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Sinusoidal Current Signal-Based Fire Detection System with Automatic Address Assignment

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Abstract: In this paper, a novel sinusoidal current signal-based fire detection system is proposed with automatic address assignment. The system model employs a conventional power line to embed fire information, i.e., the address, rather than using an additional communication line. At the transmitter, different frequencies of the sinusoidal current signal are combined and transmitted through a power line. At the receiver, fast Fourier transform (FFT) is applied to distinguish the frequency bins, which can represent the addresses of fire detectors. The proposed system model is implemented and the numerical results are presented in terms of measurements.

Keywords: sinusoidal current signal; fire detector; fast Fourier transform (FFT); embedded system; automatic address assignment

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1. Introduction

Fire is one of the major disasters that can occur in factories, which is generally attributed to a large number of events. The increased usage of sensors, electronic devices, and robots has caused significant human and property losses in industrial areas because of fires [1]. According to the National Fire Protection Association (NFPA), an estimated 37,910 fires per year in industrial and manufacturing properties were reported in the United States (US). These fires included 26,730 outside or unclassified fires, 7770 structure fires, 3410 vehicle fires and around 1.2 billion US dollars in property damage per year. Structure fires are more common in manufacturing or processing properties, while vehicle fires are more common in agricultural properties. In particular, electrical distribution and lighting equipment was involved in 24% of structure fires, and heating equipment was involved in another 16% of these fires [2]. According to the Korean Fire Protection Association (KFPA), an estimated total of 11,669 fires, and property loss totaling 112.5 billion won, were reported in the last 5 years. The most damaged sites were factories, occupying 81.1%. In 2020, fires caused 25 civilian deaths and 259 injuries. Regarding deaths, the proportion of casualties caused by burns was 28.5%, followed by smoke and toxic gas inhalation at 22.2% sequentially [3]. The most highly developed countries in the world are affected by the risk of fire in industrial areas.

Therefore, the early detection of fire reduces the risks of death, injury, and property loss. A fire detection system is one of the most fundamental safety systems for factories. In recent years, fire detection systems have been developed in two ways to improve the performance of the attached sensors [4,5] and transmit/receive fire information such as the fire level and location [6,7]. Extensive research has been conducted on fire detection systems in the manner of using fire information. In [8], a fire detection system was implemented using vision sensors, motion detection, candidate object segmentation, and frame/smoke blob detection. In [9], a federated fire protection system was developed to react and adapt to critical fires. Their results leveraged all the crucial information and computed the facilities over cloud/fog/edge devices. In [10], multichannel sensor networks were applied to real-time fire detection systems based on dynamic time warping. The proposed algorithm flexibly selected critical sensors for detecting fires in an early state. However, these conventional systems require additional communication lines [11–14]. In addition, the detectors consisted of a microprocessor, communication module, etc., which increases both costs and complexity. To cope with these issues, a novel current signal-based fire detection system is proposed in this paper.

The proposed system model employs a sinusoidal current signal to exploit both amplitude and frequency. The fire detector works on generating a sinusoidal current signal and detecting the fire via an attached sensor. Through a power line, all information is transmitted by combined sinusoidal current signals. At the receiver, these combined signals are analyzed by applying fast Fourier transform (FFT). The main contributions of this paper are as follows.

- A conventional power line is used to transmit essential fire information such as the fire level and address.
- A generalized system model is presented that comprises a single control receiver (CR) and total N number of fire detectors.
- An automatic address assignment is implemented for multiple fire detectors, which involves two steps: initial configuration and renewal configuration.
- The performance of the proposed system is demonstrated in terms of the frequency detection measurement, sinusoidal voltage/current signal measurements, and amplitude and frequency of FFT.

The remainder of this paper is organized as follows. Section 2 presents the system model that comprises the total N number of fire detectors and a single CR. The details of the proposed system model are described separately regarding how to obtain the fire information and identify the address of the fire detection. Section 3 demonstrates the numerical results obtained for the proposed system model, such as the frequency detection measurement, sinusoidal voltage/current signal measurements, and FFT information. Lastly, Section 4 presents the conclusions.

2. System Model

The generalized proposed system model consists of n number of fire detectors, where $n = 1, \cdots, N$ $(N > 1)$, and a single CR, which are shown in Figure 1. The CR includes a microcontroller unit (MCU), an amplifier, and a sensor to capture the sinusoidal current signal. Additionally, the fire detector includes an MCU that does not require high performance since it only generates a sinusoidal current signal. The attached sensor measures the temperature, which is a basic function for a fire detector. The CR has two functions: (1) observation of sinusoidal current signals and (2) automatic address assignment for multiple fire detectors. The fire information is defined as the fire level and address.

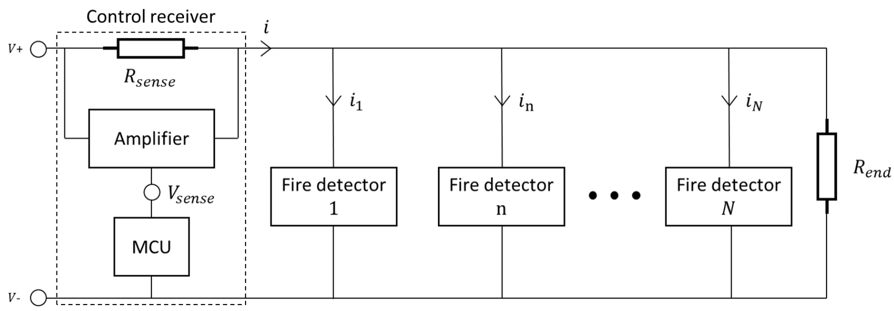
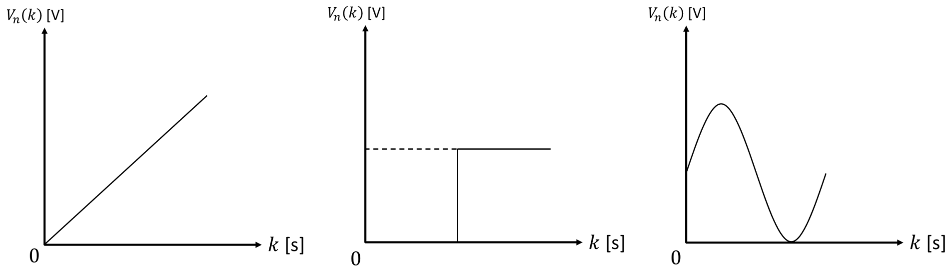


Figure 1. System model.

Conventional fire detection systems require separate communication lines to transmit the fire information. Conversely, the proposed fire detection system enables the use of a power line instead of establishing a new communication line. The generation of sinusoidal current signals enables fire detectors to transmit the fire information through a power line. Different frequencies of sinusoidal current signals are multiplexed with FFT. The individual fire detectors can be distinguished from the CR due to their different frequencies. Furthermore, an amplitude offset can be applied to avoid noise from the power line.

2.1. Sinusoidal Voltage/Current Signal Analysis

This subsection presents the analysis of the sinusoidal current signal as fire information. Firstly, the output signal from the fire detector must be separated as shown in Figure 2. The analog and on/off types are considered as output signals in the conventional system, whereas we employ a sinusoidal type to exploit both the amplitude and frequency of the signal. The output signal (a) can express a fire level that is proportional to the amplitude of the signal. However, the noise generated by multiple fire detectors may be weak. Conversely, the signal (b) only transmits a fire notification, and it can be strong for noise owing to the digital expressions, such as bits. The proposed output signal (c) can transmit both the fire level and address, thereby avoiding the noise from multiple fire detectors. Additionally, the basis noise from the power line can be avoided by applying an offset from (1).



(**a**) Analog (**b**) On/off (**c**) Sinusoidal

Figure 2. Output signal for fire detector.

In the power line, the amplitude range of the current signal can be decided and limited by a given voltage level. Therefore, the amplitude and frequency of the sinusoidal current signal are matched with the fire level and address, respectively. The transmitted current signal at k-th time slot can be expressed as

$$i_n(k) = A_n B(2\pi f_n k) + \eta \text{ [A]} \tag{1}$$

where A_n denotes the amplitude of n-th fire detector address. $B(\cdot)$ can be replaced by the cosine or sine function. f_n denotes the frequency of n-th fire detector address. η represents the offset required to avoid the basis noise from the power line.

Generally, the measurement of the current signal is more expensive and has more limitations than the measurement of the voltage signal. In the system model, a sensor resistor is used to detect the voltage level and transforms it to the current level. Therefore, the received voltage signal at k-th time slot can be expressed as

$$v_n(k) = i_n(k)R = \{A_n B(2\pi f_n k) + \eta\}R \text{ [V]} \tag{2}$$

where R denotes the sensor resistance. During the measurement, the received voltage signal is represented as the output signal for each fire detector.

Multiple voltage signals are captured at the CR. It is designated that each fire detector generates different frequencies. Therefore, the received voltage signal can be expressed as

$$v_n = \sum_{n=1}^{N}\sum_{k=1}^{K} i_n R = \sum_{n=1}^{N}\sum_{k=1}^{K}\{A_n B(2\pi f_n k) + \eta\}R \text{ [V]} \tag{3}$$

where i_n represents the current signal at a given period of time K [seconds].

The CR performs FFT to estimate the frequency bin, and the amplitude of the voltage signal is estimated as the magnitude of FFT bins. The frequency bin refers the address of the fire detector. While estimating the amplitude of the voltage signal, the offset must be eliminated to recover the original fire level. In addition, the Nyquist sampling theorem [15] is assumed to avoid aliasing problems in FFT.

From [16], the received voltage signal obtained by applying FFT can be expressed as

$$f_j = \sum_{n=0}^{N-1} v_n e^{-\frac{2\pi i}{N} jn}, \; j = 0, \cdots, N-1 \tag{4}$$

where i denotes an imaginary number, and j denotes the number of frequency bins. v_n denotes a complex number from (3). Based on the size of the FFT bin, the expressions of frequencies are determined.

2.2. Automatic Address Assignment

This subsection describes the automatic address assignment method used for the proposed system. Conventional fire detection systems use separate communication lines to assign the addresses of each individual fire detector. From [17–19], information technology can be applied to divide the discrete addresses. However, these technologies are not applicable to the proposed fire detection system, which uses a power line to transmit and receive the fire information. This inevitably leads to applying the proposed address assignment for a power line. We assume that each fire detector responds to the threshold of the current signal.

Figure 3 depicts the automatic address assignment method, which is an algorithm that shares the random addresses of fire detectors. All fire detectors are required to respond to the activation threshold from the CR. Incremental addresses are assigned for the fire detectors from 1 [Hz] to N [Hz] based on the maximum level of the voltage signal. The proposed method involves two aspects: initial address assignment and address reassignment. Likewise, the activation thresholds can be set up as two values for the initial and renewal configurations. Firstly, the purpose of the activation threshold for the initial configuration checks all addresses of fire detectors to memorize an address book. Secondly, the activation threshold for the renewal configuration is intended to check empty addresses of replaced fire detectors. Therefore, the proposed address assignment is divided into two configurations: (1) initial configuration and (2) renewal configuration.

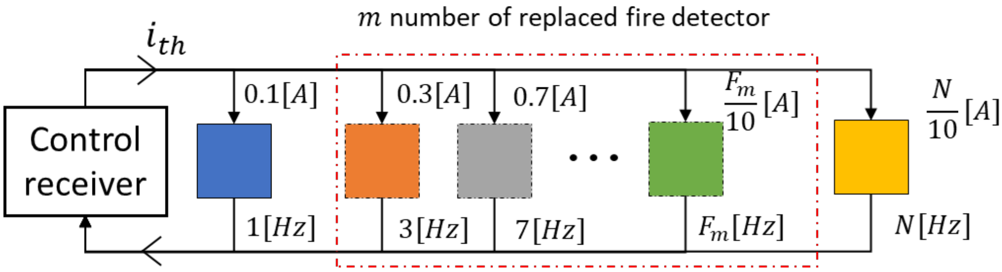


Figure 3. Automatic address assignment.

2.2.1. Initial Configuration

The CR generates n-th addresses for the fire detectors. This can be assigned by activation threshold ith from the CR to each fire detector. The CR sequentially transmits a gradient current signal such as $0.1, 0.2, \cdots, N/10$ [A], which splits the number of fire detectors. In consequence, each fire detector responds to the CR with a total of N [Hz] sinusoidal current signals. The CR memorizes responses from n-th fire detector as an address book.

2.2.2. Renewal Configuration

The renewal configuration is a procedure used to check for the empty frequency and to reassign the addresses. In the case of broken or malfunctioning fire detectors, the CR revises an address book to reassign addresses for the fire detectors. It is assumed that m number of fire detectors are replaced, as shown in Figure 3. To estimate the empty addresses of the fire detectors, the CR sends an activation threshold that is different from that of the initial configuration. The CR checks the number and addresses of replaced fire detectors. $F_m/10$ [A] and F_m [Hz] are presented to distinguish the current level and FFT bin.

Table 1 presents an example of the memorization and reassignment addresses. The total number of fire detectors and number of replaced fire detectors are $N = 10$ and $m = 3$, respectively.

Table 1. Example of assigning new address.

Number (#)	Amplitude [A]	Frequency [Hz]
1	0.5	5
2	0.4	4
3	1	10
4	0.1	1
5	0.8	8
6	0.6	6
7	0.9	9
8	0.3	3
9	0.2	2
10	0.7	7

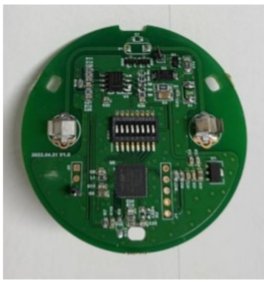
FFT Bin F_m	Reassign Frequency [Hz]
4	0.4
8	0.8
3	0.3

3. Experimental Results

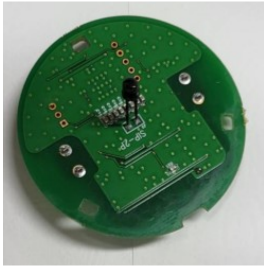
This section presents the numerical results for the proposed system model. The purposes of experiments are to validate the detection accuracy and visualization for combined signal analysis. The experimental environment is briefly shown in Table 2. The implemented fire detector and CR are shown in Figure 4. The red and yellow boxes represent the implementation of the CR and a fire detector, respectively. The output signal for the fire detector is measured using the oscilloscope in Figure 5. From Figures 6–10, it can be redrawn using a computer to clearly demonstrate the results. The output voltage/current signals have [V]/[A] units and the amplitude of FFT is normalized as 1. The frequency interval is 10 [Hz] in the voltage/current signal measurement and 5 [Hz] in multiple combined signal measurement, which is chosen according to sensor performance.

Table 2. Experimental environment

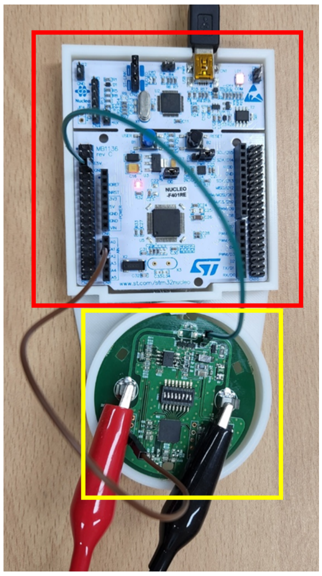
Parameter	Value
MCU for fire detector	STM32G071C8U6TR
MCU for CR	STM32F401RET6
DC supply	DIGITAL DRP-9303TP
Oscilloscope	Tektronix MDO3012
Sensor resister	91 [Ω]
Frequency range	15∼490 [Hz]



(**a**) Front of fire detector

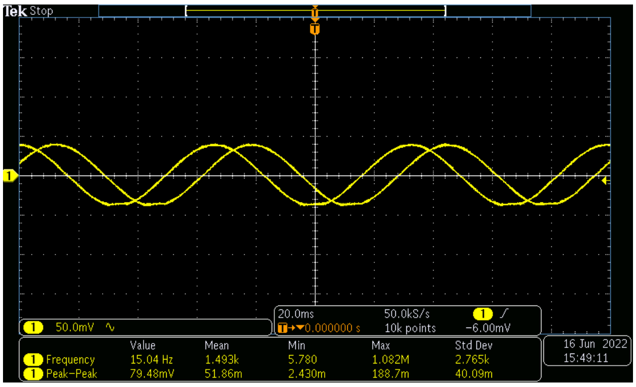


(**b**) Back of fire detector

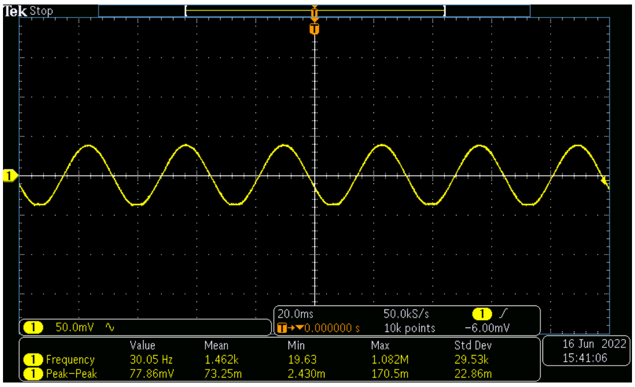


(**c**) Integration of CR and fire detector

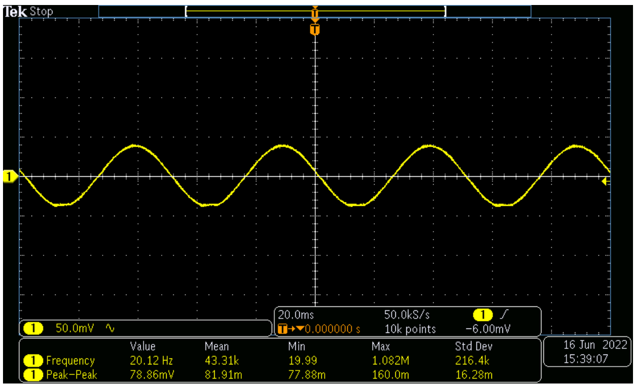
Figure 4. Implemented results.



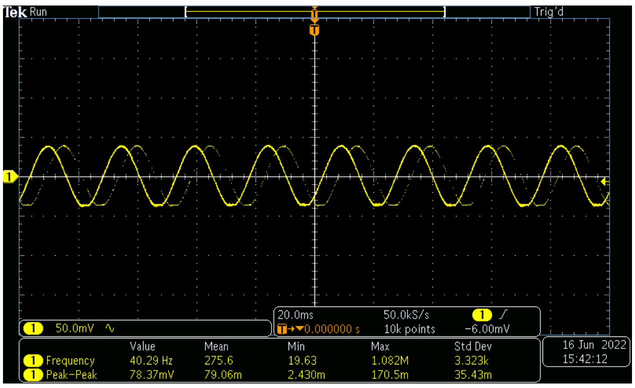
(**a**) 15 [Hz]



(**c**) 30 [Hz]



(**b**) 20 [Hz]



(**d**) 40 [Hz]

Figure 5. Oscilloscope measurements.

In Figure 6, the sinusoidal voltage signal is shown corresponding to k [seconds]. In this testbed, we fix the amplitude of the voltage signal to 0.3 [V] because the noise level is varying. As can be seen, the voltage signal includes the noise from the power line. As previously mentioned, the voltage signals are measured in the system model because the attached sensor is based on the resistor value.

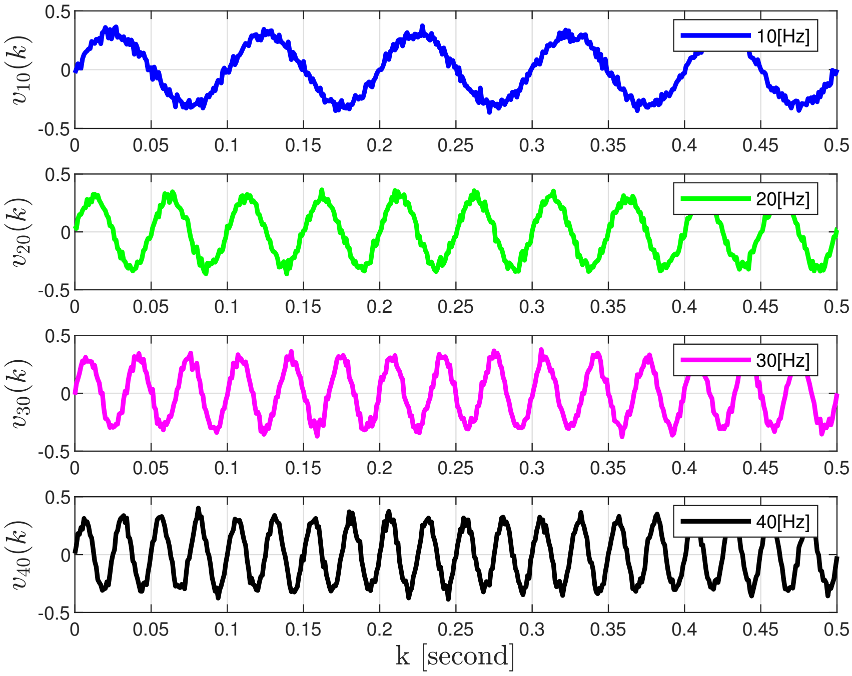


Figure 6. Sinusoidal voltage signal measurement.

In Figure 7, the sinusoidal current signal is shown corresponding to k [seconds]. Additionally, we use a current probe to verify that a higher noise level occurs in the current signal when compared to that in the voltage measurement. However, it still has a sinusoidal waveform to analyze the result of FFT. The combined sinusoidal current signal is shown in Figure 8. The combinations of frequencies are divided, such as $(10 + 15 + 30)$, $(20 + 35 + 40)$, and $(25 + 30 + 45)$ [Hz].

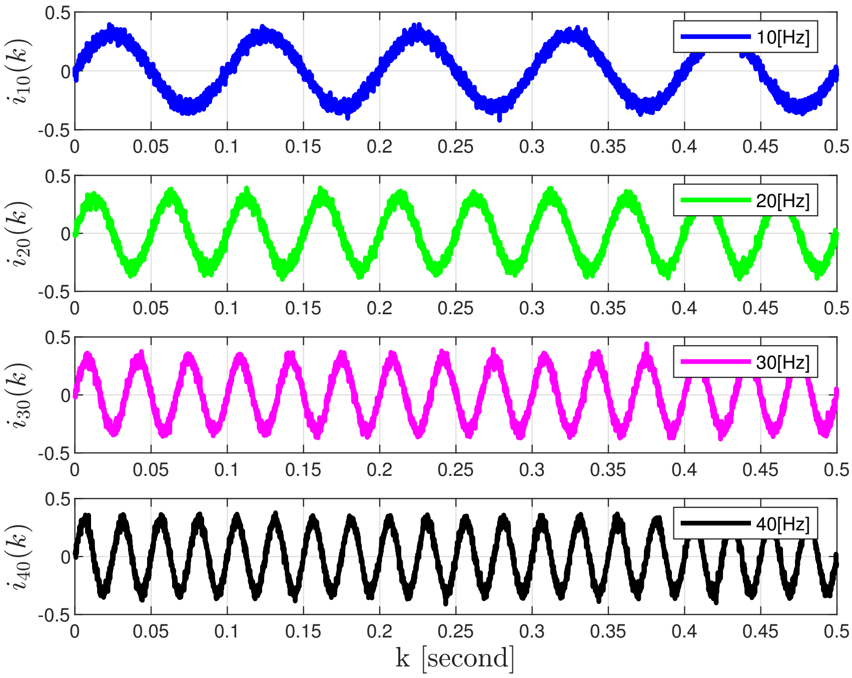


Figure 7. Sinusoidal current signal measurement.

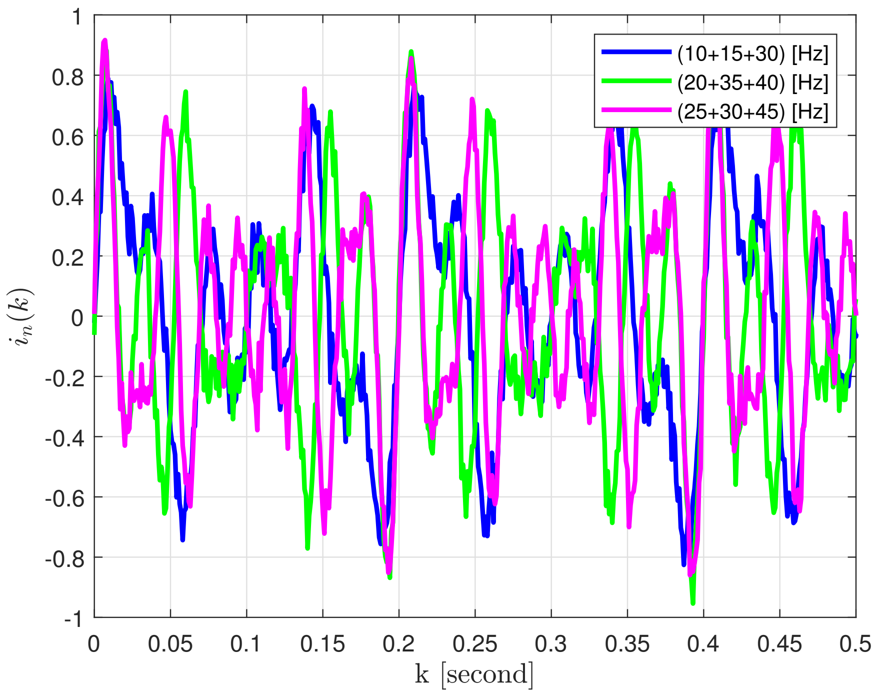


Figure 8. Multiple sinusoidal current signal measurement.

In Figure 9, the FFT output, which is the amplitude and frequency of FFT, is shown corresponding to *n* [Hz]. Each frequency is detected well, even when a low-amplitude signal is applied. The amplitude of the signal is fixed to 0.3 [A] owing to the reduced power consumption of the fire detector. A sequential experiment is shown in Table 3 for the detailed frequency measurement. The average frequency detection rate is less than 10%.

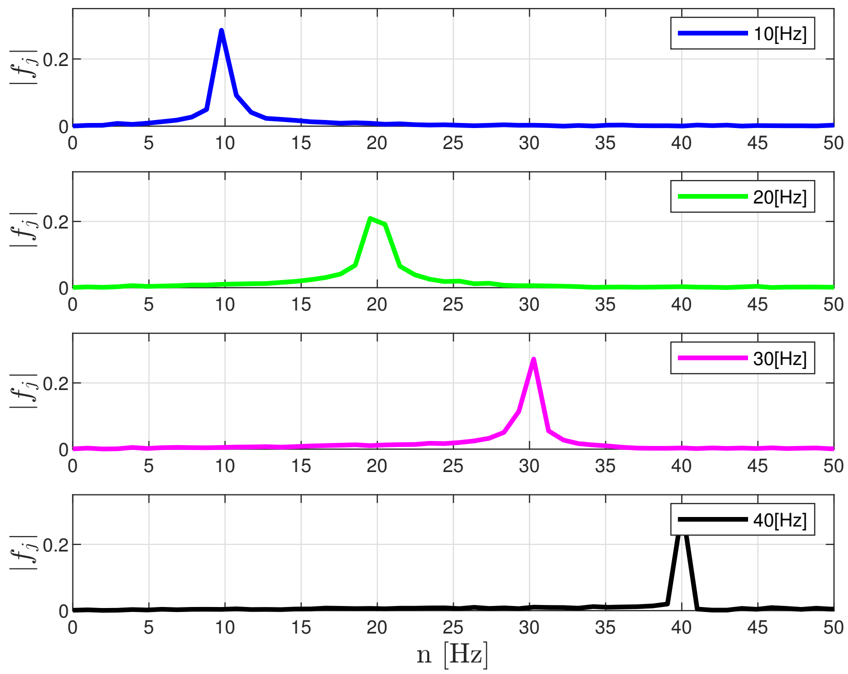


Figure 9. Amplitude and frequency of FFT.

In Figure 10, the FFT output for combined signals is shown corresponding to n [Hz]. The amplitudes are slightly varying because of the noise level. Nonetheless, the frequencies for combined signals are detected well. In this testbed, the maximum of the FFT bin is given as 1024. In the case of multiple frequency detection, the demonstration confirms the validation of the proposed system model.

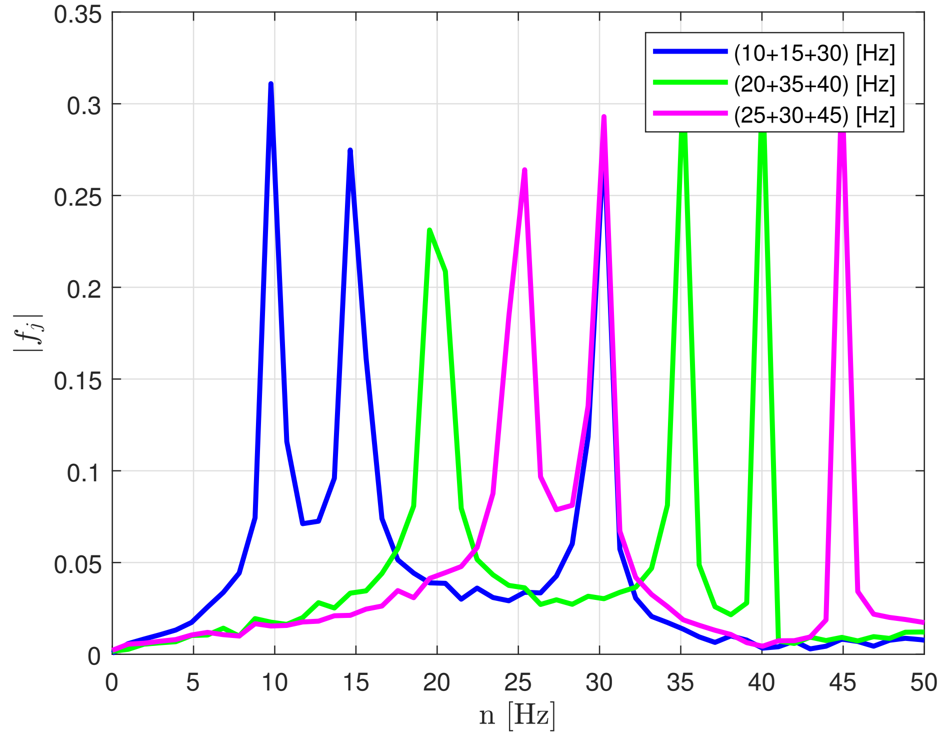


Figure 10. FFT output for combined signals.

Table 3. Frequency detection measurement.

Frequency [Hz]	#1	#2	#3	#4	#5	Avg.
15	15.04	15.00	15.04	15.03	14.98	**15.02**
17	17.04	16.97	17.01	17.06	17.05	**17.03**
19	19.08	19.03	19.01	18.99	19.06	**19.03**
20	19.98	20.11	20.02	20.05	19.99	**20.03**
22	22.01	21.97	22.06	22.07	22.05	**22.03**
24	24.06	24.08	24.10	24.11	24.04	**24.08**
26	25.96	26.05	25.95	26.07	26.13	**26.03**
30	30.04	30.02	30.02	30.01	30.04	**30.03**
40	40.01	40.06	40.11	40.04	40.08	**40.06**
42	42.14	42.20	42.11	42.08	42.16	**42.14**
43	43.04	42.97	43.04	43.03	43.11	**43.04**

4. Conclusions

This paper proposes a novel sinusoidal current signal-based fire detection system with automatic address assignment. This system employs a conventional power line to transmit the fire information. The sinusoidal current signal is analyzed and used for transmitting information. The automatic address assignment also helps to maintain the proposed system in the given malfunctioning fire detectors. A testbed is implemented to demonstrate the effectiveness of the proposed system model. Additionally, the numerical results are presented in terms of the frequency detection measurement, sinusoidal voltage/current signal measurement, and FFT output. An automatic address assignment is used to maintain the system for replaced fire detectors. In the future, we aim to improve the proposed system model to transmit the fire temperature data as additional information.

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Abbreviations

The following abbreviations are used in this manuscript:

CR	Control receiver
DC	Direct current
FFT	Fast Fourier transform
MCU	Microcontroller unit

References

1. Aashika, J.; Arthi, R. Smart Factory Using IOT. *Int. J. Multidiscip. Res. Sci. Eng. Technol.* **2019**,*2*, 224–231
2. Campbell, R.B. *Fires in Industrial and Manufacturing Properties*; National Fire Protection Association, Research, Data and Analytics Division: Quincy, MA, USA, 2018.
3. 2020 Analysis of Fire Statistics Safety Inspection Results for Special Buildings: South Korea, 2020.
4. Ullah, I.; Karimov, K.S.; Ibrahim, M.A.; Fatima, N. Flexible longitudinal and transversal displacement sensors based on a composite of CI Disperse Orange 25 and carbon nanotubes. *Color. Technol.* **2022**, *138*, 90–96. [CrossRef]
5. Asghar, U.; Karimov, K.S.; Ibrahim, M.A.; Fatima, N. Multifunctional organic shockproof flexible sensors based on a composite of nickel phthalocyanine colourant, carbon nanotubes and rubber created with rubbing-in technology. *Color. Technol.* **2022**, *138*, 176–183. [CrossRef]
6. Cheon, J.; Lee, J.; Lee, I.; Chae, Y.; Yoo, Y.; Han, G. A single-chip CMOS smoke and temperature sensor for an intelligent fire detector. *IEEE Sens. J.* **2009**, *9*, 914–921. [CrossRef]
7. Das, S.D.; Biswas, A.; Bhattacharjee, R.; Gupta, S.; Dey, B. Automatic Fire Detector. In *Advances in Communication, Devices and Networking*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 487–492.
8. Bu, F.; Gharajeh, M.S. Intelligent and vision-based fire detection systems: A survey. *Image Vis. Comput.* **2019**, *91*, 103803. [CrossRef]
9. Tricomi, G.; Scaffidi, C.; Merlino, G.; Longo, F.; Puliafito, A.; Distefano, S. A Resilient Fire Protection System for Software-Defined Factories. *IEEE Internet Things J.* **2021**. [CrossRef]
10. Baek, J.; Alhindi, T.J.; Jeong, Y.S.; Jeong, M.K.; Seo, S.; Kang, J.; Shim, W.; Heo, Y. Real-time fire detection system based on dynamic time warping of multichannel sensor networks. *Fire Saf. J.* **2021**, *123*, 103364. [CrossRef]
11. Jee, S.W.; Kim, S.K.; Yang, S.H.; Lee, J.J.; Kim, P.Y.; Lee, C.H. Detection of fire location and reliability improvement of the conventional fire detector and P-type receiver. *J. Korean Inst. Illum. Electr. Install. Eng.* **2011**, *25*, 39–44.
12. Seo, B.K.; Nam, S.G. Study of the improvement of false fire alarms in analog photoelectric type smoke detectors. *Fire Sci. Eng.* **2016**, *30*, 108–115. [CrossRef]
13. Lee, K.C.; Lee, H.H. Network-based fire-detection system via controller area network for smart home automation. *IEEE Trans. Consum. Electron.* **2004**, *50*, 1093–1100.
14. Wang, H.; Zhang, Y.; Meng, L.; Chen, Z. The research of fire detector based on information fusion technology. In Proceedings of the 2011 International Conference on Electronic & Mechanical Engineering and Information Technology, Harbin, China, 12–14 August 2011; Volume 7, pp. 3678–3681.

15. Gray, T.S.; Weinberg, L. Applied Electronics. A First Course in Electronics, Electron Tubes, and Associated Circuits. *Phys. Today* **1954**, *7*, 17. [CrossRef]
16. Nussbaumer, H.J. The fast Fourier transform. In *Fast Fourier Transform and Convolution Algorithms*; Springer: Berlin/Heidelberg, Germany, 1981; pp. 80–111.
17. Angieri, S.; García-Martínez, A.; Liu, B.; Yan, Z.; Wang, C.; Bagnulo, M. A distributed autonomous organization for internet address management. *IEEE Trans. Eng. Manag.* **2019**, *67*, 1459–1475. [CrossRef]
18. Marchal, S.; Miettinen, M.; Nguyen, T.D.; Sadeghi, A.R.; Asokan, N. Audi: Toward autonomous iot device-type identification using periodic communication. *IEEE J. Sel. Areas Commun.* **2019**, *37*, 1402–1412. [CrossRef]
19. Lv, Z.; Hu, B.; Lv, H. Infrastructure monitoring and operation for smart cities based on IoT system. *IEEE Trans. Ind. Inform.* **2019**, *16*, 1957–1962. [CrossRef]