Performance Evaluation of a BACnet-based Fire Detection and Monitoring System for use in Buildings

Won-Seok Song and Seung-Ho Hong*

Abstract: The objective of this paper is to propose a reference model of a fire detection and monitoring system using MS/TP protocol. The reference model is designed to satisfy the requirements of response time and flexibility. The reference model is operated on the basis of BACnet, a standard communication protocol for building automation systems. Validity of the reference model was examined using a simulation model. This study also evaluated the performance of the BACnet-based fire detection and monitoring system in terms of network-induced delay. Simulation results show that the reference model satisfies the requirements of the fire detection and monitoring system.

Keywords: BACnet, building, fire detection, MS/TP, simulation.

1. INTRODUCTION

In order to secure human lives against the abrupt outbreak of fire, buildings require advanced technologies for a reliable FDMS (Fire Detection and Monitoring System). As the demands on advanced automation and control technologies have increased, network-based control systems have prevailed for advanced building systems. A network-based control system not only provides real-time control and monitoring of the building facilities, but also efficiently manages the control systems by gathering, analyzing, and storing building-related information. Networking is one of the core technologies that utilize an advanced building control system. The use of network-based control has become widespread in many automation system areas [1-3].

This study proposes a MS/TP network-based reference model of a FDMS that can be applied to the buildings of the future. The reference model was designed to meet the requirements of response time and flexibility of the FDMS. The FDMS reference model proposed in this study is operated on the basis of BACnet (Building Automation and Control network): a standard communication network protocol for building automation and control systems [4]. BACnet was adopted as a Korean Standard and also an international standard from ISO [5, 6]. In this study a simulation model for the proposed FDMS reference model was developed. The simulation model was utilized to validate the performance and functional characteristics of the proposed FDMS reference model

This paper consists of six sections. Section 2 describes the requirements of the FDMS in an advanced building in terms of response time and flexibility. Based on the requirements, a FDMS reference model is proposed in Section 3. Section 4 describes a simulation model that can evaluate the validity of the reference model. Section 5 presents the results of the simulation experiments. Finally, Section 6 offers the conclusions of this study.

2. REQUIREMENTS OF FDMS

In a conventional fire detection system, fire detectors are connected to a receiver via a dedicated analog signal line with 4-20mA current signal. The conventional system has a limitation in identifying the exact location when a fire occurs in a building. In addition, if the analog line is broken down due to deterioration or corrosion before a fire occurs, the receiver will neither recognize the problem nor detect the fire. In order to overcome these problems, a networked-based addressable fire detection system has been developed [7]. In the network-based fire detection system, fire detectors, actuators, and a workstation are connected to a shared transmission medium, and the information is exchanged using digital communication. Because each detector has its own address, the location of a fire can be easily

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identified. In addition, because the workstation periodically examines the status of the fire detectors, it can easily identify a breakdown in the system. Most of the commercially available network-based fire detection systems, however, are developed using their own proprietary network protocols [8-10]. In the closed systems, performance characteristics and functions cannot be judged. In an integrated building automation system, a fire detection system must be operated with other building facilities. A closed fire detection system cannot guarantee interoperability with other building facilities.

In this study, we consider a network-based FDMS. In addition to the advantages of the network-based FDMS described above, we propose the additional requirements of the FDMS as follows;

Response Time: Fire alarm signal and any other fire related information must be delivered as fast as possible. In this study, we limit the average transmission delay of fire detection and monitoring signal to one second. One second is sufficiently small enough time for detecting fire in a building.

Flexibility: The FDMS needs to be flexible in design, installation, operation and management. Flexibility can be procured from interoperability among devices supplied by different manufacturers. Interoperability makes it easier to integrate, modify, and upgrade the FDMS. The FDMS must also be easily integrated into other building automation systems such as HVAC, lighting, security, transportation and power systems.

3. REFERENCE MODEL OF FDMS

Based on the requirements of the FDMS described in the previous section, this section presents a reference model of the FDMS. The reference model is operated on the basis of an advanced network technology. The reference model consists of (i) communication network system and (ii) FDMS.

3.1. Communication network system

Previously, most of the building's automation system has been installed with a closed proprietary network system. The building with a closed system has problems in interoperability among devices supplied by different manufacturers. Thus, building owners can be governed by system vendors. The closed system also degrades flexibility and expandability of building control systems. These problems can be solved by using an open system, and ASHRAE developed BACnet, a standard communication network for building automation and control systems [11,12]. BACnet defines a set of standard objects whose properties represent the information that is exchanged between components of the building automation system and an application layer protocol that is used to access and manipulate this information. The network layer provides a routing function for connection of several subnetworks in a building. BACnet adopts four LAN technologies, ARCNET, MS/TP (Master Slave/Token Passing), Ethernet, LonTalk, and a PTP (Point-To-Point) protocol as its data link layer protocols.

The reference model of the FDMS introduced in this study is operated on the basis of BACnet. It adopts MS/TP protocol as its backbone and local networks. Among several options for BACnet LAN, MS/TP is the most popular and widely used protocol. It is ideal for providing a simple communication function at a low cost. MS/TP uses RS-485 interface for its physical layer, and the data link layer can be implemented in firmware. MS/TP is operated on master-slave and token-passing methods. Master nodes communicate with each other using a token-passing protocol. In the token-passing protocol, a token frame is circulated along the logical ring that determines the order of data transmission for nodes in the medium. A node that receives the token can transmit its message and transfer the token to the next node in the logical ring. Slave nodes never hold the token. Slave nodes return a reply only when they receive a request from a master node. In the MS/TP protocol, we can predict the worse case message transmission delay, and it is suitable for the transmission of real-time data such as alarm and monitoring signals.

3.2. Fire detection and monitoring system

The reference model of the FDMS consists of fire detectors and actuators, fire controllers and a central operation station. The fire detector will consist of one or all of a smoke detector, a thermal detector and a light detector. Actuators include sprinkler, smoke discharger, fire wall and inducement lights. Addressable detectors and actuators are connected directly to the network line, but the others can be connected to the network by interface devices.

The fire controller receives a fire alarm signal from the detectors and sends a command signal to the actuators. Each fire controller has a zone assigned to it The fire controller periodically reports the status of fire occurrence as well as the status of field devices under its zone to the central operation station. The FDMS operator operates the central operation station. The operator monitors the fire occurrence in the entire building, and transmits any appropriate command if necessary.

Fig. 1 shows a building that is installed with a reference model of the FDMS, and a schematic diagram of the reference model of the BACnet-based FDMS. Each floor has one fire controller, and detectors and actuators are connected to the fire controller through a MS/TP local network. Fire

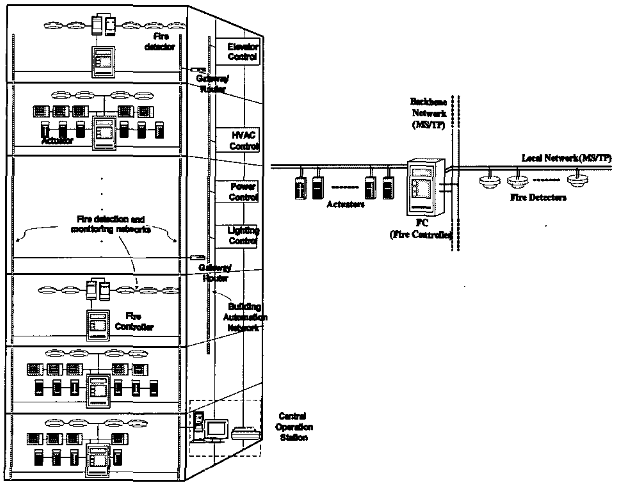

Fig. 1. Reference model of FDMS.

controllers are interconnected through the MS/TP backbone network. The central operation station is also connected to the MS/TP backbone network. As shown in Fig. 1, FDMS networks are installed apart from other building control networks such as HVAC, lighting, security, and transportation systems. Both the MS/TP backbone and local networks are duplicated in order to provide survivability. This increases the reliability of the FDMS networks. If one network line is broken due to fire or any other accidents, the other network line will back-up the broken one.

The operation scenario of the reference model is as follows;

- If a fire is detected, a detecting device transmits BACnet *Confirmed Event Notification* service messages to the fire controller. These messages are stored in the fire controller and routed to the central operation station.
- If the internal status of a device is changed, the device transmits BACnet *Confirmed COV (Change-Of-Value) Notification* service messages to report the changes to the fire controller.
- A fire controller periodically transmits BACnet *Read Property* service messages to detectors and actuators to monitor fire occurrence and status of each device.
- A central operation station periodically transmits BACnet *Read Property Multiple* service messages to fire controllers to monitor the fire occurrence and device status of each local zone.

4. SIMULATION MODEL

In order to evaluate the validity of the reference model presented in the previous section, we developed a simulation model. The simulation model also consists of a communication network system model and a fire detection and monitoring system model. The simulation model is developed using the ARENA tool, a simulation model development tool for discrete-event dynamic systems.

4.1. Communication network simulation model

The communication network simulation model contains MS/TP protocol. Fig. 2 shows the structure of the MS/TP node in the simulation model. Most of the MS/TP networks currently used in real buildings are all-master systems. In this study, we assume that all nodes in the MS/TP network consist of master nodes. The *Token management block* in Fig. 2 simulates the transmission and reception of the token, and all the token management functions. The *Frame transmission/reception block* simulates the transmission and reception of the data frame. Message transfer between the upper layer and data link layer in the MS/TP is simulated through *transmitter queue (Tx Q)* and *receiver queue(Rv Q)*.

Fig. 3 presents the structure of the BACnet protocol simulation model, which consisted of three independent modules: an application layer module, the LAN protocol module, and a common module. Table 1 shows a brief description of the modules. The Common Module provides an interface for users to set the values of all the simulation parameters. The application layer module generates the BACnet messages and collects and statistically analyzes the simulation data. As described in Section 3, the FDMS consists of a central operation station (COS), a fire controller (FC), detectors (DETs), and actuators (ACTs). These devices are modeled by the COS, FC, DET and ACT application modules, respectively. Each device module generates a BACnet message corresponding to its BACnet application service. The

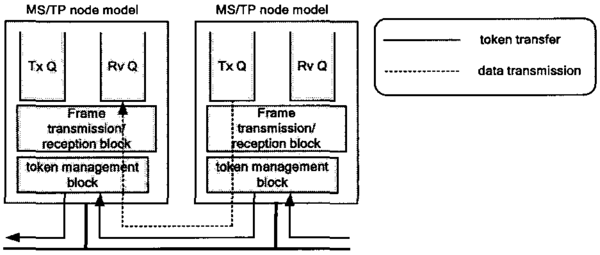

Fig. 2. Structure of MS/TP node simulation model.

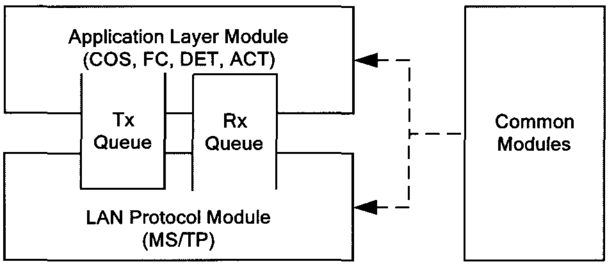

Fig. 3. Structure of communication network simulation model.

Table 1. ARENA Modules Developed for Modeling BACnet LANs.

Module	Function	Description
Common Module	- Simulation Environment - MS/TP Environment	- set the simulation time and the number of replications - set the simulation parameters for MS/TP
Application Layer Module	- Message Generation - Statistical Analysis	- schedule the generation of BACnet messages - collect and analyze statistical information
LAN Protocol Module	- MS/TP Master Node	- MS/TP master node model

LAN protocol module adopts a MS/TP simulation model.

4.2. FDMS simulation model

Fig. 4 shows the structure of the simulation model for the FDMS. In a local network, the fire controller (FC) periodically transmits a *Read Property* service message to each of the detectors and actuators. All the detectors and actuators in a local network can transmit a *Confirmed COV Notification* message when it detects change of internal status. If any fire detector detects fire occurrence, it transmits a *Confirmed Event Notification* message to the fire controller. This event notification message is routed to the central operation station in order to notify the fire occurrence to the operator. In a backbone network, the central operation station periodically transmits *Read Property Multiple* messages to fire controllers to retrieve information from their database. A *Read Property Multiple* message can transfer a large number of values from one node at a time.

Fig. 5 shows a comparison between the real device and simulation model of the detector/actuator. The detector/actuator has a MS/TP interface. The detector transmits fire alarm and monitoring data to the fire controller. The actuator receives fire control commands from the fire controller. Detectors and actuators report their condition to the fire controller.

Fig. 6 shows a comparison between the real device and simulation model of the fire controller. The fire controller has two MS/TP interfaces, one for the backbone network and the other for the local network. Application of the fire controller has a *fire detection and monitoring block* and an *alarm/status report block*. The *fire detection and monitoring block* collects fire alarm and monitoring signals as well as healthy information about field devices. It also transmits the fire control command to the actuators. The *alarm/status report block* uses backbone network interface. It reports fire alarm and monitoring signals as well as healthy information gathered from field devices to the central operation station, and receives fire control commands transmitted from the central operation station.

Fig. 7 presents a comparison between the real device and simulation model of the central operation station. The central operation station is connected to the MS/TP backbone network. Applications of the central operation station include *real-time monitoring*

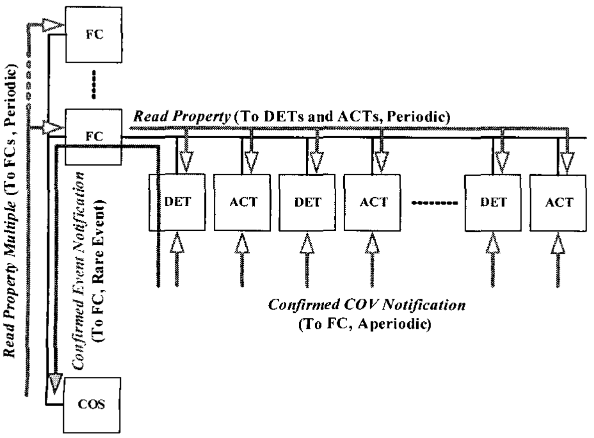

Fig. 4. Structure of FDMS simulation model.

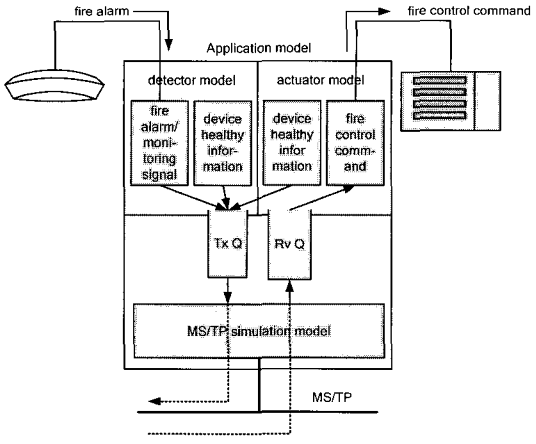

Fig. 5. Structure of detector/actuator simulation model.

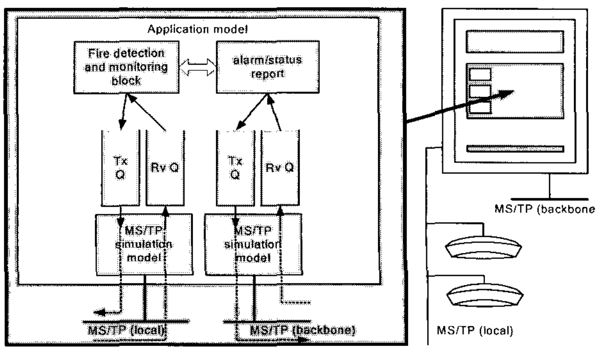

Fig. 6. Structure of fire controller simulation model.

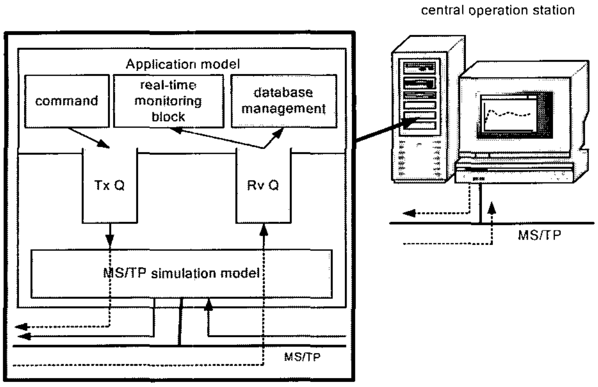

Fig. 7. Structure of central operation station simulation model.

block, *command block* and *database management block*. The *real-time monitoring block* receives fire alarm and device status data transmitted from the file controller, and displays them on the operator screen. The *command block* transmits the fire control command to the fire controller. The *database management block* receives data transmitted from the fire controllers.

In this simulation study, we measured "fire detection delay" in order to evaluate performance of the FDMS. When a DET perceives a fire occurrence, the DET generates and inserts a *Confirmed Event Notification* message to its transmitter queue. After the token is received by the DET, this notification message is conveyed to the FC. Then, the FC routes the notification message to the COS. The COS transmits acknowledgement for *Confirmed Event Notification* message to the DET through the FC. The time to be taken for this procedure is defined as "fire detection delay" in this paper.

4.3. Simulation model using ARENA

Both the communication network system and the fire detection and monitoring system are defined as discrete-event dynamic system. In the discrete-event dynamic system, the state of the system is changed when an event occurs, and the events occur at random [13]. ARENA is a simulation tool used for the development of a simulation model of the discrete-event dynamic system [14,15]. ARENA is widely used for the development of a simulation model of diverse discrete-event dynamic systems such as communication network system, manufacturing automation system, etc. In this study, the simulation model of the FDMS reference model is developed using the ARENA tool.

Fig. 8 shows the screen capture of the BACnet based FDMS simulation model. In the figure, the left window shows the basic templates as well as additional templates developed in this study. The central window displays the configuration of the simulation model. The MSTP_PARAMETERS module in the common modules is used to set the MS/TP protocol parameters such as timer and baud rate; the MSTP_LENGTH module is used to set the length of the BACnet service message; and the MSTP_PROCTIME module is used to set the processing time of application layer service for the generation of each BACnet service message. The ARENA modules define the variables and constants used in the simulation model and execute the statistical calculations used to analyze the simulation results.

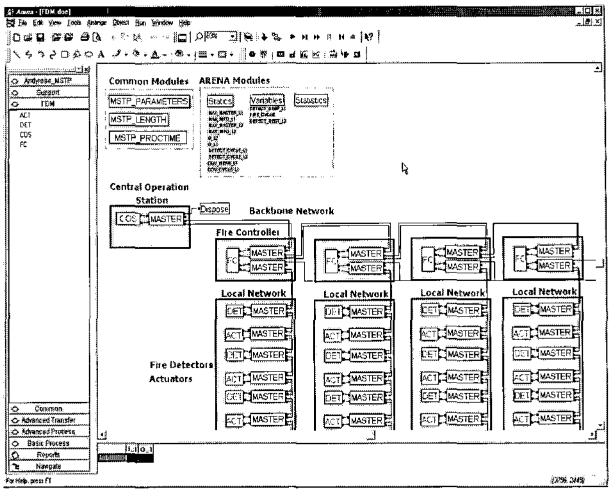

Fig. 8. Sample window of FDMS simulation model using ARENA.

The middle of the central window in Fig. 8 displays the system model that consists of MS/TP module and application layer module for the FDMS. The COS module, which is connected to one of the MASTER modules of the MS/TP communication model, monitors and manages the entire FDMS. All the other application layer modules such as FC, DET, and ACT are also connected to the MASTER modules of the MS/TP communication model.

5. SIMULATION ANALYSIS

5.1. Definition of network traffic load

Using the simulation model, this section investigates the performance of the reference model of the FDMS presented in Section 3 in terms of response time. In this study, we quantify the network traffic load as G. The physical meaning of G is defined as the fraction of the message transmission time per unit time, excluding the overhead of the network protocol itself. G can be expressed as follows:

$$G = \frac{1}{B}\sum_{i=1}^{N}\frac{L_i}{T_i},$$

where B is the data transmission rate (bits/s), N is the number of nodes that generate messages in the

Table 2. Traffic condition for the simulation.

Device	BACnet Service Message	Message Length (Request/Reply)	Message Generation Interval (Sec)	Local Network Traffic Load	Message Type
COS	*Read Property Multiple*	92 / 175 bytes	0.3477 ~ 0.0497	0.1000 ~ 0.7000	Periodic
FC	Read Property	23 / 29 bytes	0.0323	0.2099	Periodic
DETs ACTs	*Confirmed COV Notification*	48 / 15 bytes	6.3416 ~ 0.5408	0.0401 ~ 0.4702	Aperiodic
	Confirmed Event Notification	78 / 15 bytes	20.0000	0.0006	Periodic

medium, T_i is the average message generation interval at node i (s), and L_i is the average message length generated at node i (bits). G falls between 0 and 1, and the network traffic load increases as G approaches 1.

5.2. Simulation condition

In this simulation, we assumed that a single COS and 31 FCs are connected to the backbone network. It is also assumed that a single FC and 31 devices (DETs and ACTs) constitute a local network. The message generation pattern of aperiodic service messages was assumed to have a Poisson distribution, and the transmission speed was set to 76.8 kbps. To make the simulation more realistic, we included processing time for the BACnet application services in the application layers. The delay in processing the application service depends upon both the hardware and the software implementation skill of the actual device. In this study, we considered the processing time for a range from 1 ms to 30 ms. The processing time was assumed to have a uniform distribution within the given range. Table 2 indicates the detailed traffic condition of this simulation. In Table 2, the *Read Property Multiple* service message plays the role of generating traffic load in the backbone network. On the other hand, *Read Property* and *Confirmed COV Notification* service messages are used to generate traffic load in the local network. A *Confirmed Event Notification* service message is used to inform fire occurrence to FC and finally to COS.

5.3. Simulation results

In this simulation, we investigated the "fire detection delay" with respect to the change of network traffic load in backbone and local networks. Fig. 8 shows the average fire detection delay investigated in this simulation. The fire detection delay is affected by the traffic load of both local and backbone networks, because the *Confirmed Event Notification* message to report fire occurrence should be transmitted through the backbone network to the central operation station.

In Fig. 9, x-axis represents the traffic load G in the local network. The simulation results for the increment of traffic load G in the backbone network are depicted as separate curves. The average fire detection delay is increased exponentially as the network traffic load increases. The MS/TP protocol uses a token-passing mechanism to share the network medium between the nodes. As the traffic load increases, a node must wait longer to transmit BACnet service messages from its transmitter queue. This causes an increment in the network-induced delay, and eventually the fire detection delay increases. The fire detection delay, however, increases abruptly as the traffic load of both local and backbone networks approaches to saturation point. In this study, we defined this point as "traffic saturation point." In this simulation, the traffic saturation point of the local network is located between 0.6 and 0.7 when the traffic load of the backbone network is loaded under 0.7.

Table 3 indicates fire detection delay near the traffic saturation point in seconds. Fig. 8 shows that the fire report message can be completely transmitted to the

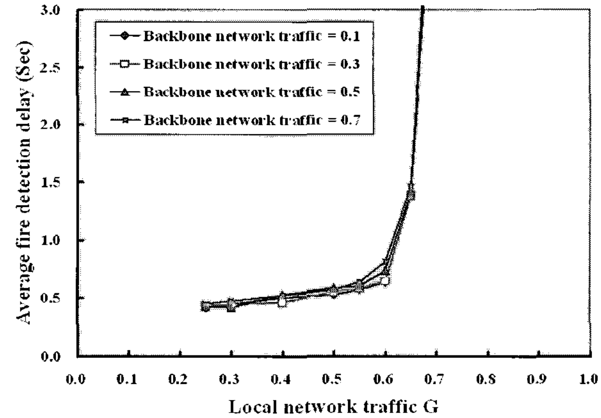

Fig. 9. Average fire detection delay.

Table 3. Average fire detection delay near the traffic saturation point.

(local)	G (backbone)			
	0.1	0.3	0.5	0.7
0.55	0.5759	0.5845	0.6056	0.6395
0.60	0.6397	0.6704	0.7362	0.8166
0.61	0.8203	0.8548	0.8753	0.8782
0.62	0.8740	0.8964	0.9327	0.9426
0.63	0.8614	0.9635	1.0807	1.1106
0.64	1.0859	1.0939	1.1242	1.2277
0.65	1.3943	1.3885	1.4113	1.4640
0.68	3.3391	3.3824	3.4543	3.5832

operator in COS within one second, on average, if the traffic of local and backbone networks is loaded sufficiently smaller than the traffic saturation points.

The traffic saturation point can be varied according to the system configuration and traffic load. A network designer can easily find the traffic saturation point for a given system configuration using the simulation model developed in this study. From the simulation analysis performed in this study, we verified that the reference model we introduced in this study is valid for FDMS.

6. CONCLUSIONS

This paper introduces a reference model of the FDMS. The reference model is operated on the basis of MS/TP protocol, a digital, serial, open, standard communication networks for building automation and control networks. In order to evaluate the validity of the proposed reference model, this paper developed a simulation model. The results obtained from the simulation model showed that the reference model satisfies the requirements of the FDMS as follows;

Response Time: Response time of the fire alarm signal is directly dependent upon the traffic load. Simulation results showed that the response time of the fire alarm signal can be restricted within one sec if the network system is designed such that the traffic loads in both local and backbone networks do not exceed traffic saturation points.

Flexibility: The reference model of the FDMS proposed in this study adopts BACnet protocol. This guarantees interoperability among field devices supplied from different vendors. The FDMS can also be easily interfaced into other building automation systems that adopt a standard BACnet protocol.

A MS/TP network designer must keep in mind that the total network traffic load should not exceed the traffic saturation point. The traffic load of a MS/TP network varies due to many factors, such as network parameters, number of nodes, message generation interval, and so on. It is very difficult to determine the traffic saturation point analytically for a given network configuration. However, the simulation model developed in this study can be effectively utilized to find the traffic saturation point for a given FDMS configuration. In our future work, we will extend this simulation analysis for FDMS where Ethernet is used as a backbone network.

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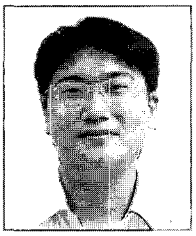

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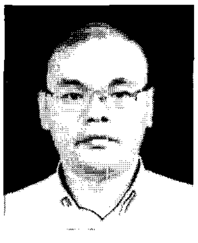

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