Development of an Experimental Model of BACnet-based Lighting Control System

Tae Jin Park, Seung Ho Hong, Member, IEEE

Department of Electronic, Electrical, Control and Instrumentation Engineering, Hanyang University, Ansan, Korea,
e-mail : tj0809@ihanyang.ac.kr, shhong@hanyang.ac.kr

Abstract − **Lighting control system provides various benefits in building management such as operational convenience, energy saving and peak demand control. BACnet(Building Automation and Control networks) is an international standard communication protocol for building automation and control networks. In this study, we developed an experimental model of BACnet-based daylighting and fluorescent lighting dimming control system. The experimental model consists of lighting control system and a mockup of indoor fluorescent lighting facility, which are interconnected using BACnet protocol. Using the experimental model, we evaluated the performance of BACnet-based lighting control system. Results from the experimental model show that the energy consumption for lighting can be reduced up to 40%.**

Index Terms – **building automation, lighting control, BACnet, MS/TP, experimental model**

I. Introduction

Modern office and residence buildings provide comfortable circumstances to the occupants using various automated facilities such as heating, ventilation and air-conditioning (HVAC), lighting, fire alarm, life safety, and security systems. In modern building automation systems, network-based control has become widespread. Network-based control not only provides real-time control and monitoring of building facilities but also efficiently manages the building system by gathering, analyzing and storing building-related information. Networking is one of the core technologies that realize advanced building automation systems [1-2].

Many vendors provided numerous products and solutions to meet the market needs using their own networking technologies. The vendor dependent proprietary technologies, however, have become a major barriers to integrate building automation systems from different vendors with the kind of 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 consensus of communication protocol standard in the world especifically designed to meet the needs of building automation and control systems [3-5].

Lighting control system provides various benefits in managing building systems such as operational convenience, scheduled control, reducing energy consumption, moderating peak demand and so on. Automated lighting contorl is one of the important methods to realize intelligent buildings and green buildings[9-10].

In our previous studies, the performance of BACnet LANs was evaluated using a simulation model and the performance of BACnet MS/TP network system was evaluated using an experimental model [11-12].

The objective of this study is to propose an integrated daylighting and fluorescent lighting dimmging control system using BACnet protocol and evaluate the performance of the proposed BACnet-based lighting control system using an experimental model.

This paper consists of six sections. Section 2 describes the BACnet and MS/TP(Master-Slave/Token-Passing) protocol briefly. Section 3 presents the configuration of the lighting control system considered here. Section 4 describes the experimental model of the BACnet-based integrated daylighting and fluorescent lighting dimming control system developed here. Section 5 analyses the performance of the BACnet-based lighting control system using the results obtained from the experimental model. Finally, conclusions and future works are presented in Section 6.

II. BACnet and MS/TP

BACnet is based on four-layer protocol architecture with the physical, data link, network, and application layers. BACnet application layer defines application objects, services and an abstract object-oriented representation of information which is communicated between building automation equipments. BACnet network layer provides a way to convey the information across a variety of local and wide-area networks that may be interconnected to form an internetwork in buildings. The data link layer of BACnet provides four LAN technologies and one point-to-point (PTP) protocol. The four LAN technologies include Ethernet, ARCNET, MS/TP and LonTalk. Among these 5 data link layer options, MS/TP is the most widely used protocol to establish connections between field level devices because it is rather easy to implement and very cost effective[6-8].

BACnet MS/TP protocol was designed to be implemented using a single-chip microprocessor with a USART(Universal Synchronous and Asynchronous Receiver and Transmitter). It uses EIA-485 signalling over a twisted-pair cable. The maximum communication length is 1200 meters with AWG 18($0.82mm^2$) cable and its supported baud rates are 9600, 19200, 38400 and 76800 bits per seconds. The name reflects the fact that MS/TP networks can be configured as a master/slave network, a peer-to-peer token passing network, or a mixture of the two.

Figure 1 shows the general system architecture of BACnet-based building automation system which consists of HVAC, lighting, safety and security facilities. It has 3 level

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hierarchies; field level, controller level and management level. Building automation equipments are connected to their corresponding MS/TP local field level networks, and these local field level networks are interconnected with Ethernet backbone network using BACnet network layer functions[5].

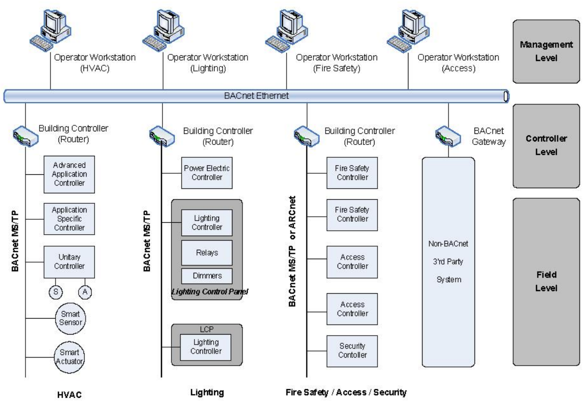


Fig 1: BACnet based building automation system

III. Lighting control system

In general, the main features of lighting control system are represented with soft-wiring and digital communication. Soft-wiring means that the relationships between switches and luminaries are maintained by the software in the lighting controller instead of conventional electric wirings. And digital communication means control and monitoring operations are performed by the information exchanged between lighting control equipments using communication networks instead of conventional hardware signals. Lighting control system makes it easy to implement complex lighting operations such as group control, scene control and scheduled control. By integrating lighting control system together with other building automation systems, more enhanced operations are also available such as reducing energy consumption, moderating peak demand and light alarm in intrusion detection.

Our previous study showed that MS/TP protocol is quite suitable for field level network in building automation systems [11-12]. In this study, we propose BACnet based lighting control system as shown in Figure 2, which uses MS/TP protocol as its field level network and lighting level network. An LCP (Lighting Control Panel) controls lighting facilities in a pre-assigned control zone. Lighting controller, relay controllers, incandescent lamp dimmers and fluorescent lamp dimmers are installed In an LCP and they are connected on a local lighting level network using BACnet MS/TP protocol. Luminaries are controlled and managed by these lighting controller and control devices. Local lighting level MS/TP network can be extended to accommodate smart sensors and smart actuators such as outdoor photocells, PIR (Passive Infrared) sensors, IR(Infrared) remote control receivers, blind controllers and sunscreens. LCPs are interconnected with each other using field level MS/TP network (as shown in Figure 1), or it can be directly connected to Ethernet backbone network if necessary.

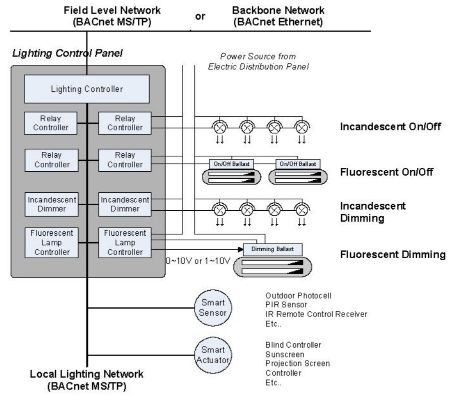


Fig 2: BACnet based lighting control system

IV. Experimental model

In this study, we developed an experimental model of BACnet-based lighting control system. It provides integrated daylighting and fluorescent lighting dimming control in a mockup of indoor fluorescent lighting environment. This section describes a BACnet lighting controller developed in this study, and installation of BACnet-based lighting control system in the mockup of indoor fluorescent lighting facility.

A. BACnet lighting controller

Figures 3 and 4 show the hardware structure and the picture of the BACnet lighting controller developed in this study, respectively. BACnet lighting controller consists of power supply, CPU, SRAM, hardware inputs and outputs, serial communication and other peripherals. Power supply generates DC 5V and DC 15V from AC/DC 24V power input. We adopted ATmega128 as the CPU of the BACnet lighting controller. We also developed firmware that includes BACnet MS/TP protocol, network layer protocol, application layer protocol and lighting control application programs, and the firmware was implemented in ATmega128's 128Kbyte internal flash memory and 32Kbyte external SRAM. ATmega128 can extend its memory space up to 64Kbytes using 16 bits address bus. In this study, upper 32Kbytes are mapped to external SRAM and lower 32Kbytes are mapped to RTC(Real Time Clock), address switch and future extension. RTC has internal NVRAM(Non-Volatile RAM) whose data can be maintained during the power reset or power fail. Local configuration parameters and network configuration parameters are saved in the NVRAM of RTC.

ATmega128 also provides two USARTs for serial communication. EIA-485 port is used for MS/TP communication and additional EIA-232 port is connected to a PC to monitor and gather experimental data. BACnet lighting controller has 8 channel 10 bit analog inputs, 4 channel 10 bit analog outputs and 4 channels relay outputs as shown in Table 1. These hardware inputs and outputs are maintained by BACnet application layer protocol and lighting control application programs.

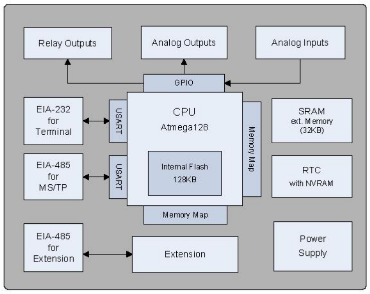


Fig 3: Hardware structure of BACnet lighting controller

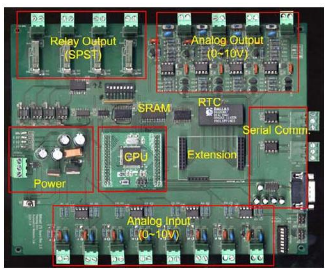


Fig 4: Picture of BACnet lighting controller

TABLE I
HARDWARE INPUTS AND OUTPUTS

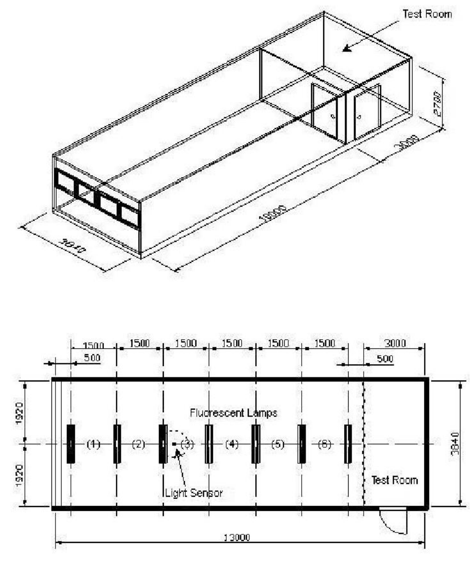
Type	Channel	Description
AI	8 ch, 10 bit	0~10V
AO	4 ch, 10 bit	0~10V
Relay	4 ch.	Single Pole Single Through

B. Mockup for indoor fluorescent lighting

We developed a mockup for indoor fluorescent lighting facility. Figure 5 shows the structure of mockup and Figure 6 shows its picture. Mockup is constructed with 10 meter length. 7 troffers are mounted on the ceiling with 1.5 meter intervals and each troffer has two 32 watt T8 fluorescent lamps as shown in Figures 5 and 6. An indoor illumination sensor is mounted between the third and fourth fluorescent lamps from window side and it detects the indoor illumination condition of the mockup. In order to monitor and evaluate the indoor illumination condition on the desktop height, 6 monitoring photocells are installed on 0.75 meter height.

C. BACnet-based lighting control system

Lighting control system developed for the experimental model is composed of five BACnet lighting controllers, and they are connected on BACnet MS/TP network. Figure 7 show the configuration and Figure 8 shows the picture of the BACnet-based lighting control system developed in this study, respectively.



(1) ~ (6) : monitoring photocells on desktop height

Fig 5: Mockup of indoor fluorescent lighting facility (unit: mm)

Fig 6: Picture of the inside of mockup

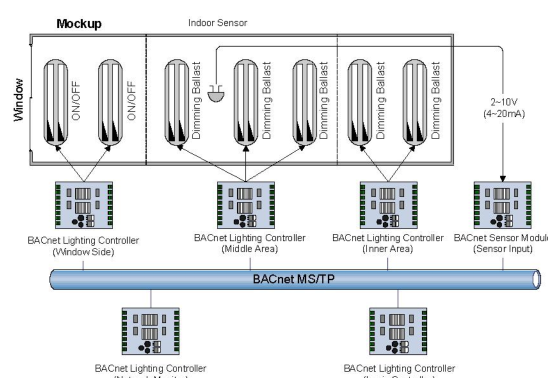


Fig 7: Configuration of the lighting control system

Fig 8: Picture of the lighting control system

Mockup is divided into three zones; window side, middle area and inner area. Each zone is controlled by a BACnet lighting controller. Fluorescent lamp is controlled by BACnet AO (Analog Output) object as shown in Figure 9. AO object represents the control output value of the fluorescent lamp with a range of 0~100 %. Fluorescent lamp is dimmed by the control signal with a range of 0~10V and it can also be on-off controlled with SPST (Single Pole Single Through) relay. In this study, the first and the second fluorescent lamps from the window side are on-off controlled and the rest are controlled by the dimming ballasts.

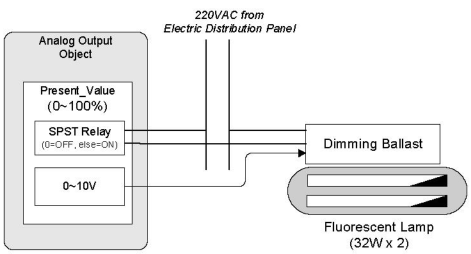


Fig 9: Fluorescent lamp and AO object

BACnet sensor module (see Figure 7) samples 4~20 mA illumination sensor signal with an interval of 1 millisecond, and convert it into a range of 0~1000 lux value. BACnet sensor module maintains the sensor information with AI (Analog Input) object as shown in Figure 10.

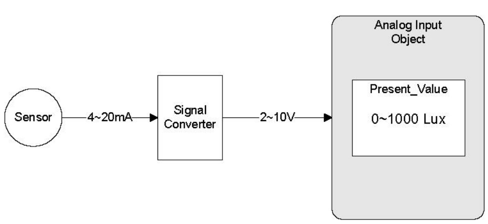


Fig 10: Indoor illumination sensor and AI object

Figure 11 shows the concept of the automated lighting control in the experimental model. Logic controller (see Figure 7) executes BACnet *Confirmed ReadProperty* request services to read indoor illumination sensor value (AI object) from the BACnet sensor module every two seconds. Based on the sensor signal, the logic controller generates seven control output values, and transmits them to the fluorescent lamp controllers for window side, middle area and inner area (see Figure 7) using BACnet *Confirmed WriteProperty* service. All these BACnet messages are delivered thought 76.8Kbps MS/TP network.

There exist network-induced delays while reading sensor values and sending control outputs through MS/TP network. In this study, we define these network-induced delays as *Read_delay* and *Write_delay*. *Read_delay* is defined as the elapsed time to complete one transaction of BACnet *Confirmed ReadProperty* service to read sensor value. *Write delay* is defined as the elapsed time to complete seven transactions of BACnet *Confirmed WriteProperty* services to control seven fluorescent lamps.

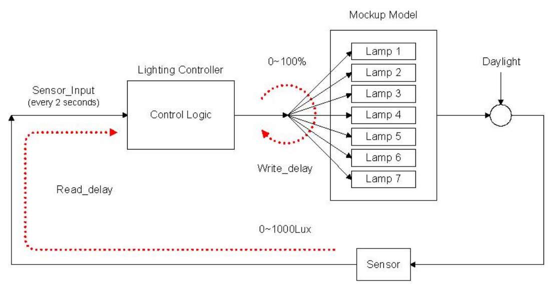


Fig 11: Automated lighting control system

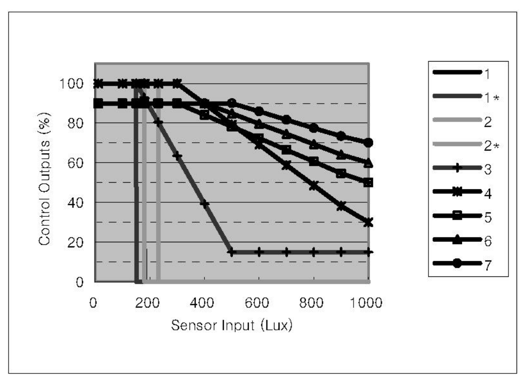


Fig 12: Control outputs for lumen maintenance

D. Lighting control scheme

In this study, we applied *daylight, lumen maintenance, and scheduling* control scheme introduced in [9] for integrated daylighting and fluorescent lighting dimming control system. The lighting control system was designed to maintain the illuminance on desktop height over 700 lux during 7 a.m. to 7 p.m., which is the ordinary office hour in buildings. For daylight and lumen maintenance, 7 control outputs for fluorescent lamps were tuned with respect to the change of sensor feedback value as shown in Figure 12.

The first and the second fluorescent lamps are on-off controlled with hysteresis bands to prevent chattering condition (see 1-1* and 2-2* in Figure 12). The other lamps in the middle area and inner area are dimmed down when the indoor luminance is increased by daylight. They are dimmed up when the indoor luminance is insufficient.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Performance of MS/TP network

In this study, we evaluated the performance of MS/TP network with respect to the change of traffic load. We quantify the traffic load as G. The physical meaning of G is defined as a fraction of message transmission time per unit time, excluding the overhead of the network protocol itself. G is expressed as:

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

where, B is a data transmission rate (bits/sec), N is the number of nodes that generate messages in the medium, T_i is an average interval of message generation at node i in seconds, and L_i is an average message length in bits generated at node i. G has a value between 0 and 1. G approaches 1 as the traffic load in the network increases.

We increased the network traffic using the traffic load generator program which was implemented in every node on MS/TP network except the network monitor node. Traffic load generator generates additional 44 bytes BACnet *Unconfirmed COV Notification* messages with Poisson distribution.

Figure 13 shows the experimental results of average TRT(Token Rotation Time), average *Read Delay* and average *Write Delay* with respect to the change of network traffic load when $N_{max\_info\_frames}$, the network configuration parameter of MS/TP protocol, was set to 10 (see reference [11] for more details of $N_{max\_info\_frames}$).

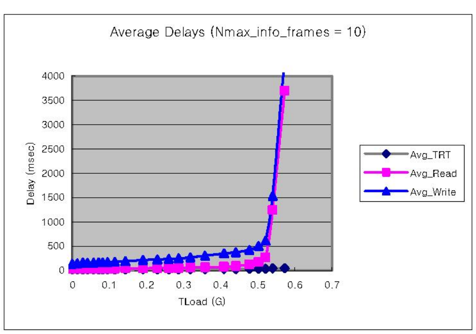


Fig 13: Average delays of MS/TP network when $N_{max\_info\_frames} = 10$

Figure 13 shows that, while the average TRT is increasing slowly from 15msec to 40msec, the average *Read Delay* and the average *Write Delay* are increasing drastically especially when the traffic load exceeds 0.5. In the high traffic condition, untransmitted messages are continuously stacked in the transmitter queue and it increases *Read Delay* and *Write Delay* exponentially. The untransmitted messages are eventually discarded from the transmitter queue or overwritten by newly generated messages. When the network-induced delays exceed sensor sampling interval of 2 seconds, the normal operation of lighting control can not be guaranteed. In our experimental model, the network traffic load should be properly tuned and managed such that it should not exceed the threshold value of 0.5.

B. Lumen Maintenance and Energy Saving

In order to evaluate the performance of BACnet-based lighting control system in terms of energy saving, we measured lumen maintenance and power consumption of the lighting system. Figure 14 shows the result obtained from the experimental model on November 22, 2005 when the automated lighting control scheme was not applied and Figure 15 shows the result with automated lighting control scheme on December 27, 2005 when the weather condition was very similar to November 22. The value of indoor illumination sensor, monitoring photocells(#1~#6), and power consumption(W) were monitored from 7 a.m. to 7 p.m.

As shown in Figure 14 and 15, the illuminance on desktop heights was maintained over 700 lux level while the daylight was changed from 8 a.m. to 5 p.m. Table 2 summarizes the experimental results of power consumption and energy saving during the office hour from 7 a.m. to 7 p.m. Table 2 shows that 40% of lighting energy saving was achieved using the BACnet-based lighting control system. Within this 40%, 28% are saved by the on-off control of the window side lamps and the other 12% are saved by the dimming control. This result demonstrates that the automated lighting control system introduced in this study is very suitable for moderating peak demand in the day time when the power consumption is increasing in buildings. Despite the substantial reduction in lighting energy, the luminance on desktop height remained over 700 lux as shown in Figure 15.

TABLE 2
ENERGY SAVING RESULT

	Without control	Automated lighting control
Avg. Power consumtion	414W	248W
Energy used	4.968KWh	2.976KWh
Energy saving	40% (on-off 28% + dimming 12%)	

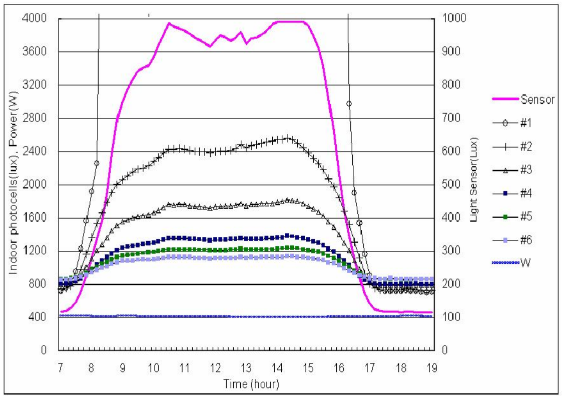


Fig 14: Experimental results without control, 100% outputs (Nov. 22. 2005)

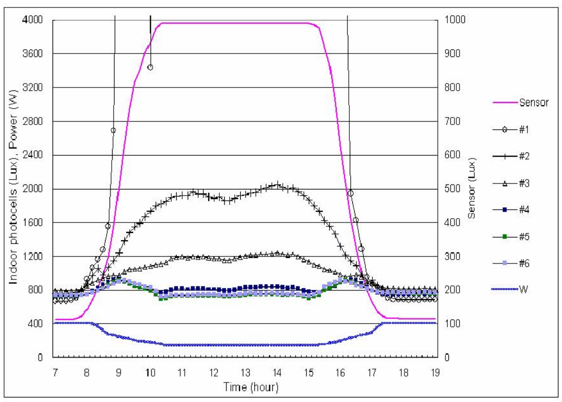


Fig 15: Experimental results with automated lighting control (Dec. 27. 2005)

VI. CONCLUSION AND FURTHER ISSUES

In this study, we developed an experimental model of BACnet-based lighting control system. Using the experimental model, we evaluated the network performance and energy saving performance for integrated daylighting and fluorescent lighting dimming control system.

Our experimental result showed that the lighting control system proposed in this study reduces 40% of average power consumption. In our experimental model, it is recommended to manage the traffic load of MS/TP network such that it does not exceed the threshold point of 0.5. In this paper, we focused our presentation on the development of the experimental model. We included some preliminary results obtained from our experimental model. Currently, we are gathering and analyzing more experimental data for various operating conditions using our experimental model. More results of experimental analysis will be presented in the future.

Currently, proposals to support the requirement of lighting control application are discussed in LA-WG (Lighting Applications Working Group) in ASHRAE SSPC (Standing Standard Project Committee) 135 which leads the standardization of BACnet protocol. IEC is also developing IEC 60929, DALI (Digital Addressable Lighting Interface) protocol for lighting control devices. All these approaches are still in progress, and we are going to study the possibility of exploiting new technologies and standards in network-based lighting control system using our experimental model.

ACKNOWLEDGEMENT

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