Network-based Fire-Detection System via Controller Area Network for Smart Home Automation

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Abstract — *This paper presents a network-based fire-detection system via the controller area network (CAN) to evaluate the feasibility of using such a home automation protocol in a smart home. In general, a conventional fire-detection system has several shortcomings, such as weakness to noise, because it uses an analog transmission with 4 – 20 mA current lines. Hence, as an alternative to a conventional system, this paper describes the structure of a CAN-based fire-detection system and the design method of a CAN communication network. The performance of the proposed system is evaluated through experimental tests. The CAN has several advantages, such as low cost and ease of implementation, as compared to other low layers of the BACNet, such as Ethernet or ARCNET. Therefore, if the CAN is selected for the low layer of the BACNet, a home automation system can be implemented more effectively*[1].

Index Terms — network-based fire-detection system, controller area network (CAN), home automation system, home network system, intelligent building.

I. INTORDUCTION

Recently constructed buildings tend to be "intelligent" to enhance the convenience and safety of occupants [1][2]. Thus, the requirements for home networks and automation systems have increased with the demand for smart homes [3]. To satisfy the needs of occupants, home appliances such as refrigerators or microwave ovens, multimedia devices such as televisions or audio systems, and Internet devices such as PCs have been included in intelligent buildings, as shown in Fig. 1. In smart homes, appliances are connected to the home network so that it becomes possible to control and monitor the appliances from inside the house or remotely using a cellular telephone or PDA. To realize a home network system, several standards, such as Echonet, Konnex, LnCP, and LonWorks, are being developed by standards organizations and corporations [4].

In addtition, home automation systems, such as HVAC (heating, ventilation, and cooling), lighting, anti-crime, and fire-detection systems are being used to improve convenience and safety for occupants. Generally, in a conventional home automation system, home equipments, such as switches, valves, or fire detectors, are directly connected to controllers for the HAVC or fire-detection systems. However, because of the analog transmission method, which uses a 4 – 20 mA current, conventional fire-detection systems detect a fire as occurring when the current received from a fire detector exceeds a predefined threshold. Hence, the system has disadvantages such as a weakness to noise of various forms, including impulses or short-circuits, and a lack of awareness of the actual location of a fire. Recently, in order to solve these problems, research on fire-detection systems that use digital or wireless transmission instead of analog transmission has been conducted [5][6]. In parallel with this, research is also being performed on communication protocols, such as the BACNet or LonWorks [7].

Recently, researchers have proposed applying the controller area network (CAN) [8] to the home network protocol, and attention has increasingly been centered on the CAN in automation (CiA) [9]-[11]. Especially, the price of a CAN microcontroller, which can be integrated into one-chip by semiconductor manufacturing companies, is low and many CAN development tools are coming onto the market. Also, many application programs had been developed in various fields such as automotive, robotic, and industrial automation systems. Therefore, a home automation system using the CAN be more easily implemented, because realization at the sensor or actuator level is relatively straightforward as compared to a system using an Ethernet that is the lower layer of the BACNet.

To evaluate the feasibility of the CAN for home automation protocols, this paper introduces a network-based fire-detection system via the CAN. The paper is organized into five sections, including this introduction. Section II gives the architecture of the network-based fire-detection system. Section III presents the design method of the CAN-based fire-detection system, and verifies that a CAN communication network satisfies the real-time requirements of a home automation system. Section IV describes an experimental testbed that was implemented to verify the feasibility of the proposed system. Finally, a summary and the conclusions are presented in Section V.

II. ARCHITECTURE OF NETWORK-BASED FIRE-DETECTION SYSTEM

A. *Conventional fire-detection system*

Fig. 2(a) shows the architecture of a conventional fire-detection system. As shown in the figure, fire detectors (*e.g.*,

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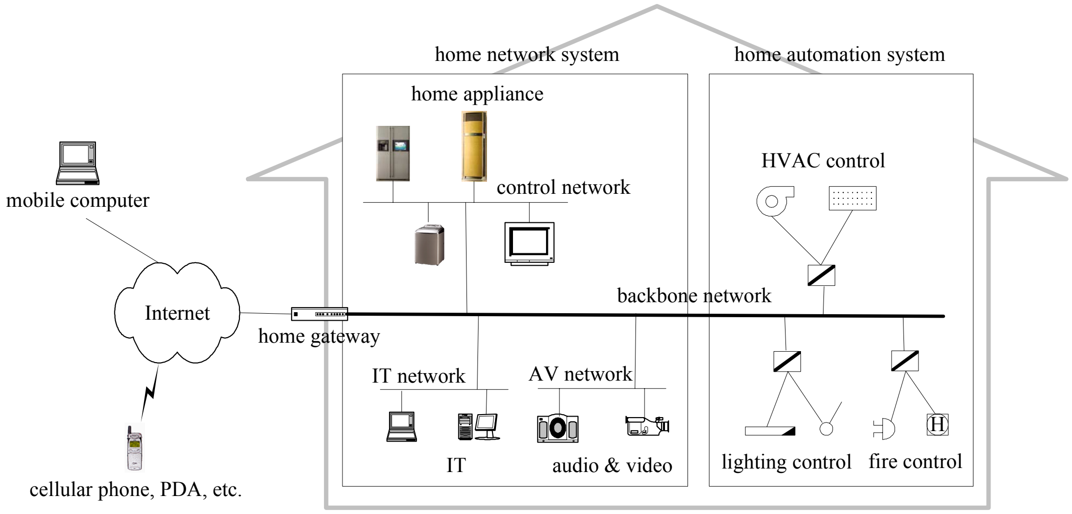


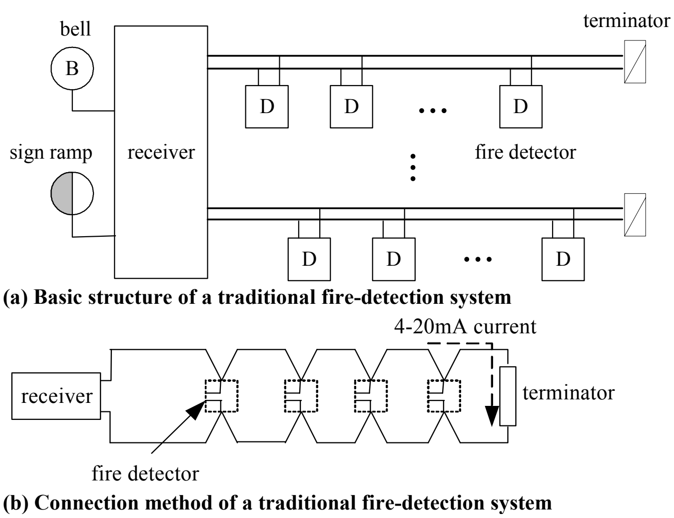
Fig. 1. Schematic diagram of a home network system.

smoke detector, heat detector, gas detector, *etc*.) and actuators (*e.g.*, guide light, fire wall, sprinkler, smoke ventilator, *etc.*) are connected to a receiver via a dedicated analog signal line with a current of 4 – 20 mA. In particular, several fire detectors that guard the same area are connected to a single signal line. Fig. 2(b) shows the connection method used between the receiver and the fire detector in a conventional fire-detection system. As shown in the figure, the receiver perceives a fire based on the fact that the current increases in the corresponding analog connection line when a fire occurs. That is, the fire detector that perceives the fire causes the analog line to short-circuit so that the current increases. At this time, when the receiver detects that the current in a corresponding line has increased, it relays this information using a bell or a signal lamp to indicate that a fire has occurred in the corresponding area.

Generally, the current in an analog line will be increased if any one of the fire detectors connected to that line perceives a fire in the conventional fire-detection system. Hence, the receiver cannot distinguish which detector connected in a single analog line has sensed a fire, so the location where a fire has occurred can not be indentified. Furthermore, because the receiver recognizes that a fire has occurred only by the increase in the current above a specific threshold, a conventional fire-detection system cannot process data such as the quantity of smoke or the degree of heat detected by the fire detectors. If there is a breakdown in the analog line owing to deterioration or corrosion before a fire occurs, the receiver will neither recognize the problem nor detect the fire. Therefore, there is a very high probability that a conventional fire-detection system may misfunction.

B. Network-based fire-detection system

Fig. 3 shows the architecture of a network-based fire-detection system that is able to overcome the shortcomings of a conventional fire-detection system. As shown in the figure, a fire detector, an actuator, a bell, and a display device are connected by a shared transmission medium, and information is exchanged using digital communication. Using this connection method, the receiver can identify which fire detector senses a fire because each fire detector has its own address. Also, because the receiver periodically examines the state of the fire detectors, it can recognize a breakdown in the system, such as the failure of a fire detector or an open circuit in the transmission medium. In addition, the number of false alarms is less than with conventional systems because analog data such as the quantity of smoke and the amount of heat



(a) Basic structure of a traditional fire-detection system

(b) Connection method of a traditional fire-detection system

Fig. 2. Basic structure of a traditional fire-detection system.

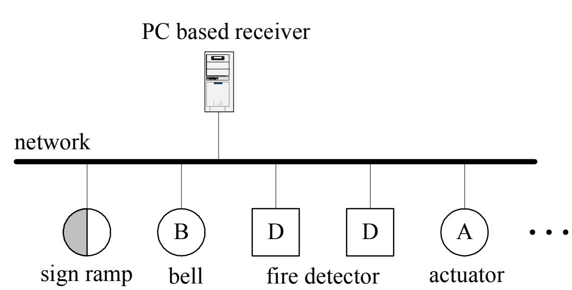


Fig. 3. Structure of a network-based fire-detection system.

measured by each fire detector can be sent to the receiver. It is straightforward to apply such a system to an intelligent fire detection system and to apply a reasoning algorithm, because the receiver can make use of the digitized detection values of the smoke and heat from multiple fire detectors installed in the same guard area. As changes in the detection signals can be calculated and compared, assessment of risk can be improved [12].

Besides, a PC-based receiver can be used in a network-based fire-detection system for greater convenience. Generally, it is easier to install and maintain a PC-based receiver than a conventional dedicated receiver. Since man-machine interface (MMI) technology can be applied to a PC-based receiver, it is straightforward to create a user interface and integrate the fire-detection system into a home network system. Recently, several protocols, such as BACNet, LonWorks, and Bluetooth, have been developed to implement network-based fire-detection systems in intelligent buildings [5][6].

III. DESIGN OF A CAN-BASED FIRE-DETECTION SYSTEM

A. Overview of the CAN protocol

CAN 2.0B is a network protocol that was specifically developed for connecting the sensors, actuators, and ECU's of a vehicle. CAN 2.0B supports data rates from 5 kbps to 1 Mbps, which allows the CAN network to be used to share status information and for real-time control. The network topology can be either a linear bus or a star.

CAN 2.0B has the following properties:

- distributed medium access control, meaning that each device has the same privilege to use the shared medium.
- contention-based and nondestructive bus access, indicating the access to the bus has to be obtained through some type of competition but with no loss of network capacity due to the contention.
- content-based addressing, implying that each message packet has a unique identifier according to its content.
- cyclic redundancy check for error detection, and
- error confinement to block any adverse effects of a network component failure.

A device on the network can transmit its message whenever the network is idle. When the network is busy, the packet transmission has to be delayed until the on-going transmission has finished. Because electronic signals on the network have a finite speed of propagation, there is always the possibility that multiple devices will start their transmissions within a short interval. This situation, called message collision, is resolved by comparing the identifiers of the messages involved; that is, the message with the lowest identifier value wins the right to use the network, while the other devices must stop their transmissions immediately. As the identifier is located at the beginning of the packets and the electronic signal for zero is designed to overwrite the signal for one, the message with the lowest identifier value finishes the contention with no damage to the packet. The other devices will try to resend their packets when the first transmission has finished. This arbitration procedure is shown in Fig. 4.

B. Design of a CAN-based fire-detection system

This section presents the design methodology of a CAN for a fire-detection system. Fig. 5(a) shows the frame exchange between the receiver and the fire detector during the normal state. In the figure, the receiver inspects the state of the fire detectors by sending a poll frame to each fire detector and actuator in the poll list once every T_P (polling period). When it receives the poll frame, each fire detector and actuator transmits a status frame that includes its own fire detection value back to the receiver. Thus, the receiver can periodically perceive the state of a fire-detection system such as a fire detector failure or a breakdown such as an open circuit.

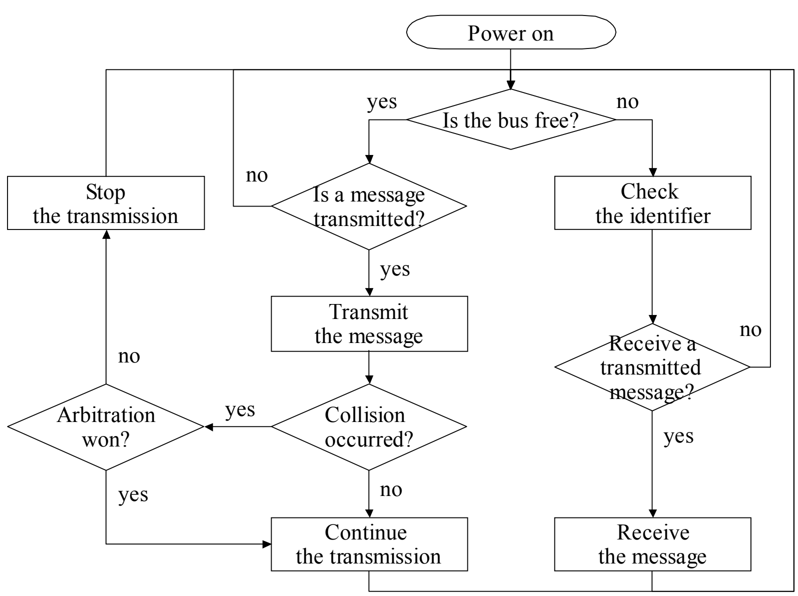
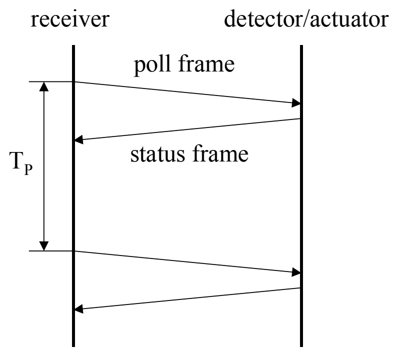
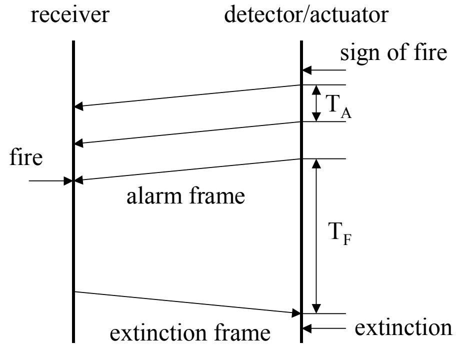


Fig. 4. Flowchart of the CAN protocol.



(a) Exchange of the status frame



(b) Exchange of the fire alarm and extinction frame

Fig. 5. Frame definition in a CAN-based fire-detection system.

Fig. 5(b) shows the frame exchange between the receiver and a fire detector when a fire occurs. In the figure, the detector measures values such as the amount of heat, quantity of smoke, or quantity of gas, and thus detects the signs of a fire. It then transmits an alarm frame that includes the detected values to the receiver once every T_A (alarm period). When the receiver receives an alarm frame, it analyzes the real-time fire information from multiple fire detectors located in the same area to judge whether a fire has occurred. If the fire detection values exceed a predefined threshold, the receiver considers a fire to have occurred and transmits an extinction frame to the corresponding actuators to put out the fire. The fire detectors stop transmitting the alarm frame when they receive the extinction frame. Here, the response time, T_F, is the elapsed time between the transmission of the alarm frame by the fire detector and the reception of the extinction frame by the actuator.

Using these methods, a network-based fire-detection system will be superior to the conventional fire detectors, because the receiver can synthetically judge whether a fire has occurred using the directly received fire detection data from multiple fire detectors. However, to satisfy the real-time requirements of a CAN-based fire-detection system, the alarm frame and extinction frame must be transmitted earlier than other frames.

In order to guarantee that a network-based fire-detection system meets the above requirement, we introduced an ID allocation method, shown in Fig. 6. As shown in the figure, a 29-bit ID field for the CAN is organized into five ID sub-fields to classify the four types of frame. The first portion of the frame ID defines the type of frame. Here, to ensure that the extinction frame is transmitted before any other frames, the value of the extinction, alarm, poll, and status frames are set to 00, 01, 10, and 11, respectively. Fig. 7(a) shows an example of the transmission order when several frames with different frame IDs are generated simultaneously. In the figure, the extinction frame of the receiver (frame ID of 00) is transmitted before any other frames, as determined by a feature of the CSMA/NBA algorithm used in the CAN. The alarm frame B of a fire detector B (frame ID of 01) is then transmitted before the status frame of a fire detector A (frame ID of 11).

The second portion of the frame ID defines the fire level, which is used to ensure that older frames are transmitted before newer frames. The initial fire level ID value is set to 1111. Fig. 7(b) shows an example of how the fire level ID changes. Suppose that two frames with the same frame ID of 00 are simultaneously generated in fire detectors B and C, and that the unique ID of the fire detector B is higher than that of a fire detector C. At this point, the other IDs (block, sensor type, and unique IDs) of the two frames are compared, and the frame of the fire detector B, which has a higher priority, is transmitted first. While, the frame of the fire detector C fails in transmission due to a loss of competition, and then its fire level ID value is decreased from 1111 to 1110 so that its priority increases. Now suppose that another frame with the same frame ID of 00 is generated in the fire detector A, before the fire detector B starts its transmission procedure. The frame value of the fire detector A is 001111, and that of the fire detector C is 001110. Hence, the frame of the fire detector C is transmitted before that of the fire detector A. Finally, the frame of the fire detector A is transmitted. Using this logic, when several fire detectors recognize signs of fire and transmit alarm frames simultaneously, each frame will be transmitted to the receiver in the correct order with a minimum amount of delay, and the receiver can correctly identify the location of the fire.

The third portion of the frame ID is the block, which is used to divide the fire sensors and actuators into groups. For example, if a fire occurs in a certain area, this field is used to transmit an extinction frame to all of the actuators that are located in that area to put out the fire. The fourth portion of the frame ID, the sensor type, is used to identify the types of fire

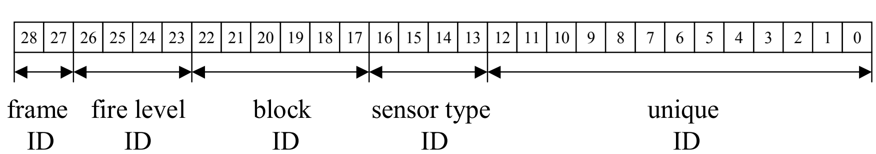
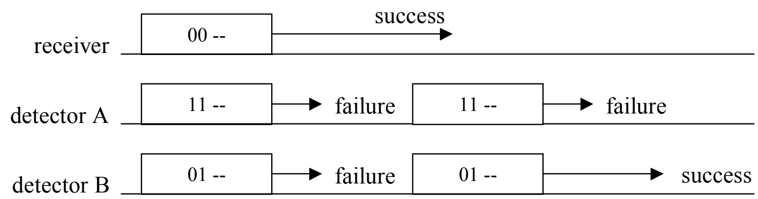
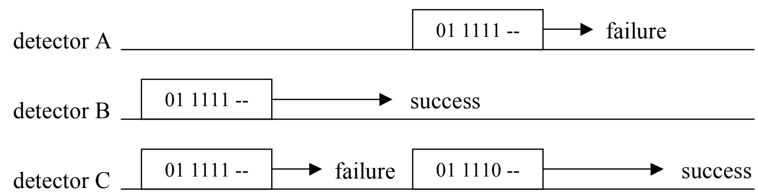


Fig. 6. ID allocation method in a CAN-based fire-detection system.



(a) Example of contention owing to the frame ID



(b) Example of contention owing to the frame and the fire level IDs

Fig. 7. Example of contention owing to ID.

detector and actuators, such as smoke sensors, heat sensors, gas sensors, sprinklers, fire walls, *etc*. Finally, the last portion of the frame ID is a unique value that is assigned to each fire detector and actuator.

C. Maximum transmission delay of a CAN-based fire-detection system

Since a frame with a higher priority ID should be transmitted before the other frames in the CAN, the lowest priority ID may be transmitted after the maximum allowable delay, which is defined by the network designer. Therefore, to guarantee the performance of a CAN-based fire-detection system, a polling cycle, T_P, and an alarm cycle, T_A, must be selected appropriately so that the delay of any frame is less than the maximum allowable delay.

In order to select T_P and T_A, the worst-case transmission time (C_m) of the CAN with a 29-bit ID field can be calculated as follows [13]-[15]:

$$C_m = \left(\left\lfloor \frac{54 + 8s_m}{4} \right\rfloor + 67 + 8s_m \right) \tau_{bit} \tag{1}$$

where τ_{bit}, which is the bit time, is the inverse of the transmission speed [16]. For example, if the transmission speed of the CAN is 500 kbps, the bit time is 2 μs. Also, s_m is the byte length of the CAN message. The first part of s_m is the size of the worst case bit value, the second part of s_m is the overhead length of the CAN message, and the last part of s_m is the bit length of the CAN message.

In the worst case that alarm frames are received from all fire detectors and extinction frames are transmitted to all actuators, all frames must be transmitted within the maximum allowable delay to guarantee the performance of the CAN-based fire-detection system. Hence, T_P and T_A should be selected as follows:

$$(T_P, T_A) > \sum_{i=1}^{Nd} C_{Ai} + \sum_{i=1}^{Na} C_{Ei} + \sum_{i=1}^{Nd+Na} (C_{Pi} + C_{Si}) \tag{2}$$

where C_{Ai} is the transmission time of an alarm frame generated in the i^{th} fire detector, C_{Ei} is the transmission time of an extinction frame generated in the i^{th} actuator, C_{Pi} and C_{Si} are the transmission times of a poll frame and status frame that are transmitted to a fire detector or an actuator, and N_d and N_a are the number of fire detectors and actuators that are connected to the CAN-based fire-detection system. For example, suppose that the data length of all frames is 1 byte, and that 8,000 fire detectors and 2,000 actuators are connected to the CAN-based fire-detection system. Here, the data length has been set to 1 byte because that is sufficient to transmit the data measured by the fire detectors. In this case, C_{Ai} is 180 μs from (1), and T_P and T_A are 5.4 s from (2). Hence, if T_P and T_A are greater than 5.4 s, all frames can be transmitted within one cycle and the performance of the CAN-based fire-detection system can be assured.

The National Fire Protection Association (NFPA) suggests that the fire warning response time for a fire alarm signal, which is defined as the interval between when sensors detect a fire and when actuators start to extinguish it, should be less than 90 s [5][17]. This response time can be regarded as the maximum allowable delay for a CAN-based fire-detection system. The transmission delay of 5.4 s in the above example is much less than the maximum allowable delay, so the performance of our CAN-based fire-detection system meets the NFPA guidelines. As far fewer fire detectors and actuators are installed in home automation systems than in our example, our CAN-based fire-detection system can be effectively implemented in such systems.

IV. EXPERIMENTAL EVALUATION OF A CAN-BASED FIRE-DETECTION SYSTEM

The experimental model shown in Fig. 8 is used to evaluate the feasibility of our CAN-based fire-detection system. In this experimental setup, four communication modules for one PC-based receiver, two smoke detectors, one gas detector, and an additional communication module to emulate the actuator are connected to the CAN. The transmission speed of the CAN is set to 500 kbps, and one CAN repeater is used to expand the transmission range of the network. Also, a PC-based receiver is programmed using CAPL by CANalyzer. The smoke sensors are NEMOTO NIS-05As, and the gas sensor is a NEMOTO NAP-55A. An Atmel AT89C51CC01 microcontroller is used as a communication module that acted as a CAN 2.0B controller, and a Philips PCA82C250 is used as the CAN transceiver for signaling.

Fig. 9(a) shows the operation algorithm of the PC-based receiver in the experimental model. As shown in the figure, the receiver transmits poll frames to the fire detectors in a given order, once every T_P cycles. At this time, if a collision occurred, IDs are compared, and the frame with the highest priority ID is transmitted first. The fire level ID of the frame that lost the competition is increased, and it then waits until the transmission medium is idle. If an alarm frame with a fire quantity that exceeds the threshold value is detected during the carrier sensing, an extinction frame is transmitted to activate the corresponding actuators. In these tests, T_P is set to 10 ms, which is sufficient because all frames generated in the experimental model are transmitted within this time.

Fig. 9(b) shows the operation algorithm for a fire detector and an actuator in the experimental model. As shown in the figure, when the fire detector received a poll frame under a no-fire condition, it transmitted a status frame containing its detection value. If the fire detector perceived a fire, it transmitted an alarm frame that included the changed detection value and waited to receive an extinction frame. If the fire detector did not receive an extinction frame from the receiver within a period of T_A, it repeated its transmission of an alarm frame with a new detection value. Here, T_A was set to 10 ms.

Fig. 10 shows a transmission frame in our CAN-based fire-detection system measured by an oscilloscope. Fig. 10(a) shows the poll and status frames that are periodically exchanged between the receiver and fire detector. If a fire occurred, the fire detector transmits an alarm frame to the receiver, as shown in Fig. 10(b). When the receiver acknowledges that a fire have occurred after receiving a fire detection value beyond a threshold value, it transmits an extinction frame to the corresponding fire detectors. Here, the response time of the fire alarm signal is 0.27 ms, which is much smaller than the NFPA requirement of 90 s [5][17].

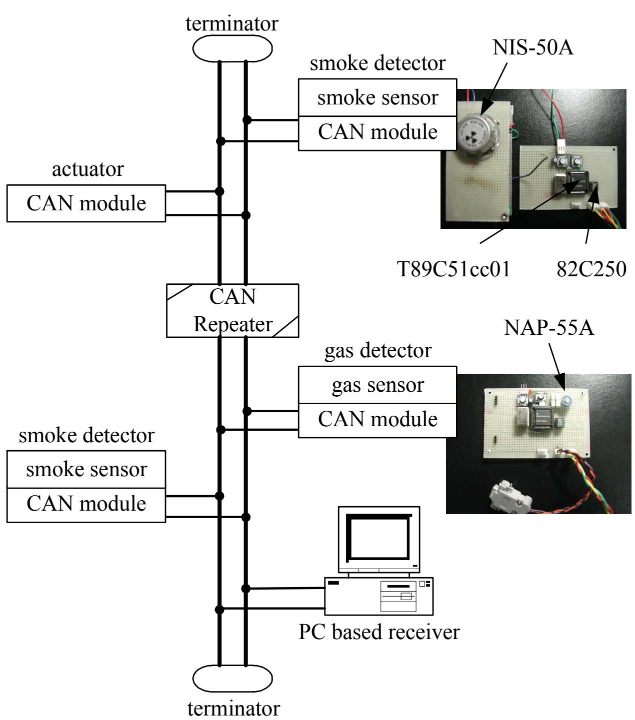
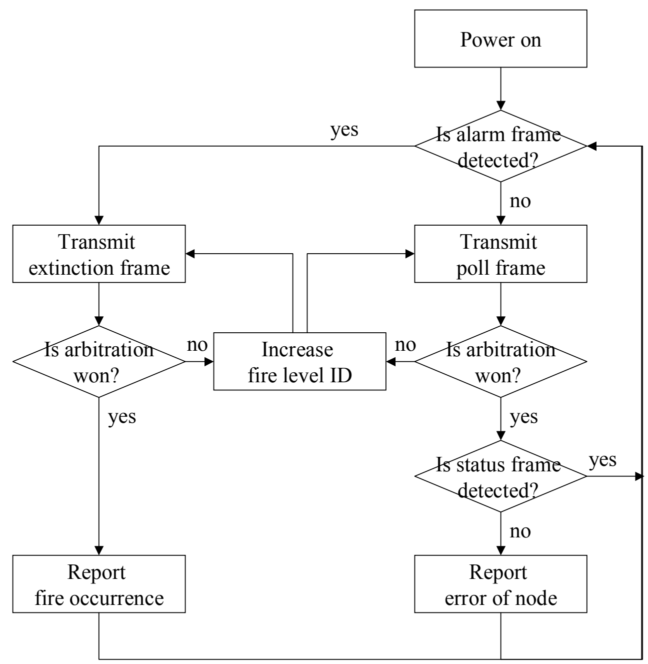
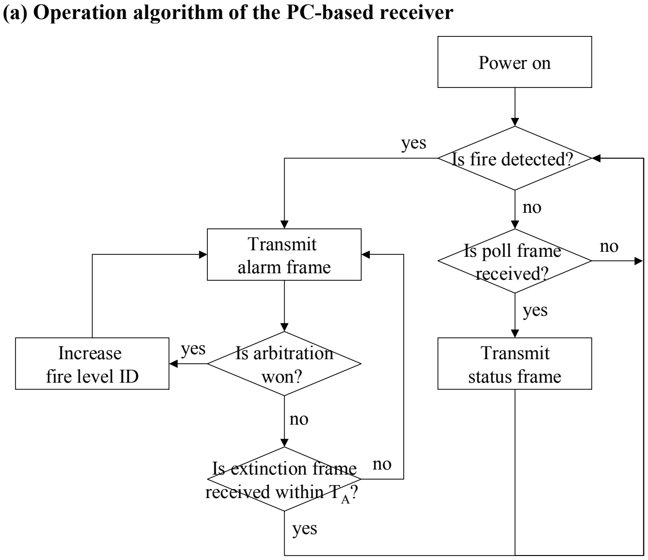


Fig. 8. Experimental testbed of a CAN-based fire-detection system.



(a) Operation algorithm of the PC-based receiver



(b) Operation algorithm of the fire detector or actuator

Fig. 9. Operation algorithm of a CAN-based fire detector.

Fig. 11 shows a measured analog fire value from a smoke sensor obtained by the receiver. As shown in the figure, if the receiver continuously receives a smoke voltage greater than 4 V from the smoke sensor, it judges that a fire has occurred and transmits an extinction frame to the corresponding actuators. If it receives a value lower than 4 V from the smoke sensor, it judges that the fire has been extinguished.

In a conventional fire-detection system, when the receiver receives a value greater than 4 V owing to a temporary malfunction from noise, it decides that a fire has occurred and activates the actuators. However, A CAN-based fire detector transmits analog values of fire detection data to the receiver when it detects a fire, which can be used to avoid false alarms. Also, a CAN-based receiver receives fire detection data from several fire detectors, and can use this information to evaluate whether a fire has indeed occurred. Therefore, owing to its advanced features, a CAN-based fire-detection system is more accurate than a conventional fire-detection system. In addition, if two or three fire detectors are installed at any particular point, a CAN-based fire-detection system can accurately detect a fire despite of a malfunction in any one of fire detectors.

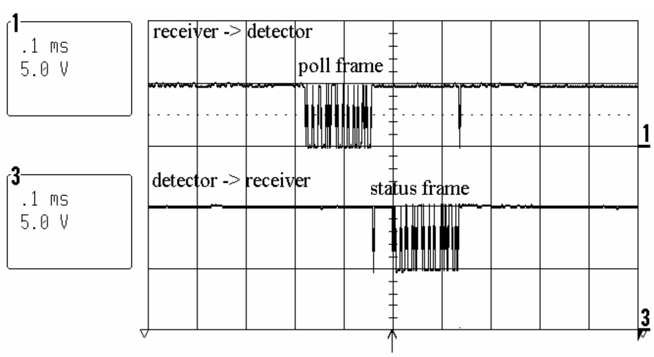
V. Summary and Conclusions

This paper presents a CAN-based fire-detection system and verifies that such a system can be used in a smart home. We describe the structure of a CAN-based fire-detection system and the design method of the CAN. Also, an experimental model is used to evaluate the performance of the system.

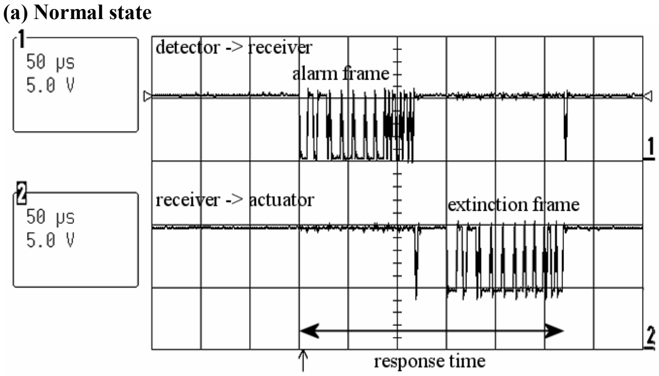
From several experiments, it can be said that the system satisfies the NFPA requirements in that the fire warning response time is very short. Also, as the receiver obtains fire detection data directly from the fire detectors, it can be said that the system is more accurate than the conventional fire-detection systems. In addition, if two or three fire detectors are installed at any particular point, the CAN-based fire-detection system can accurately detect a fire despite of a malfunction occurring in any one of fire detectors.

Especially, the price of a CAN microcontroller, which can be integrated into one-chip by semiconductor manufacturing companies, is low, and many CAN development tools are coming onto the market. Hence, a fire-detection system based on the CAN has the advantage that the implementation of sensors or actuators is straightforward as compared to a system using an Ethernet that is the lower layer of the BACNet. This makes it easier to design a home automation system.

However, this paper focuses only on the basic structure of a CAN-based fire-detection system. For practical application of these research results, the implementation of an application layer and a power supply should also be studied. In addition, research into the redundancy of the communication module will be required to obtain the necessary fault-tolerance properties required in a CAN-based fire-detection system.



(a) Normal state



(b) Fire detection

Fig. 10. Message transmission in the CAN-based fire-detection system.

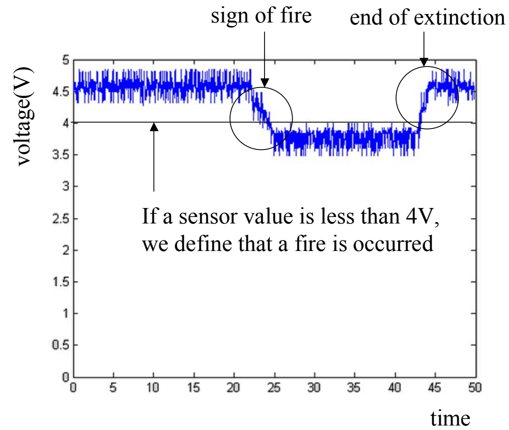


Fig. 11. Message transmission for fire detection using an actual sensor value.

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