernet can satisfy the real-time requirements and can be a very promising alternative for industrial networking.

B. Worst Case Communication Delay of the Switched Ethernet With Multiple Switching Hubs

The worst case communication delay of the switched Ethernet serving multiple levels of automation hierarchy can be calculated using a method similar to that for one switching hub. First of all, we start from the analysis of the switched Ethernet with two levels, as shown in Fig. 5(a), in order to derive a general calculation method for the worst case communication delay. In the figure, stations n1 and n2 are connected to switching hub s11, and stations n3 and n4 are connected to

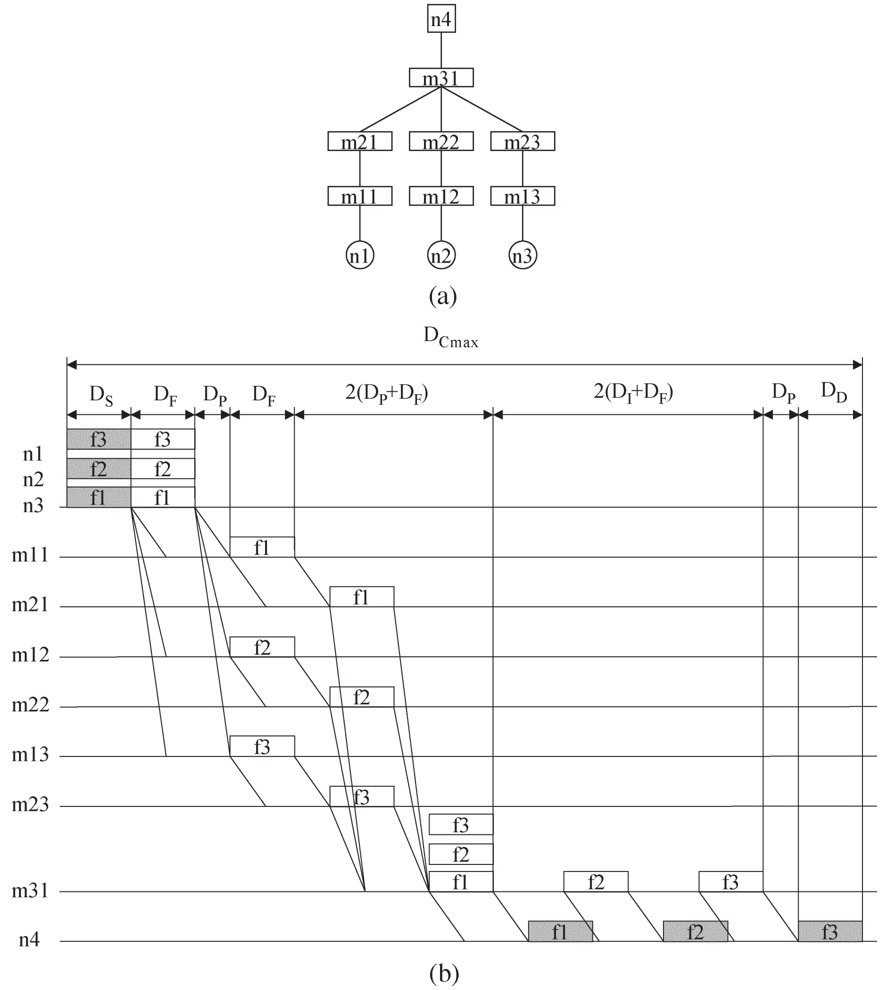

Fig. 6. Worst case communication delay for modified structure of switched Ethernet.

switching hub s12. In addition, switching hubs s11 and s12 are connected to switching hub s21. Given this structure, if stations n1, n2, and n3 transmit frames to station n4 (because the worst case communication delay will be when all the stations except the destination transmit frames to the destination), the original structure [Fig. 5(a)] can be represented by the rearranged structure shown in Fig. 5(b). Here, the worst case communication delay of the rearranged structure can be calculated from the timing diagram, as shown in Fig. 5(c).

First, suppose that frames are generated in n1, n2, and n3 simultaneously. Then, frames f1 and f2 are transmitted from n1 and n2 to s11, and frame f3 is sent from n3 to s12. Next, f1 is sent from s11 to s21, while f2 waits in the buffer of s11, and f3 is sent from s12 to n4. Finally, f1 is transmitted from s21 to n4, and f2 follows f1 after the interframe delay.

From this sequence, we can derive the communication delay of the switched Ethernet with multiple switching hubs as follows:

$$D_{\mathrm{C}} = D_{\mathrm{Cmin}} + (N_{\mathrm{S}} - 1)(D_{\mathrm{P}} + D_{\mathrm{F}}) + (N_{\mathrm{Q}} - 1)(D_{\mathrm{I}} + D_{\mathrm{F}}) \tag{6}$$

where D_{Cmin} is the minimum communication delay of the switched Ethernet with one switching hub, and N_{S} is the maximum number of switching hubs located between the source and destination stations. Here, the maximum N_{S} is the number of switching hubs located in the longest path between the source and destination stations. Next, N_{Q} is the number of frames that can be stored in one of switching hubs. Here, N_{Q} reaches its maximum when all the stations except the destination generate frames, and all the generated frames are stored in one of switching hubs simultaneously.

For example, because three switching hubs are located between stations n1 and n4 (the longest path between the source and destination), as shown in Fig. 5(b), N_{S} is 3. In addition, because two frames are stored in switching hub s12, N_{Q} is 2. Therefore, the communication delay that may occur in the timing diagram, as shown in Fig. 5(b), can be calculated as follows:

$$\begin{aligned} D_{\mathrm{C}} &= D_{\mathrm{Cmin}} + (3 - 1)(D_{\mathrm{P}} + D_{\mathrm{F}}) + (2 - 1)(D_{\mathrm{I}} + D_{\mathrm{F}}) \\ &= 382.6\ \mu\mathrm{s}. \end{aligned} \tag{7}$$

To calculate the worst case communication delay that may occur in the switched Ethernet with multiple switching hubs, we developed the modified structure as shown in Fig. 6(a). In the figure, the maximum number of switching hubs located on the longest path between the source (n1, n2, and n3) and destination (n4) is three (path from n1 to n4). Here, if all source and destination pairs have the maximum number of switching hubs, the rearranged structure [Fig. 5(b)] can be changed to the modified structure [Fig. 6(a)].

The worst case communication delay of the modified structure can be calculated from the timing diagram, as shown in Fig. 6(b). In the figure, frames f1, f2, and f3 are transmitted from n1, n2, and n3 to m11, m12, and m13 simultaneously. Next, f1, f2, and f3 move to m21, m22, and m23. Then, f1, f2, and f3 reach m31 simultaneously, and all the frames are stored in the buffer of m31. Finally, each frame is transmitted to n4 one by one. From this sequence, we can find that the N_{S} is 3 and the N_{Q} is 3. Therefore, the worst case communication delay in the switched Ethernet with two levels is calculated as follows:

$$\begin{aligned} D_{\mathrm{Cmax}} &= D_{\mathrm{Cmin}} + (3-1)(D_{\mathrm{P}} + D_{\mathrm{F}}) + (3-1)(D_{\mathrm{I}} + D_{\mathrm{F}}) \\ &= 449.8\ \mu\mathrm{s}. \end{aligned} \tag{8}$$

From (8), we can expect that the worst case communication delay can occur when all the frames generated at all the sources expect the destination are transmitted to a switching hub attached to the destination simultaneously. In this situation, we can conclude that the N_{Q} is "the number of stations $(N_{\mathrm{N}}) - 1$" and the N_{S} is the number of switching hubs on the longest path between the source and destination.

From this analysis, the worst case communication delay is determined by the number of levels and number of stations connected to the switched Ethernet, as shown in (6). Therefore, appropriate numbers of levels and stations should be chosen to satisfy the real-time requirements in the switched Ethernet with multiple levels.

For example, let us think a case of switched Ethernet with following conditions: 1) the real-time requirement of this system is 10 ms; 2) the length of a message to be transmitted in the network is 2 B; and 3) the number of levels is 3. Then, because the maximum switching hubs that can be located between two stations is five (the longest path between two stations), N_{Smax} is calculated to 5. Therefore, in order to satisfy the real-time requirement of this network system, N_{Qmax} should be smaller than 143 as shown by the following calculation:

$$\begin{aligned} D_{\mathrm{Cmax}} &> D_{\mathrm{Cmin}} + (N_{\mathrm{Smax}} - 1)(D_{\mathrm{P}} + D_{\mathrm{F}}) \\ &\quad + (N_{\mathrm{Qmax}} - 1)(D_{\mathrm{I}} + D_{\mathrm{F}}) \\ 10\,000 &> 200 + [(5-1)(1+576) \\ &\quad + (N_{\mathrm{Qmax}} - 1)(96 + 576)]\, 0.1 \\ N_{\mathrm{Qmax}} &< 143.4. \end{aligned} \tag{9}$$

IV. Performance Evaluation Through NCS

In order to verify the efficacy of the switched Ethernet, an experimental NCS is implemented for evaluating the control performance. Fig. 7 shows the structure of the NCS that has three major system components [8]: controller, sensor, and actuator. These components are connected to the shared transmission medium, and control information such as plant output or control signal is exchanged via a switched Ethernet. This configuration allows the system components to be almost anywhere. However, the control information is delayed by the network delay in order to gain the access to the shared medium.

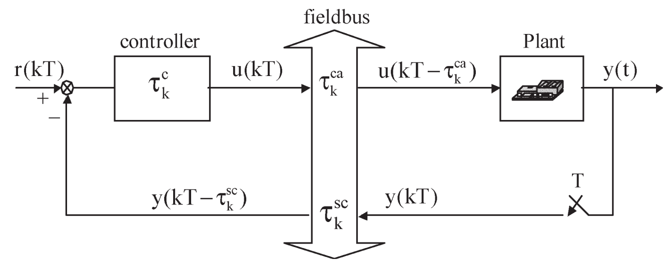

Fig. 7. Structure of NCS.

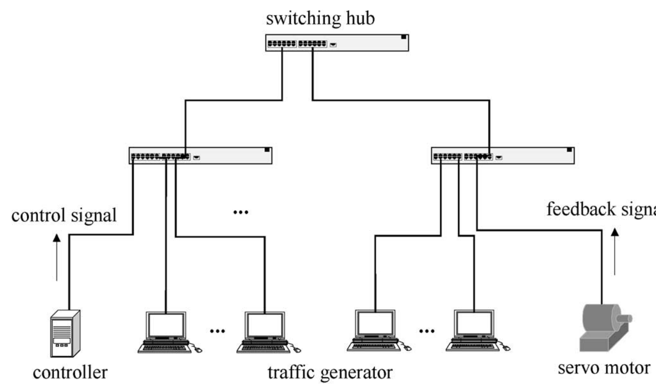

Fig. 8. Testbed of NCS via switched Ethernet.

The network delay is composed of three parts: 1) sensor-to-controller delay (τ_k^{sc}); 2) controller-to-actuator delay (τ_k^{ca}); and 3) computational delay (τ_k^{c}) for computing the control signal. Here, the computational delay is determined by the performance of the controller, but the sensor-to-controller and controller-to-actuator delays are affected by protocol characteristics and network traffic.

Fig. 8 shows the experimental NCS using the Ethernet and switched Ethernet with two-level structure. The NCS consists of one controller, one servomotor, and eight traffic generators. Here, the controller and servomotor exchanges 2-B encoder and control signals every 10 ms, and the traffic generators transmit 2 B data every 1 ms in order to add additional traffic. For the Ethernet network, SAMSUNG SmartEther SH2024S is used as the hub, while 3COM SuperStack II Switch 1100 is used for the switched Ethernet network. The data rate of the network is set to 10 Mb/s for better noise immunity in the industrial environment. In addition, a Tamagawa's TS3728 dc servomotor is used, and NI's NI6025E board is used for control input of servomotor and plant output of encoder. Finally, the reference input is chosen to be 1000 r/min.

In order to compare the control performance, the servomotor control system is put together in three different ways: 1) centralized motor control system without using any network; 2) distributed motor control system with traditional Ethernet; and 3) distributed system with switched Ethernet. For all of these control systems, a common PID controller is used, which is designed for maximum overshoot $\leq 20\%$, 2% settling time

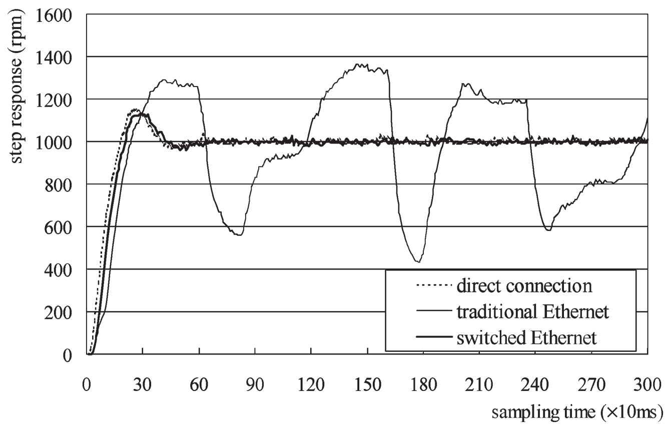

Fig. 9. Comparison on step response of NCS.

≤ 1 s, and damping ratio ≤ 0.5 by the root locus method [16]. The transfer function of the controller is given below.

$$G_{\mathrm{PID}}(s) = K_d s + K_p + \frac{K_i}{s} = \frac{0.02s^2 + 0.015s + 0.1}{s}. \tag{10}$$

Fig. 9 shows the comparison of motor responses with the PID controller via direct connection, traditional Ethernet, and switched Ethernet. In the figure, the maximum overshoot with direct connection is 15% and the 2% settling time is 0.5 s, which satisfies the design specifications. However, the motor response with the traditional Ethernet shows its instability. This catastrophic deterioration results from the delayed or lost control information due to frame collisions. On the other hand, the maximum overshoot with the switched Ethernet is 13% and the 2% settling time is 0.54 s, which is almost the same as the motor response with direct connection.

From the result, we observe that the network delay of the switched Ethernet is very small as calculated in (11) using (6), and the control input or plant output can be transmitted within one sampling time. This result proves that the performance of switched Ethernet with multiple levels may be acceptable industrial network with real-time requirements.

$$\begin{aligned} D_{\mathrm{Cmax}} &= 200 + [(3-1)(1+576) + (9-1)(96+576)] \times 0.1 \\ &= 852.8\ \mu\mathrm{s}. \end{aligned} \tag{11}$$

From this result, even if an NCS uses a controller designed for the directly connected control system without network, the NCS with the switched Ethernet with multiple switching hubs can still satisfy the desired design specifications.

V. SUMMARY AND CONCLUSION

This paper focused on the performance evaluation of the switched Ethernet with multiple switching hubs for real-time industrial networking. In this paper, the worst case communication delay is derived based on timing analysis of the switched Ethernet with multiple switching hubs. In addition, the control performance of an NCS via the switched Ethernet with two levels is evaluated through a series of experiments. The conclusions derived from this research are as follows.

1) From the analytical derivation using timing diagrams, the communication delay of the switched Ethernet with single-switching hub is very small compared to the speed of most control systems. Therefore, the communication delay of the switched Ethernet is small enough for satisfying the real-time requirements.
2) If the number of stations and levels are chosen appropriately, the switched Ethernet with multiple switching hubs can be used for the real-time industrial network.
3) From the observation made on the NCS using the switched Ethernet, the control performance was affected very little by the network delay, if the network is designed appropriately. In this case, the controller designed for the centralized control system without network can be used for the NCS with the switched Ethernet without any modification of the controller.

Based on these conclusions, the switched Ethernet with multiple switching hubs is a very promising alternative for real-time industrial network. The adoption of the switched Ethernet for real-time industrial network is expected to overcome existing difficulties in cost, interoperability, and application development of some fieldbus protocols. However, hardware aspects such as medium shielding, connectors, and ruggedness of switching hubs have to be addressed in order to use the switched Ethernet for industrial applications.

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