Experimental Performance Evaluation of BACnet MS/TP Protocol

Tae Jin Park, Won Seok Song, and Seung Ho Hong*

Abstract: BACnet is a standard data communication protocol especially designed for building automation and control networks. BACnet uses the Master-Slave/Token-Passing (MS/TP) protocol as one of its field-level networks. In this study, the performance of the BACnet MS/TP protocol is evaluated using an experimental model. The network performance is investigated and evaluated in terms of token rotation time and round trip time. The experimental results show that the performance of the MS/TP network is heavily influenced by the network traffic load, the assignment of MS/TP node address and the network configuration parameter called $N_{max\_info\_frames}$. Based on the experimental results, simple practical designing guidelines for BACnet MS/TP network systems are also proposed.

Keywords: BACnet, experimental model, MS/TP, network performance.

1. INTRODUCTION

Modern office and residence buildings provide a comfortable environment for the occupants using various automated facilities such as heating, ventilation and air-conditioning (HVAC), lighting, fire alarm, life safety, and security systems. Advanced building automation and control systems require real-time monitoring and control of building facilities, and as the demands on automated building facilities and services have increased, the use of distributed, network-based control systems have become widespread. Network-based control not only provides real-time control and monitoring of building facilities but also efficiently manages the building systems by gathering, analyzing, and storing building-related information. Thus, networking is one of the core technologies enabling the realization of advanced building automation systems [1-4].

Many vendors provide various products and solutions using their own networking technologies. The vendor-dependent proprietary technologies, however, have become major barriers to integrating those building automation systems supplied by different vendors, resulting in a lack of the flexibility and expandability that building owners want. In order to solve these problems, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) developed BACnet, the only communication protocol standard specifically designed to meet the needs of building automation and control systems [1-4].

BACnet provides five options for its data link layer protocol: Ethernet, ARCnet, MS/TP (Master-Slave/Token-Passing), PTP (Point-To-Point), and LonTalk. MS/TP is the most widely used protocol to establish connections between field-level devices due to its cost-effectiveness and ease of implementation.

Some simulation results about the performance evaluation of BACnet LANs and their charateristics were introduced in [9] and some simulation results concerning the network performance in a BACnet-based fire detection and monitoring system were also introduced in [10]. These simulation results are also very helpful when designing and installing BACnet-based control systems but it is difficult to completely simulate the interactions between communiation devices and their internal procedures. Therefore, more practical and more actual experimental analysis results are required for BACnet-based control systems.

The objective of this study is to evaluate the performance of the BACnet MS/TP protocol using an experimental model in terms of token rotation time and round trip time. The first stage version of the experimental model and its brief experimental analysis results were introduced in [11]. In this study, a new experimental model is developed with new hardware and software in order to get more detailed experimental results. The experimental model developed in this study consists of ten BACnet MS/TP

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field controllers, one central controller and one monitoring computer. The BACnet MS/TP field controller is developed in the form of BACnet Application Specific Controller (B-ASC) [5]. The experimental results show that the performance of the BACnet MS/TP protocol is greately influenced by the network traffic load, the assignment of MS/TP node address and the network configuration parameter "$N_{max\_info\_frames}$." The experimental results from this study will facilitate the design and installation of the BACnet MS/TP network-based control systems in building automation area.

This paper consists of five sections. Section 2 briefly describes the BACnet and MS/TP protocols. Section 3 presents the experimental model of the BACnet MS/TP network system developed in this study. Section 4 evaluates the performance of the BACnet MS/TP protocol using the results obtained from the experimental model. Finally, conclusions and recommendations are summarized in Section 5.

2. BACNET AND MS/TP

BACnet is based on a four-layer architecture with the physical, data link, network, and application layers as shown in Fig. 1 [6]. The BACnet application layer defines application objects and services as the abstract object-oriented representation of information which is communicated between building automation equipments. The BACnet network layer provides a way to convey the information across a variety of local and wide-area networks that might be interconnected to form an inter-network in buildings. BACnet provides six options for the data link layer protocol including Ethernet, ARCNET, MS/TP, LonTalk, PTP and BACnet/IP. Among these six data link layer options, MS/TP is the most widely used protocol to establish connections between field level devices because of its cost-effectiveness and ease of implementation [5-8].

Fig. 2 shows the model of BACnet application process [6]. The BACnet ASE (Application Service Entity) represents the set of functions or application services. Application service primitives are passed to the network layer through the NSAP (Network Service Access Point). The BACnet User Element carries out several functions in addition to supporting the local

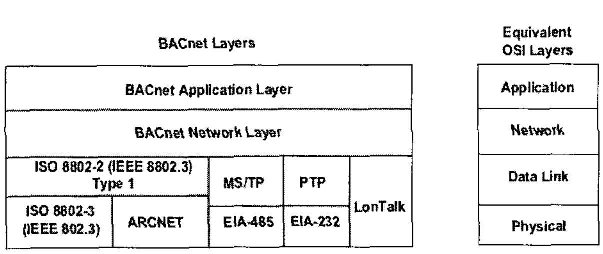

Fig. 1. BACnet architecture.

API (Application Program Interface). It is responsible for the service procedure of each application service and it is also responsible for maintaining information about the context for a transaction. The BACnet User Element also presides over the mapping of a device's activities into BACnet objects.

The BACnet MS/TP protocol is designed to be implemented using a single-chip microprocessor with a UART (Universal Asynchronous Receiver and Transmitter). It uses EIA-485 signaling over a twisted-pair cable. The maximum communication length is 1200m and its supported baud rates are 9600, 19200, 38400 and 76800 bits/sec. As the name suggests, MS/TP networks can be configured as a master-slave network, a peer-to-peer token passing network, or a combination of the two.

Fig. 3 shows the state machine of the MS/TP master

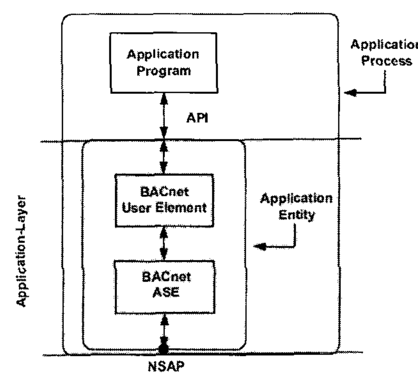

Fig. 2. Model of BACnet application process.

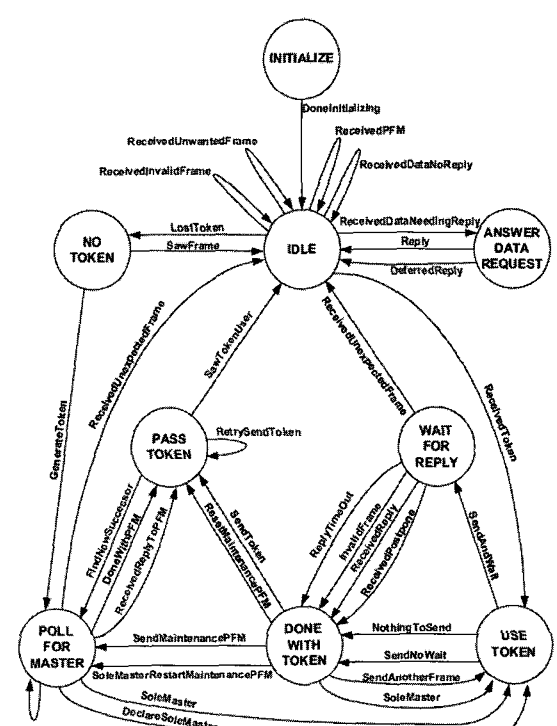

Fig. 3. MS/TP master node state machine.

node [6]. The MS/TP master nodes maintain a token frame that regulates the access to a medium. More detailed descriptions about the state machine are given in [6].

The token is circulated from one master node to another according to a predetermined, address-based order. A master node that holds the token can transmit messages to the other masters or to slaves before passing the token. A master node that holds the token can transmit messages up to the value of the network configuration parameter called "$N_{max\_info\_frames}$." According to the simulation results of our previous studies [9,10], this network parameter most strongly affects the performance of the MS/TP network system. A master node that receives a request returns the reply immediately if a reply is available from the higher layers within "T_{reply_delay}" timer or a master node may return a "Reply_Postponed" frame, which means that the actual reply will be returned when it holds the token. The implementation of reply mechanism in the BACnet MS/TP protocol is specified as a local matter [6]. Whole master nodes with the "Reply_Postponed" mechanism prevail in recent building automation systems that adopt the BACnet MS/TP protocol as their field-level network.

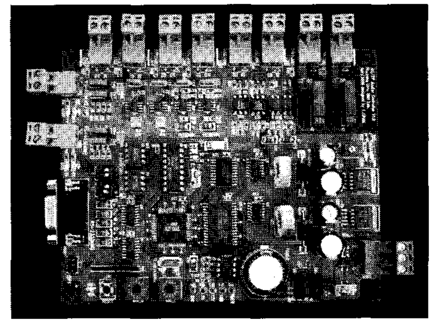

Fig. 4. Photograph of the BACnet MS/TP field controller.

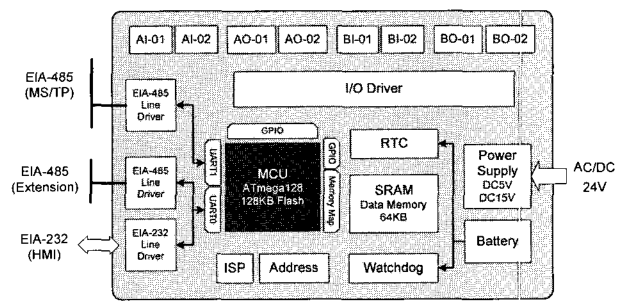

Fig. 5. Hardware structure of BACnet MS/TP field controller.

3. EXPERIMENTAL MODEL

In this study, the experimental model of the BACnet MS/TP network system is composed with ten BACnet MS/TP field controllers and one central controller. The BACnet MS/TP field controller is designed and implemented in the form of BACnet Application Specific Controller (B-ASC). The BACnet MS/TP protocol, network layer, application layer and application specific program are implemented in the BACnet MS/TP field controller. The central controller is developed with the same hardware and the same protocol stack, but special application programs such as network traffic monitoring and performance monitoring functions are implemented in the central controller.

3.1. BACnet MS/TP field controller hardware

The BACnet MS/TP field controller is designed and developed as a B-ASC so that it can maintain the BACnet MS/TP communication function and application specific functions together using a single chip microcontroller. Fig. 4 presents a photograph of the BACnet MS/TP field controller developed in this study and Fig. 5 shows its hardware structure.

ATMEL's ATmega128 is adopted as the MCU (Micro-Controller Unit) of the BACnet MS/TP field controller. ATmega128 has internal 128KB flash memory for ROM (Read-Only Memory) data and it can extend its memory space up to 64KB using a 16-bit address bus. BACnet MS/TP data link layer, network layer, application layer and application programs are implemented in ATmega128's internal 128KB flash and external 64KB SRAM. Moreover, the ATmega128 has an internal 4KB EEPROM (Electrically Erasable and Programmable ROM) whose data can be maintained even during the power reset or power failure. Local configuration parameters and network configuration parameters are stored in the internal EEPROM.

UART1 is used as the BACnet MS/TP communication port using EIA-485 medium. UART0 is used as the extension port using EIA-485 medium or it also can be used as the HMI (Human-Machine Interface) port using EIA-232 medium. The external RTC (Real-Time Clock) maintains local time clock and provides more precise and reliable time information to the MCU. The external RTC is controlled by the MCU through the GPIO (General Purpose Inputs and Outputs). The external watchdog monitors the input power and the operation status of the MCU. The power supply generates DC 5V and DC 15V from AC/DC 24V power input. 1F semi-permanent and self-rechargeable super condenser is used as a battery so that it can supply the power source to the RTC and watchdog at least more than 24 hours in power failure condition.

ATmega128 has internal 10-bit ADC (Analog-to-Digital Converter) and 10-bit PWM (Pulse Width Modulation) output drivers. The BACnet MS/TP field controller is designed and developed with 2-channel analog inputs, 2-channel analog outputs, 2-channel

Table 1. Hardware inputs and outputs.

Type	Channel	Description	BACnet application objects
Aanalog Input	2ch, 10bit	0-10 V	Analog Input object (AI-01, AI-02)
Analog Output	2ch, 10bit	0-10 V	Analog Output object (AO-01, AO-02)
Digital Input	2ch	Dry Contact	Binary Input object (BI-01, BI-02)
Digital Output	2ch, Relay	Single Pole, Single Through	Binary Output object (BO-01, BO-02)

digital inputs and 2-channel digital outputs. These hardware inputs and outputs are managed by the BACnet application objects as described in Table 1.

3.2. BACnet protocol stack and firmware

Fig. 6 shows the structure of BACnet protocol stack and firmware implemented in the BACnet MS/TP field controller. BACnet protocol stack and firmware are implemented with 6 major parts: "UART", "DL", "NL", "ASE", "User Element" and "Application Program."

The "UART" sends and receives MS/TP frames. When a master node holds the token, the MS/TP master state machine transmits MS/TP frames in the transmitter queue (TxQ) up to the value of network configuration parameter "$N_{max\_info\_frames}$." MS/TP receive state machine is implemented in the receive interrupt service routine of UART1. The MS/TP receive state machine receives octet stream from the UART and it checks the validity of received frame with frame check sequence. When a complete MS/TP frame is received, MS/TP master state machine stores the received frame into the receiver queue (RxQ).

"DL" maintains MS/TP master state machine and BACnet MS/TP data link layer functions. "DL" exchanges MPCI (MAC Protocol Control Information) and NPDU (Network Protocol Data Unit) with "NL" using the DL_UNITDATA.request and DL_UNITDATA.indication primitives. "NL" exchanges NPCI (Network Protocol Control Information) and APDU (Application Protocol Data Unit) with the application layer using the N_UNITDATA.request and N_UNITDATA.indication primitives.

The BACnet application layer is implemented with two parts: "User Element" and "ASE" as presented in Fig. 2. Device object and 8 hardware-related objects *in the Table 1 are implemented in the "User Element."*

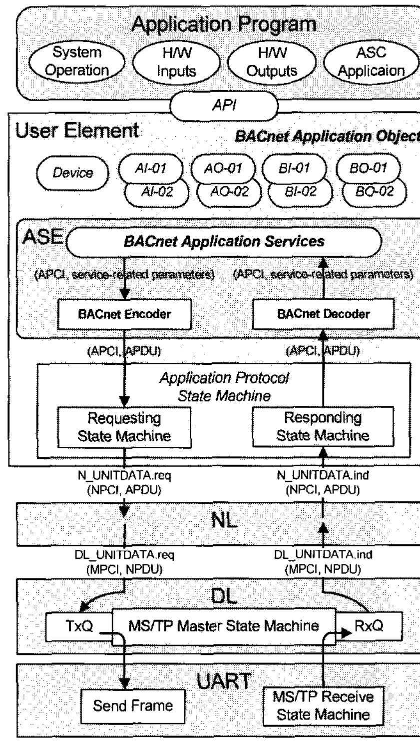

Fig. 6. BACnet protocol stack and firmware structure.

These BACnet application objects exchange application-related information with application programs through the APIs. BACnet is based on client-server communication model. The BACnet MS/TP field controller is able to act as a requesting BACnet-user (client) when it generates a BACnet application service request and it is also able to act as a responding BACnet-user (server) when it receives a BACnet application service request. The TSM (Transaction State Machine) is maintained by the "Requesting State Machine" and "Responding State Machine" in the application protocol state machine.

"*Who-Is*", "*I-Am*", "*ReadProperty*" and "*Write-Property*" services are implemented in the "ASE". BACnet APDU encoding function and decoding function are also implemented in the "ASE." The BACnet encoder composes a BACnet APDU from the APCI and the service-related parameters in the application service primitive generated by the local BACnet-user. BACnet decoder receives APCI and APDU from the responding state machine when the application service primitive is received from the peer BACnet-user. BACnet decoder extracts service-related parameters from the received APDU and sends the APCI and the service-related parameters to the corresponding application service elements.

System operation task, hardware input task, hardware output task and ASC application tasks are implemented in the "Application Program." System operation task maintains internal application parameters and local operations such as HMI communication and status LED (Light Emitting Diode) control. Hardware input task samples 2-channel analog inputs and 2-channel binary inputs. Hardware output task drives 2-channel analog outputs and 2-channel relay outputs. In order to evaluate the performance of BACnet MS/TP protocol with respect to the change of network traffic load, local traffic load generation program is also implemented as the ASC application task.

3.3. Experimental model

The experimental model of the BACnet MS/TP network system is developed as illustrated in Fig. 7. The experimental model consists of ten BACnet MS/TP field controllers, one central controller and one monitoring computer. The central and field controllers are connected on 76800bps BACnet MS/TP network. The BACnet protocol stack in Fig. 6 is implemented in every node. The central controller gathers and analyzes the performance-related information from the MS/TP messages transmitted through the MS/TP network, and reports the analysis results to the monitoring computer through the EIA-232 port. Fig. 8 shows a photograph of the experimental model developed in this study.

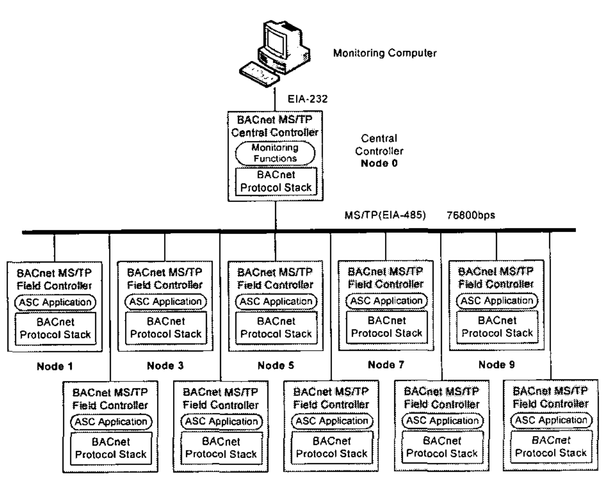

Fig. 7. Anticipated configuration of the experimental model.

Fig. 8. Photograph of the experimental model.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The performance of the BACnet MS/TP protocol is evaluated in terms of *TRT* (*Token Rotation Time*) and *RTT (Round Trip Time)*. *TRT* is defined as the elapsed time that the token circulates every node on the network. *TRT* is updated and reported to the monitoring computer whenever the central controller receives the token.

RTT is defined as the elapsed time to complete one transaction of a BACnet confirmed *ReadProperty* service between the central controller and each field controller. In order to fairly measure the *RTT* of each field controller, the queueing delays in the central controller are excluded as illustrated in Fig. 9. *RTT* is defined from the time when a request message is transmitted from the transmitter queue of the central controller to the time when a reply message transmitted by the peer field controller has completely arrived at the receiver queue of the central controller. The central controller cyclically measures the *RTT* of each field controller in every five seconds using the BACnet confirmed *ReadProperty* service. BACnet confirmed *Read-Property* is the most commonly used application service in BACnet systems to read a property of an object.

In order to evaluate the network performance with respect to the change in network traffic, the network traffic load is quantified as *G*. The physical meaning of *G* is defined as a fraction of the message generation ratio per unit time, excluding the overhead of the network protocol itself. *G* is expressed as

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

where B is the data transmission rate (bits/sec), N is the number of nodes that generate messages in the medium, T_i is the average interval of message generation at node i in seconds, and L_i is the average message length in bits generated at node i. Note that EIA-485 octets are calculated as 10 bit times including start bit and stop bit. G has a value between 0 and 1, and G approaches 1 as the traffic load in the

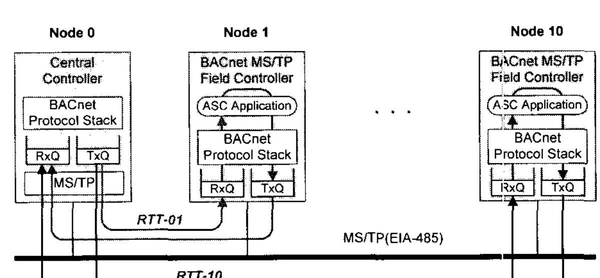

Fig. 9. The definition of round trip time.

network increases.

In this experiment, parameters are applied as L_i = 440 with 44 bytes *Unconfirmed COV Notification* message, B = 76800bps, and N = 10 master nodes. Each node generates 44 bytes *Unconfirmed COV Notification* messages symmetrically in the network with random exponential distribution. T_i is used to adjust the traffic load G. The traffic load generation program is implemented based on the "Minimal Standard" random number generator [12] with Bays-Durham shuffling procedure [13] and the exponential deviates generation algorithm introduced in [14].

According to the simulation results from the previous studies [9,10], $N_{max\_info\_frames}$ is the network configuration parameter that most greatly affects the performance of MS/TP network systems. The MS/TP field controllers transmit messages in the transmitter queue up to the value of $N_{max\_info\_frames}$ when they receive the token. Untransmitted messages remain in the transmitter queue and are transmitted at the next token receipt.

Recent draft addendum 135-2004b proposes that the BACnet MS/TP protocol allows "BACnet Data Expecting Reply" frames to be broadcasted [15]. The validity of the proposed broadcasting "BACnet Data Expecting Reply" mechanism is investigated with the experimental model. The central controller broadcasts a *ReadProperty* service requesting the value of *Present_Value* property in the *AI-01* object, and the *AI-01* object exists in every field controller on the network. Fig. 10 shows the average and maximum *TRT* with respect to the change of network traffic load when the $N_{max\_info\_frame}$ is set to its default value 10.

As shown in Fig. 10, the average *TRT* in broadcast mechanism has very similar values to the average *TRT* in original unicast mechanism, and they are increasing slowly near to 400ms as the traffic load increases. However, the maximum *TRT* in broadcast mechanism increases exponentially over 2s as the traffic load increases, and it is much higher than the maximum

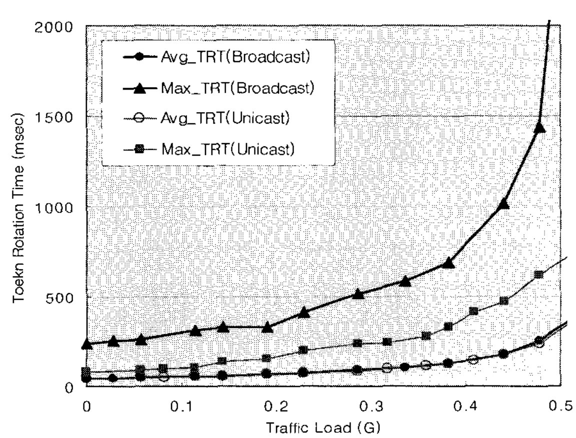

Fig. 10. Token rotation time with broadcasting "BACnet Data Expecting Reply" frames.

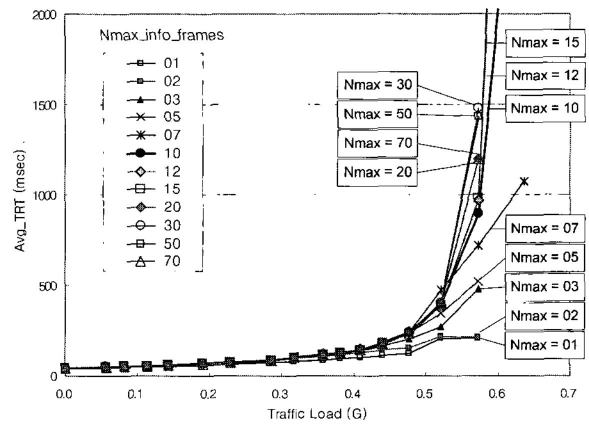

Fig. 11. Average token rotation time.

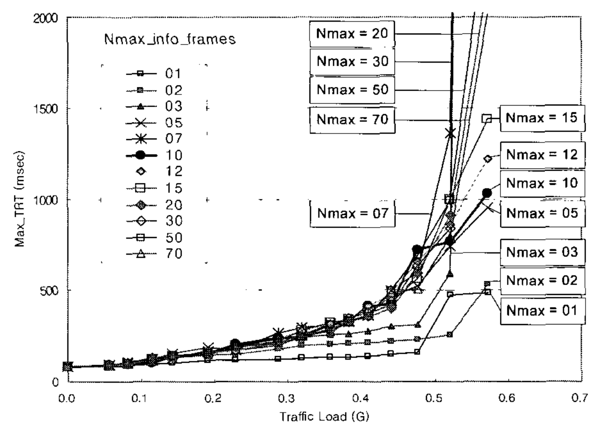

Fig. 12. Maximum token rotation time.

TRT in original unicast mechanism. According to the experimental result, broadcasting the "BACnet Data Expecting Reply" frame is not desirable because the broadcasted service request causes every node in the BACnet MS/TP network to respond to the request almost at the same time so that the broadcasted request leads instant increment of traffic load on the network and it causes *TRT* to increase instantly. The broadcasting "BACnet Data Expecting Reply" mechanism is neglected in the following experiments.

Figs. 11 and 12 show the average and maximum *TRT* with respect to the change of network traffic load and $N_{max\_info\_frames}$.

A lower $N_{max\_info\_frames}$ value restricts each node to transmit messages only up to $N_{max\_info\_frames}$, even under high traffic conditions. Untransmitted messages are stacked in the transmitter queue. With lower $N_{max\_info\_frames}$ values, the average and maximum *TRT* saturate to a certain value even though the network traffic increases.

A higher $N_{max\_info\_frames}$ value allows each node to transmit more messages when it receives the token. Under high traffic conditions, messages are transmitted up to $N_{max\_info\_frames}$ from each node before the token is handed over to the next node. Therefore, a higher $N_{max\_info\_frames}$ value causes the average and

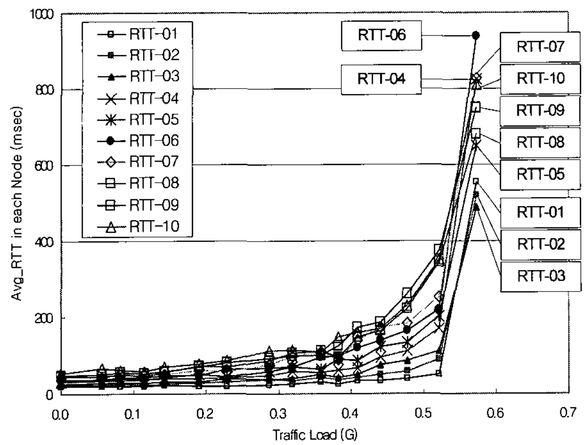

Fig. 13. Average round trip time.

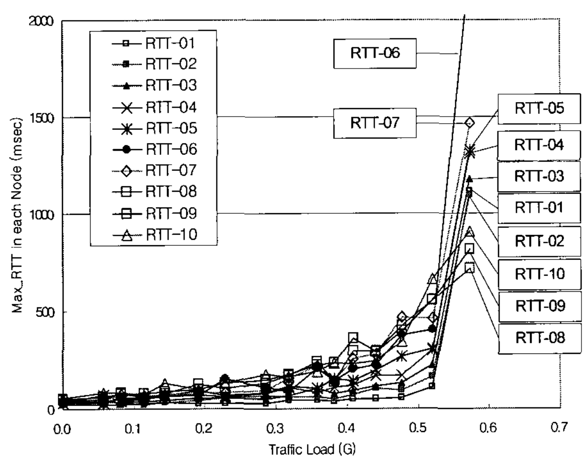

Fig. 14. Maximum round trip time.

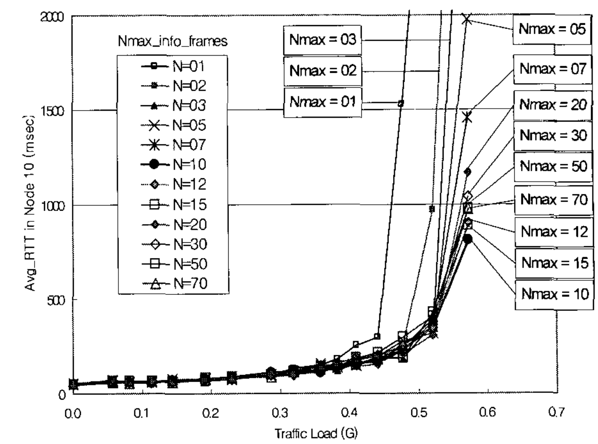

Fig. 15. Average round trip time in node 10.

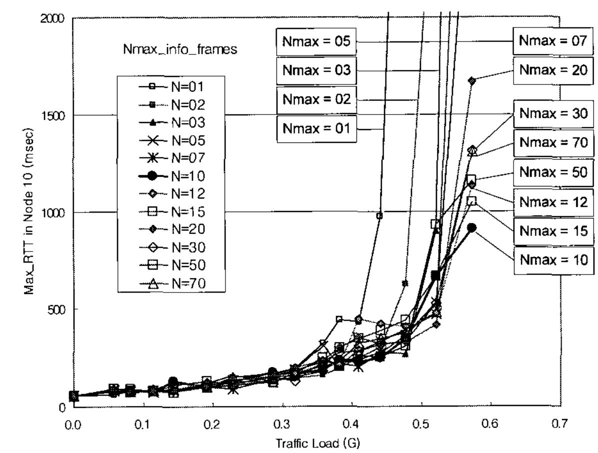

Fig. 16. Maximum round trip time in node 10.

maximum *TRT* to increase exponentially as network traffic increases. An incremental increase in *TRT* causes an incremental increase in *RTT*. The average *TRT* and maximum *TRT* increase drastically when the network traffic load exceeds the threshold point of 0.5.

Figs. 13 and 14 show the average and maximum *RTT* with respect to the change of network traffic load when the $N_{max\_info\_frames}$ is set to its default value 10. The *RTT-01* means the round trip time from the central controller to the field controller node 1 and *RTT-10* means the round trip time from the central controller to the field controller node 10.

As shown in Figs. 13 and 14, *RTT* is affected by the MS/TP node address. Under the same traffic condition, the average and maximum *RTT* in the lower node address is smaller than those in the higher node address. Because the token is circulated from lower address to higher address, the master node with higher address should wait until the token is circulated and used by the master nodes with lower addresses. Therefore, the MS/TP node address should be properly assigned according to the system configuration when designing and installing the BACnet MS/TP network-based control system. The gap between *RTTs* increases as the traffic load increases because each node transmits more messages while the node holds the token in higher traffic condition. The average and maximum *RTT* increases drastically when the network traffic load exceeds the threshold point of 0.5.

Figs. 15 and 16 show the average and maximum *RTT* in the last node (node 10) with respect to the change of network traffic load and $N_{max\_info\_frames}$.

Under the same traffic condition, the average and maximum *RTT* decrease as the $N_{max\_info\_frames}$ value increases, but when the $N_{max\_info\_frames}$ value exceeds 10, the average and maximum *RTT* increase in higher traffic condition. Because lower $N_{max\_info\_frames}$ values restrict nodes by allowing them to only transmit messages up to $N_{max\_info\_frames}$, lower $N_{max\_info\_frames}$ values increase the queuing delay of untransmitted messages in the transmitter queue. Higher $N_{max\_info\_frames}$ values, however, allow each node to transmit more messages while the node holds the token and it causes *TRT* and *RTT* to increase in higher traffic condition. Under the network configuration and traffic conditions of this experimental model, the proper value to minimize the average and maximum

RTT is 10.

According to the experiment results, the *RTT* is also affected by the MS/TP node address. Therefore, MS/TP node address should be properly assigned according to the system configuration. In this study, some address assignment guidelines are introduced with system configuration examples.

Fig. 17 shows the timeline of a centralized monitoring system that a central ASC monitors sensor values from *N* smart sensors (SS). Because the sensor value is delivered using the *Read-Property.response* primitive, in this case, the node address of the smart sensor which needs fast response such as fire alarm or life-safety sensor should be assigned close to the ASC. It is similar when a central BC (Building Controller) monitors *N* ASCs. The node address of the ASC which needs fast response such as fire alarm controller or life safety controller should be assigned close to the BC.

Fig. 18 shows the timeline of a feedback control system composed with ASC, SS and SA (Smart Actuator). T_{sc} is defined as the elapsed time to complete a transaction to read a sensor value from SS. T_{ca} is defined as the elapsed time to complete a transaction to write a control value to SA. The sensor

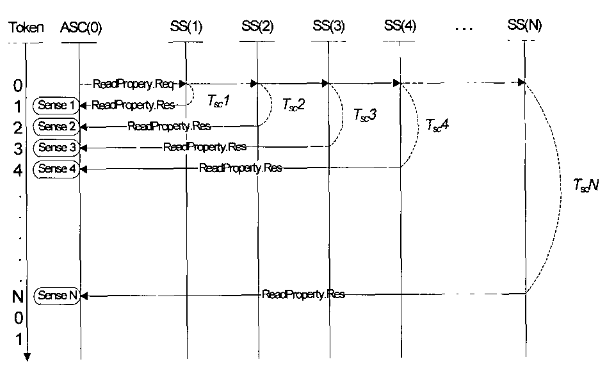

Fig. 17. Timeline of a centralized monitoring system.

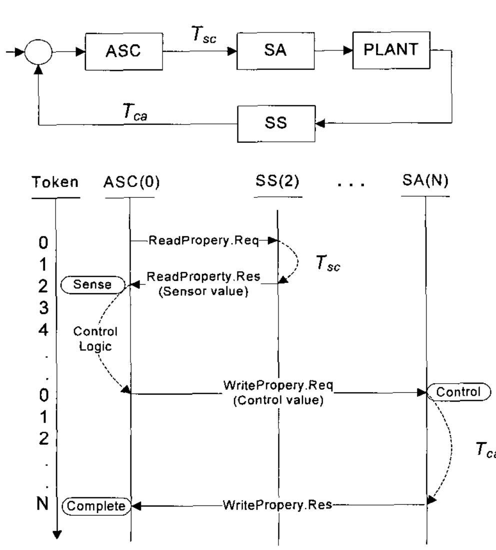

Fig. 18. Timeline of feedback control system.

value is delivered to the ASC using the *ReadProperty.response* primitive but the control value is delivered from ASC to SA using the *WriteProperty.request* primitive when the ASC holds the token. Therefore, the performance of feedback control system is more affected by *TRT* and T_{sc} rather than T_{ca}. If the SS's node address is assigned close to the ASC, the control command might be immediately put in the front part of the ASC's transmitter queue so that the control command can be transmitted by the ASC as soon as possible when it holds the token again. But If the SS's node address is assigned far away from the ASC, the control command might be put in the rear part of the ASC's transmitter queue so that the control command might not be transmitted in the next token circulation. In order to reduce T_{sc}, the SS's node address should be assigned close to the ASC and prior to the SA because when T_{sc} exceeds the macro cycle of control loop, stable operation of the feedback control system can not be guaranteed.

In general building automation systems, several ASCs, SSs, SAs are connected on the same network composing multiple control loops. In this case, the MS/TP nodes in the same control loop are recommended to be grouped together in order to reduce the network-induced delays in the control loop, and each group is recommended to be placed according to its response time as shown in Fig. 19. The control group which needs fast response such as fire alarm system should be placed close to the BC, and the control group that fast response is not required such as lighting control system can be place behind.

Fig. 20 shows the timeline of a reduced feedback control system composed with SS and actuating-ASC which has the internal actuator function. In this case, T_{ca} is ignored because the actuating-ASC directly manipulates the internal actuator in itself. In this case, the MS/TP node address of SS should be assigned close to the ASC in order to reduce the T_{sc}, and then the control loop can be completed within one token rotation. A controlling-SA which has the internal controller function could be applied instead of the actuating-ASC.

In order to maximize network performance and reduce the network-induced delays, the experimental results obtained in this study suggest that a network designer should select the appropriate $N_{max\_info\_frames}$

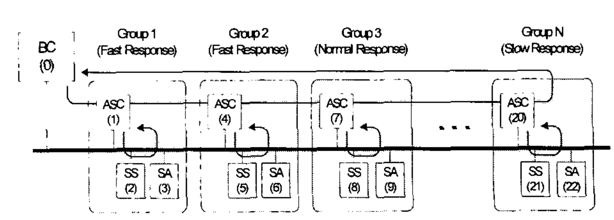

Fig. 19. Address assignment example of multiple control groups.

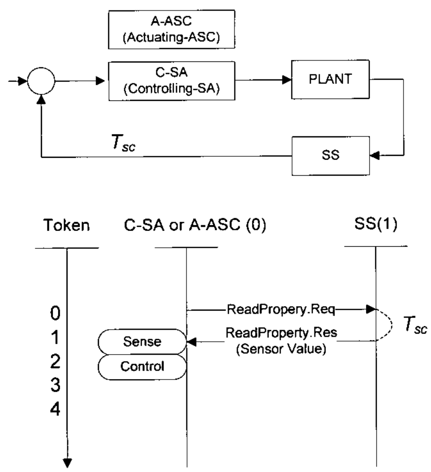

Fig. 20. Timeline of a reduced feedback control system.

value according to the system configuration and message distribution in the BACnet MS/TP network, and the MS/TP node address should be properly assigned according to the system configuration. The actuating-ASC which has the internal actuator function or the controlling-SA which has the internal controller function is more desirable in the BACnet MS/TP network-based control system.

Under the network configuration and traffic conditions of our experimental model, the proper value of $N_{max\_info\_frames}$ is 10. The experimental results also suggest that the network traffic load should be properly tuned and managed so that it does not exceed the threshold value of 0.5 in order to guarantee stable operation of the network system.

5. CONCLUSION

In this study, a BACnet MS/TP field controller and an experimental model of a BACnet MS/TP network system are developed to evaluate the performance of the BACnet MS/TP protocol. The experimental results show that the broadcasting the "BACnet Data Expecting Reply" frame is not desirable because it causes the instant increment of *TRT*. The experimental results also show the effect of *TRT (Token Rotation Time)* and *RTT (Round Trip Time)* with respect to the change of network traffic load and the network configuration parameter $N_{max\_info\_frames}$. According to the experiment results obtained in this study, the rules of thumb are summarized as follows, which can be practically applied when designing or installing the BACnet MS/TP network-based control systems.

(1) In order to guarantee stable operation of the network system, the traffic load of the MS/TP network should be tuned and managed to not exceed the threshold value of 0.5.

(2) Higher $N_{max\_info\_frames}$ values increase *TRT* as the network traffic load increases. Lower $N_{max\_info\_frames}$ values increase *RTT* because they increase the queuing delay in the transmitter queue. *RTT* is primarily affected by the increment of the queuing delay due to lower $N_{max\_info\_frames}$ values. To reduce network-induced delays and maximize network utilization, a network designer should select the appropriate value of $N_{max\_info\_frames}$ according to the network configuration and message distribution in the MS/TP network system.

(3) *RTT* is also affected by the assignment of MS/TP node address and system configuration. A network designer should select the proper MS/TP node address according to the system configuration. In the centralized monitoring system, the MS/TP node which needs fast response should be addressed close to the central controller. In the feedback control system, sensor node should be addressed close to the controller. In the multiple control loop system, the MS/TP nodes in the same control loop should be grouped in each control loop and the control group which needs fast response should be placed close to the BC.

(4) The actuating-ASC which has the internal actuator function or the controlling-SA which has the internal controller function is more desirable in the BACnet MS/TP network-based feedback control system.

The experimental results from this study will facilitate the design and installation of the BACnet MS/TP network-based control systems in building automation area.

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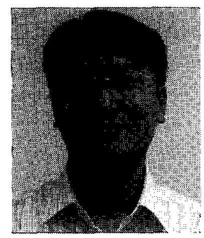

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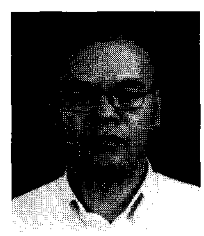

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