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A Comprehensive Real-Time Indoor Air-Quality Level Indicator

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Abstract: The growing concern about Indoor Air-Quality has accelerated the development of small, low-cost air-quality monitoring systems. These systems are capable of monitoring various indoor air pollutants in real time, notifying users about the current air-quality status and gathering the information to the central server. However, most Internet of Things (IoT)-based air-quality monitoring systems numerically present the sensed value per pollutant, making it difficult for general users to identify how polluted the air is. Therefore, in this paper, we first introduce a tiny air-quality monitoring system that we developed and, based on the system, we also test the applicability of the comprehensive Air-Quality Index (AQI), which is widely used all over the world, in terms of its capacity for a comprehensive indoor air-quality indication. We also develop design considerations for an IoT-based air-quality monitoring system and propose a real-time comprehensive indoor air-quality level indication method, which effectively copes with dynamic changes and is efficient in terms of processing and memory overhead.

Keywords: indoor air-quality; air-quality index; real-time air-quality monitoring

1. Introduction

Over the last few decades, indoor air-quality has become a matter of growing concern. This concern was initially triggered by occupants' reports of various indoor environments; specifically, occupants complained about a variety of unspecific symptoms, such as irritation or dryness of mucous membranes, burning eyes, headache, or fatigue. Considering that, in some cases, these symptoms could be related to elevated concentrations of specific pollutants, such as formaldehyde, in indoor air, increasing attention was devoted to determining climate conditions and chemical compounds in the air of rooms whenever people complained about bad indoor air-quality [1].

In addition to the growing concern about indoor air-quality, advances in the Internet of Things (IoT) and sensor technologies enabled the development of small, low-cost air-quality monitoring systems [2–4]. In particular, unlike professional air-quality monitoring instruments for a precise air-quality measurement, the IoT-based air-quality monitoring systems consisting of various communication technologies and cheap sensors are aimed to monitor air-quality of users' life space in real time and therefore allow users to purify indoor air using evacuation or air cleaner systems by identifying the current air-quality in real time.

However, since most air-quality monitoring systems present the sensed numerical value of the corresponding pollutant as it is, it is difficult for non-expert users to identify how polluted the air is or what the pollution criteria of each pollutant are. In fact, one of the major roles of IoT-based air-quality monitoring system is to notify the current air-quality status more intuitively and comprehensively in real time, rather than to provide general users with individual numerical information with respect to each pollutant. To achieve this aim, it is necessary for air-quality monitoring system to have the capability of notifying users of the information about the current air-quality using an intuitive display device that can indicate the air-quality level in real time.

For ambient air-quality, a comprehensive air-quality index (CAQI) is already used in a number of nations [5–13] to present the polluted level of the air; people can thereby easily identify the current status of air-quality. However, unlike the CAQI for ambient air-quality that is regulated nationally or regionally, it is difficult to define CAQI for indoor air-quality, since the criteria of air-quality vary according to the indoor environment (e.g., home, parking station, factory, etc.). In addition, indoor air-quality can rapidly vary by several activities, such as ventilation, cooking, cleaning, and so on. Actually, the CAQI for ambient air is calculated by a section mean of pollutant values collected for 1 h or 24 h, so the index might not represent the present air-quality.

Therefore, in this paper, we first introduce our tiny IoT-based air-quality monitoring system and propose a comprehensive indoor air-quality level indication method derived by CAQI for ambient air. In particular, the proposed method is capable of indicating comprehensive indoor air-quality level based on the information collected from low-cost sensors in real time, using an intuitive color LED display.

The remainder of this paper is organized as follows. Section 2 introduces a comprehensive air-quality index used in several countries. In Section 3, initial experiments are conducted to test the usability of CAQI to indoor air-quality index, and some problems are presented. Furthermore, the proposed comprehensive real-time indoor air-quality level indicator is designed in Section 4. The experimental results and evaluations are presented in Section 5. Finally, conclusions of this paper are drawn in Section 6.

2. Comprehensive Air-Quality Index

An air-quality index (AQI) is a number used by government agencies [14] to communicate to the public how polluted the air currently is or how polluted it is forecast to become [15,16]. A high AQI value means that air-quality is poor and that the air can therefore impact people's health. Therefore, different countries, such as Canada [5], Hong Kong [6], Mainland China [7], India [8], Singapore [9], South Korea [10], UK [11], Europe [12], and United States [13], have their own air-quality indices that correspond to different national air-quality standards. Even though their specific standards are slightly different, calculation and representation methods are similar across countries. For reference, an example of AQI used in South Korea is presented in Figure 1.

Computation of the AQI requires an air pollutant concentration over a specified averaging period obtained from an air monitor or model. Taken together, concentration and time represent the dose of the air pollutant. Health effects corresponding to a given dose are established by epidemiological research [17]. Air pollutants vary in potency and the function used to convert from air pollutant concentration to AQI varies by pollutant. Air-quality index values are typically grouped into ranges. Each range is assigned a descriptor, a color code, and a standardized public health advisory. For example, as shown in Figure 1, South Korea divides the AQI level into four categories: Good, Moderate, Unhealthy, and Very Unhealthy. The index level of each pollutant is determined by Equation (1) [18]:

$$I\left(n\right) = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}}\left(C - BP_{LO}\right) + I_{LO} \tag{1}$$

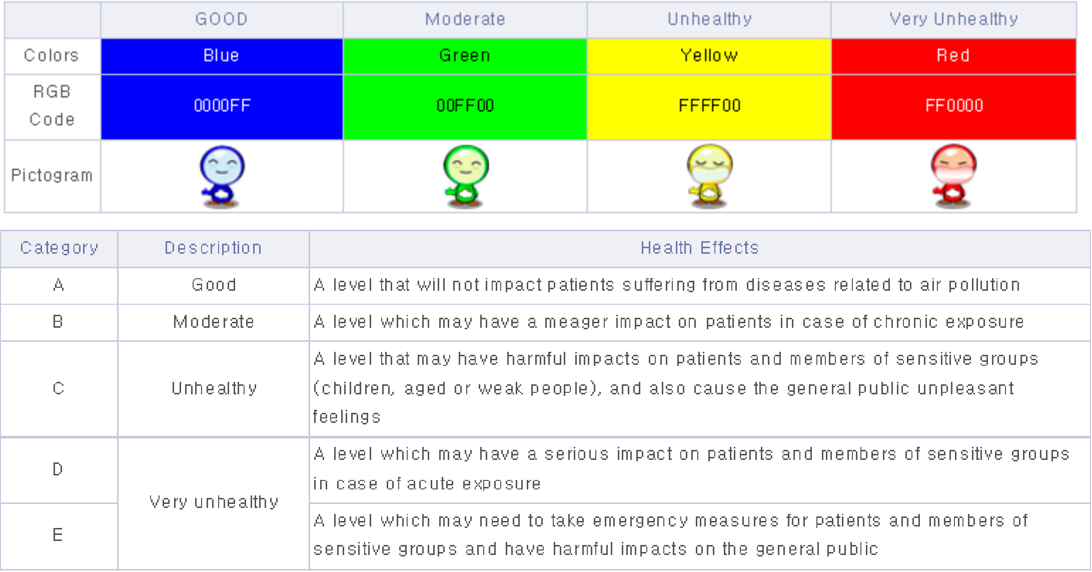
where:

$I(n)$ = the (Air-Quality) index of pollutant n,
C = the pollutant concentration,
BP_{LO} = the concentration breakpoint that is $\leq C$,
BP_{HI} = the concentration breakpoint that is $\geq C$,
I_{LO} = the index breakpoint corresponding to BP_{LO}, and

I_{HI} = the index breakpoint corresponding to BP_{HI}.

Equation (1) converts a concentration value into generalized index value with respect to its breakpoint. Since the characteristics and value of each pollutant are different, the breakpoint of each level is referred to in Figure 2.

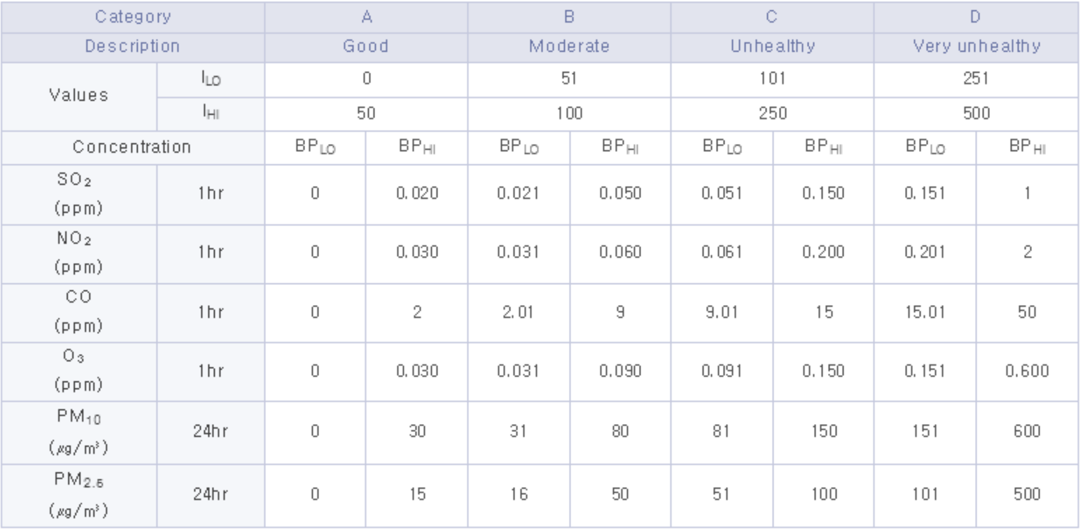
Based on the individual air-quality value (level), CAQI is determined. In general, the worst index out of all the pollutants becomes CAQI. However, if there are two or more pollutants that show an "unhealthy" level, an additional weight is added to the pollutant with the worst index. For example, in Korea, if there are two "unhealthy" levels, 50 is added to the calculated CAQI and, if there are three "unhealthy" levels, 75 is added to the calculated CAQI.



	GOOD	Moderate	Unhealthy	Very Unhealthy
Colors	Blue	Green	Yellow	Red
RGB Code	0000FF	00FF00	FFFF00	FF0000
Pictogram				

Category	Description	Health Effects
A	Good	A level that will not impact patients suffering from diseases related to air pollution
B	Moderate	A level which may have a meager impact on patients in case of chronic exposure
C	Unhealthy	A level that may have harmful impacts on patients and members of sensitive groups (children, aged or weak people), and also cause the general public unpleasant feelings
D	Very unhealthy	A level which may have a serious impact on patients and members of sensitive groups in case of acute exposure
E		A level which may need to take emergency measures for patients and members of sensitive groups and have harmful impacts on the general public

Figure 1. Air-Quality Index Description (South Korea) [10].



Category		A		B		C		D	
Description		Good		Moderate		Unhealthy		Very unhealthy	
Values	I_{LO}	0		51		101		251	
	I_{HI}	50		100		250		500	
Concentration		BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}
SO_2 (ppm)	1hr	0	0.020	0.021	0.050	0.051	0.150	0.151	1
NO_2 (ppm)	1hr	0	0.030	0.031	0.060	0.061	0.200	0.201	2
CO (ppm)	1hr	0	2	2.01	9	9.01	15	15.01	50
O_3 (ppm)	1hr	0	0.030	0.031	0.090	0.091	0.150	0.151	0.600
PM_{10} ($\mu g/m^3$)	24hr	0	30	31	80	81	150	151	600
$PM_{2.5}$ ($\mu g/m^3$)	24hr	0	15	16	50	51	100	101	500

Figure 2. Ambient Air-Quality Index Table.

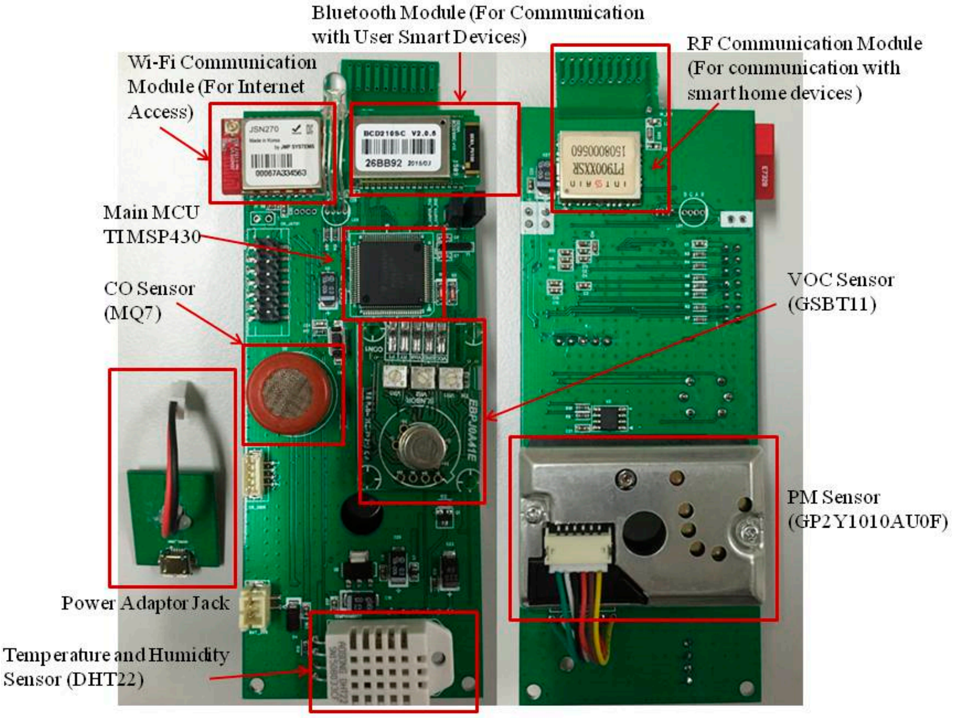
3. Experiments with a Tiny Air-Quality Monitoring System

In order to monitor indoor air-quality in real time and to gather air-quality information, we developed a tiny air-quality monitoring system (see Figure 3). The developed system aims to provide comprehensive real-time information about air-quality information using an intuitive color

LED display, as well as to aggregate relevant air-quality information from a number of air-quality systems through the Internet. In addition, unlike high-end professional air-quality measurement devices, the system is composed of low-end sensors and an embedded system, as an IoT device, which makes it very useful to provide a low-cost analysis of the variation and trend of air-quality associated with home network or intelligent smart building or factory.

Our tiny air-quality monitoring system is composed of several communication interfaces and sensors. For communications, Wi-Fi is used to access the Internet, and Bluetooth enables for configuring several functions and connectivity by users' smart devices, while the RF communication (IEEE 802.15.4g) module supports the system's connection with home network. The system also includes several sensors: Sharp GP2Y1010AU0F [19] for Particulate Matter (PM), GSBT11 [20] for Volatile Organic Compounds (VOC), MQ7 [21] for Carbon monoxide (CO), and DHT22 [22] for Temperature and Humidity, which are essential for an indoor air-quality monitoring system. Furthermore, additional add-on sensors can be connected through external sensor interfaces: UART, SPI, I2C, and ADC, among others.

One of the major goals of the system design is to notify the comprehensive status of current indoor air-quality in real time using an intuitive display. For that purpose, we first experimented with the CAQI method mentioned in Section 2. Since CAQI is based only on the pollutants affecting ambient air and some pollutants for indoor air-quality differ from those of ambient air-quality, only two sensors (CO and PM) were considered in this experiment. In fact, this experiment was conducted to test the real-time capability of the CAQI method, more specifically, the air-quality index (AQI) of each pollutant, since, due to several activities such as ventilation, cooking, cleaning, and so on, indoor air-quality is apt to vary more rapidly than ambient air.



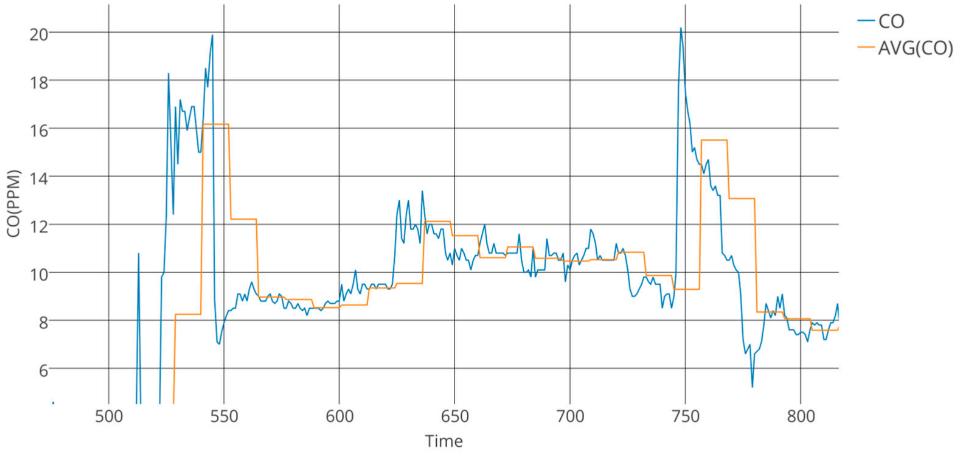
(a) Top (b) Bottom

Figure 3. The Prototype of a Real-Time Air-Quality Monitoring System.

Table 1 shows the basic environment for our experiments. Figure 4 shows the results where AQI calculation is applied to the CO and PM sensor, respectively. In order to facilitate the analysis of the collected data, we used the time index number instead of the sampled time stamp information. The blue line represents the distribution of each value sensed at each time, while the yellow line represents the AQI calculated at every sensing interval. In addition, to observe realistic indoor air environment, smoking and cooking were performed several times in the experiment room. It is important to note that the results suggest that the variation of AQI was significantly slower with respect to the rapid changes in the real sensing value. Moreover, when AQI got seriously worse, the AQI did not promptly respond to those changes due to the dependence on the old values. This means that, when we apply the AQI method to our system, it does not notify the user about the current status of air-quality in real time.

Table 1. Experimental Environment.

Location	**Embedded Networked System Architecture Lab, INU**
Type of Sensors	VOC CO PM_{10} Temperature Humidity
Collection Period	5 min
Collection Duration	355 h (about 2 weeks)
Number of Collected Data	4006
Data Analysis Tool	R Studio [23]
Plotting Tool	Plotly [24]
Database	MySQL Workbench 5.1 CE



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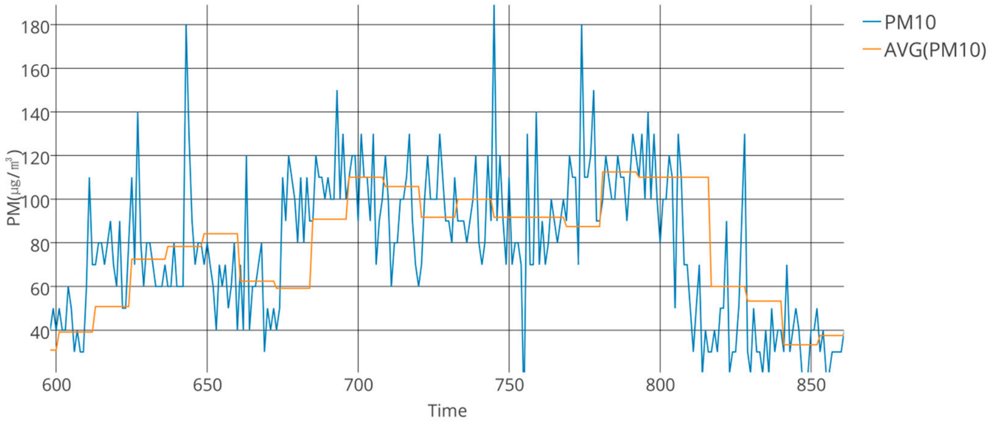


(**b**)

Figure 4. Real-Time AQI Representation for Air-Quality. (**a**) CO variation and CO AQI; (**b**) PM value and AQI.

4. Designing a Comprehensive Real-Time Indoor Air-Quality Level Indicator

4.1. Overview

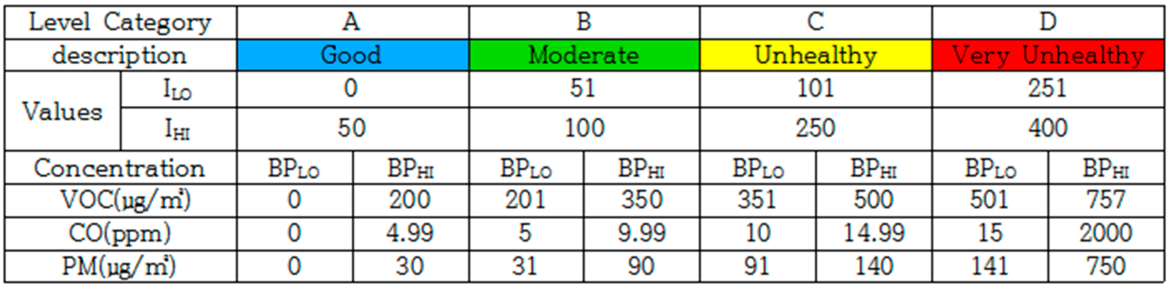
The experimental results presented in Section 3 demonstrate that ambient AQI is not suitable for real-time air-quality representation and that it is therefore necessary to develop a new index or indicating method that would be suitable for the real-time assessment of air-quality. In addition, for IoT-based air-quality monitoring, the following requirements should be considered:

- *Minimum overhead in processing*: IoT devices generally use low-end MCU, so processing overhead should be minimized.
- *Small memory usage*: When calculating a comprehensive and individual air-quality index, memory consumption should be minimized, since, due to cost-efficiency, the system has a small memory.
- *Outlier or missing value handling capability*: The sensors used in IoT-based air-quality systems can effectively cope with several outliers or missing values caused by frequent sensing interval and concurrent-intensive operations.
- *Indication representing comprehensive pollutants*: In order to notify the current air-quality information in real time, an intuitive indication method is necessary.
- *Quick response with respect to real-time air-quality changes*: A comprehensive index (or indicator) should be able to quickly respond to dynamic indoor air-quality changes.

Therefore, in this section, we first redefine air-quality level indicator consisting of pollutants affecting air-quality, and then a new index (indicator) calculation method to enhance a real-time ability is developed.

4.2. CIAQI: Comprehensive Indoor Air-Quality Indicator

We newly redefined the level category table for a comprehensive indoor air-quality level indicator (see Figure 5). Unlike ambient AQI, the CIAQI includes VOC, CO, and PM_{10}, which are basic pollutants for air-quality; in our experiments, the concentration level of each pollutant is based on indoor air-quality maintenance and recommendation levels [25,26]. In addition, the IAQI and CIAQI calculation method is the same as in Equation (1). In addition, the concentration range with respect to each pollutant is configurable by a specific user. The range value will vary according to the indoor environment used: home, parking station, factory, etc.



Level Category		A		B		C		D	
description		Good		Moderate		Unhealthy		Very Unhealthy	
Values	I_{LO}	0		51		101		251	
	I_{HI}	50		100		250		400	
Concentration		BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}
VOC($\mu g/m^3$)		0	200	201	350	351	500	501	757
CO(ppm)		0	4.99	5	9.99	10	14.99	15	2000
PM($\mu g/m^3$)		0	30	31	90	91	140	141	750

Figure 5. CIAQI Table (newly defined).

4.3. Real-Time Enhancement

As discussed in Section 4.2, one of the critical problems of AQI is that the AQI calculation method based on the section average is too slow in responding to the current air-quality, which makes it difficult to use it to represent real-time air-quality data. Therefore, in order to effectively cope with current air-quality variations, we employ a more dynamic moving average method in the real-time CIAQI calculation. In particular, we enhance the real-time ability of CIAQI by using the Exponential

Moving Average (EMA) [27–30], which shows a good performance in smoothing outliers and requires a small memory usage. The EMA can be calculated as follows (see Equation (2)):

$$S_t = \alpha \cdot Y_t + (1 - \alpha) \cdot S_{t-1} \tag{2}$$

where α is an exponential coefficient, and Y_t is the current concentration value (measured).

Figure 6 illustrates the CIAQI computation flow when EMA is applied. The AIQ monitoring system performs a get_sensing task at every interval, and each current sensing value is obtained in the get_sensing task. EMA is performed for each pollutant, and the updated values by EMA are used for the IAQI calculation; after the IAQI decision process for each sensor, CIAQI is determined according to the number of items having BAD (unhealthy) index. The finally determined CIAQI level is displayed on a color LED. Therefore, anyone without any environmental knowledge can easily identify the current indoor air-quality status.

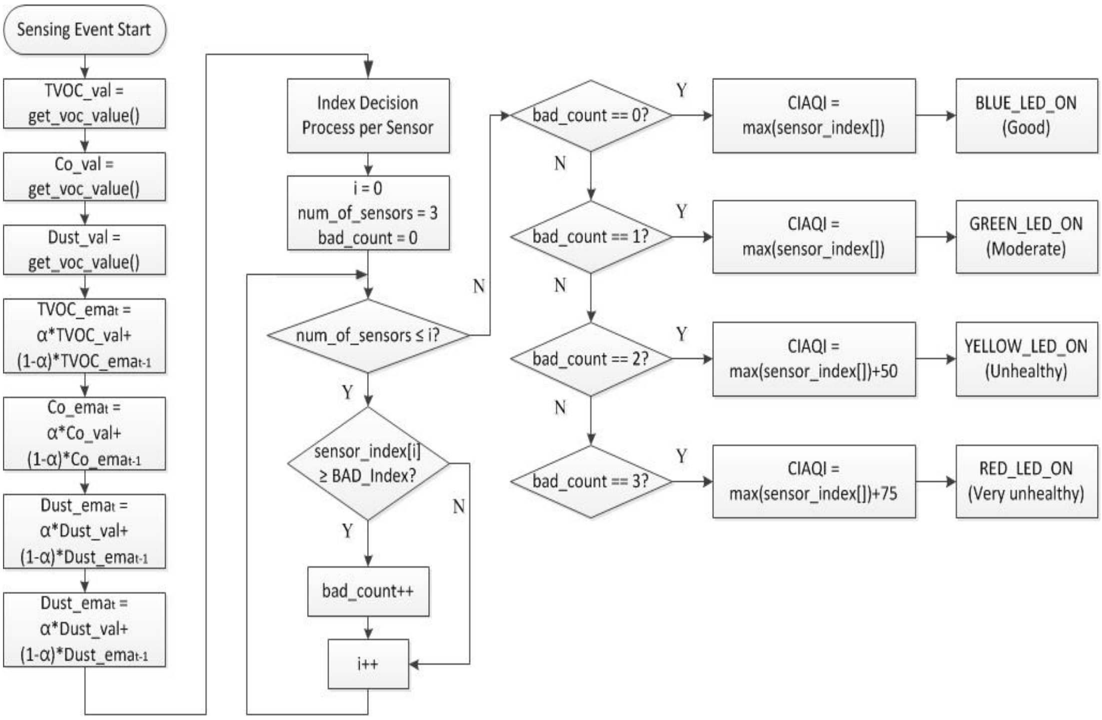
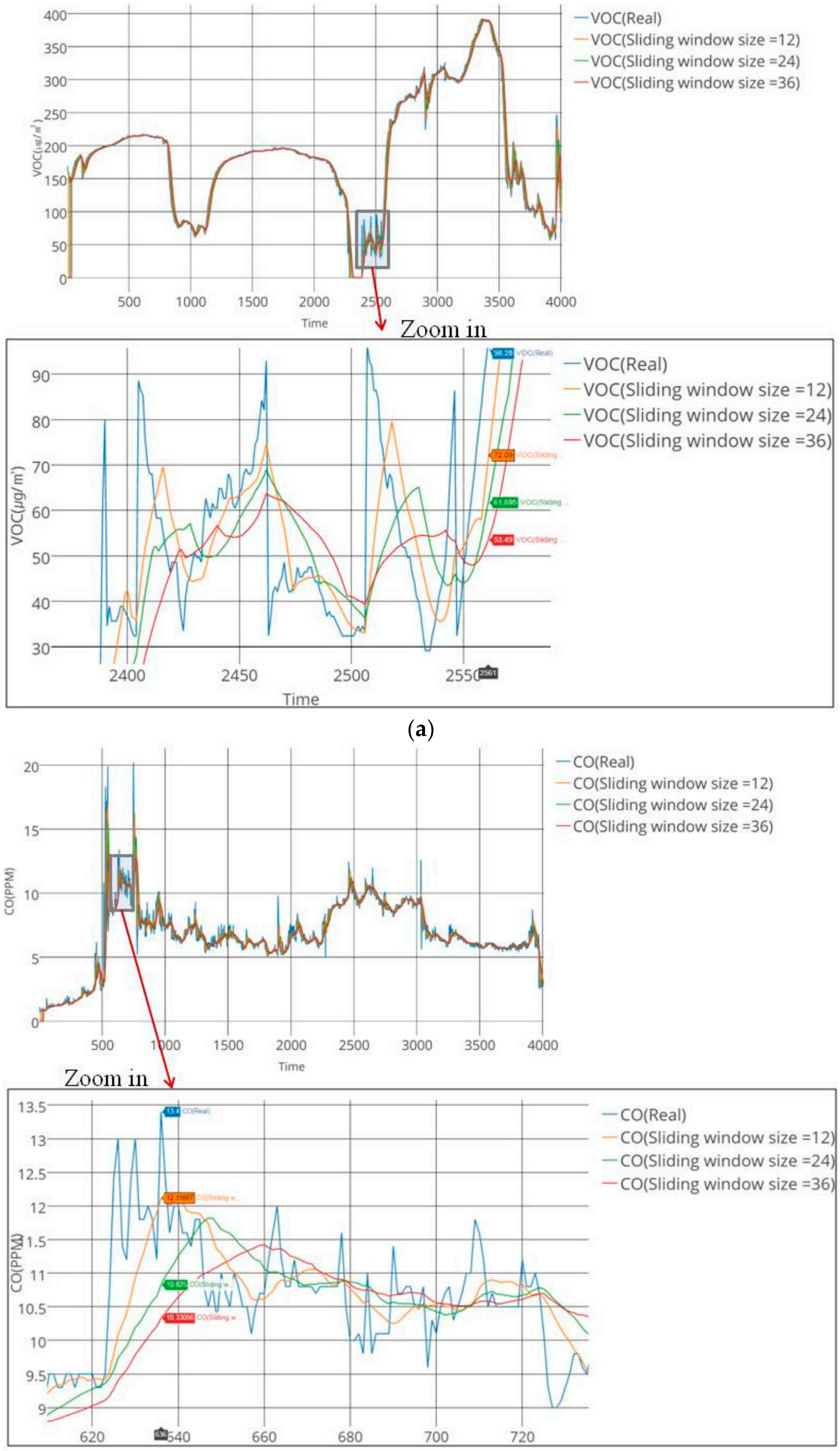


Figure 6. Flowchart of Real-Time CIAQI.

5. Evaluations

Our evaluation aimed to test how well the proposed CIAQI method can respond to real variations. For a more objective assessment, we also implemented various calculation methods for CIAQI, namely, the section average (AVG) used in ambient AQI and the simple moving average (SMA), which uses a sliding window. In addition, for the pollutants consisting of CIAQI, the total volatile organic compound (VOC), CO, and particulate matter (PM_{10}) values were collected in real time. The rest of the experimental environment was the same as shown in Table 1. Figure 9a–c show the variation of single pollutant index per sensor: (a) VOC; (b) CO; and (c) PM_{10}. Actually, the figures show each snapshot of the critical section with respect to the long-time observation. Each straight line indicates a breakpoint of concentration for each sensor, for example, Moderate, Bad (unhealthy), and so on.

Before conducting the performance comparison of the section average, simple moving average, and EMA, we conducted an experiment to select the best window size to be used for SMA. As shown in Figure 7, in all pollutants, window size 12 showed a superior performance over other window sizes (24, 36). In addition, we also conducted an experiment to select the best EMA coefficient (α). As shown in Figure 8, when $\alpha = 0.3$, the smoothing performance was the best. Therefore, we used the selected values, window size = 12 and $\alpha = 0.3$, in the next experiment.



(**a**)

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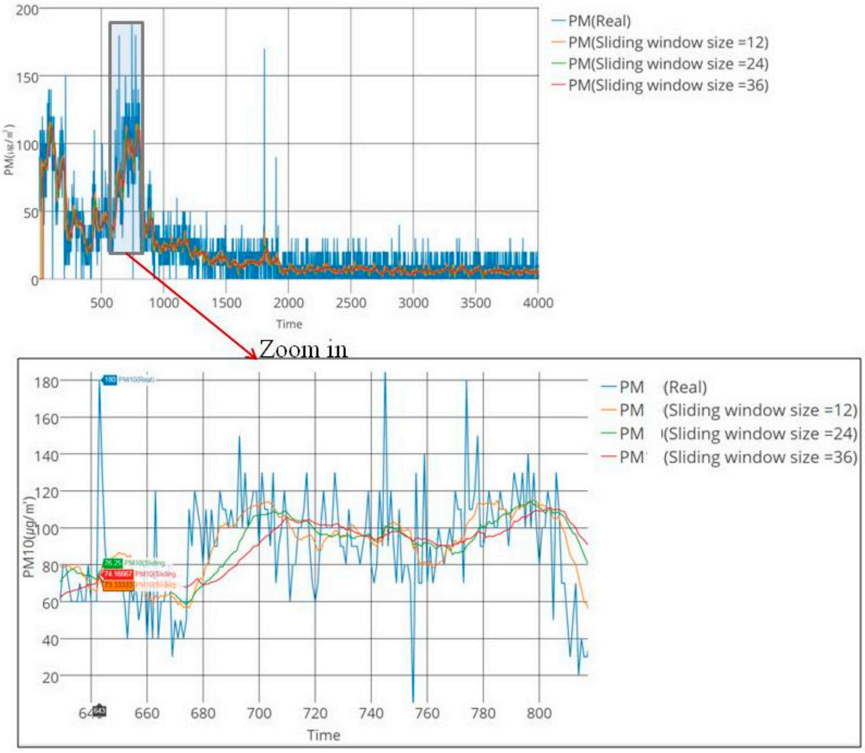
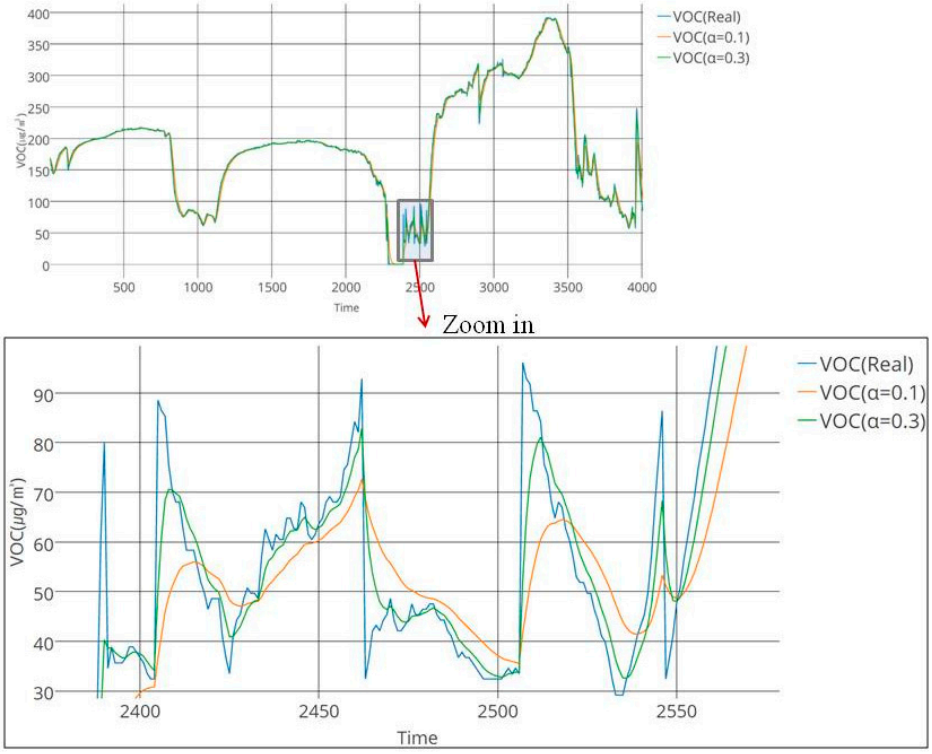
Figure 7. *Cont.*



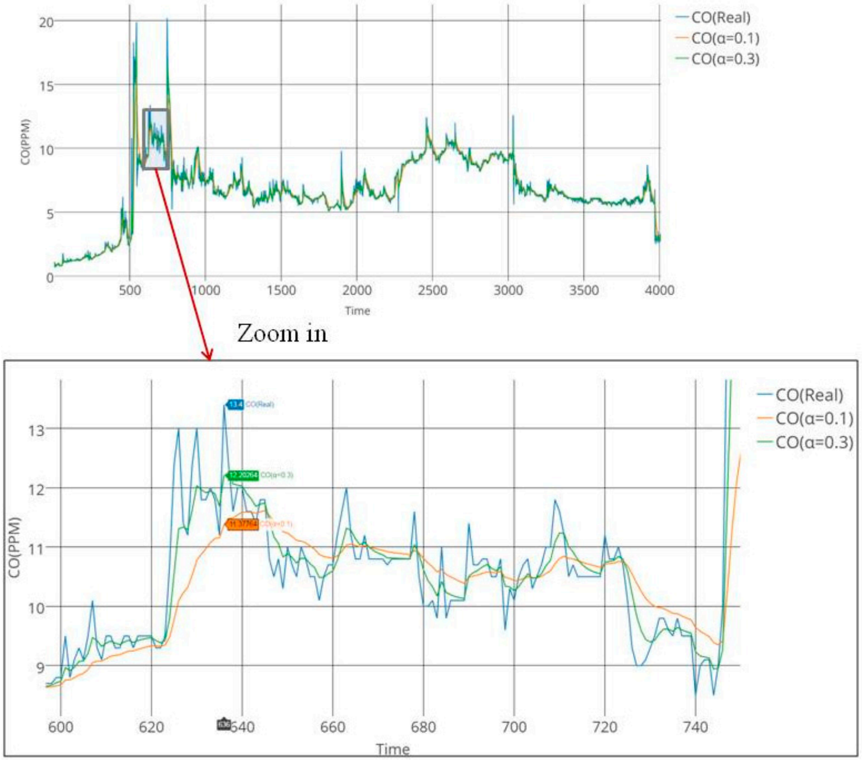
(**c**)

Figure 7. Smoothing variation with respect to different SMA sliding window sizes. (**a**) VOC smoothing with respect to different window sizes (12, 24, 36); (**b**) CO smoothing with respect to different window sizes (12, 24, 36); (**c**) PM_{10} smoothing with respect to different window sizes (12, 24, 36).



(**a**)

Figure 8. *Cont.*



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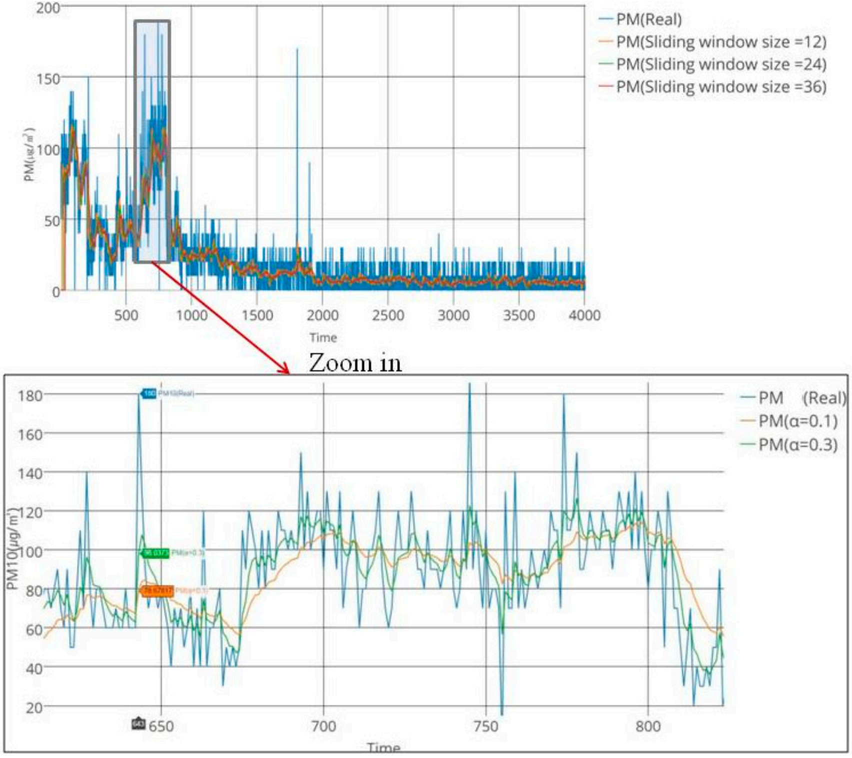

(**c**)

Figure 8. Smoothing variation with respect to different EMA coefficients (α). (**a**) VOC smoothing with respect to different EMA coefficients ($\alpha = 0.3, 0.5$); (**b**) CO smoothing with respect to different EMA coefficients ($\alpha = 0.3, 0.5$); (**c**) PM_{10} smoothing with respect to different EMA coefficients ($\alpha = 0.3, 0.5$).

Figure 9a shows the section average, simple moving average, and EMA, and these are represented by VOC_AVG_index, VOC_SMA_index, and VOC_EMA_index, respectively. The real sensing value of VOC is represented by VOC_real_index. As shown in Figure 9a, the section average method used in CAQI shows the worst performance over others. In addition, we found several critical points in which some methods show index levels that differ from the real sensing value; the critical points are designated by markers. At the critical point, both the real index level and the proposed EMA became bad; however, the section average and simple moving average still showed moderate. These critical points are shown not only in VOC, but also in other pollutants, CO and PM, (see Figure 9b,c). Furthermore, the critical points lasted for quite a long time when the value rapidly changed after similar values had lasted for a long time. Therefore, these results proved that indices based on the section average and SMA methods do not effectively cope with rapid changes in air-quality. However, the index calculation method based on EMA was shown to effectively cope with rapid changes in air-quality. In addition, as shown in Figure 9d, the variations of CIAQI are based on different index calculation methods. Like the individual index, CIAQI also shows several critical where the two methods, the section average and SMA, show different (old) index level.

In fact, with the comparison of the results in Figure 9 alone, it is difficult to assure which algorithm is the best. Therefore, in order to evaluate a more concrete and objective performance, we employed additional metrics, namely, root mean square error (RMSE), variability, and memory usage. These metrics are useful to perform a quantitative analysis as to how each algorithm is fulfilled with various requirements defined in Section 4. RMSE (3) is used to measure the accuracy of the smoothed data compared to the raw data; to evaluate reliability, we observed the variability of each method. In addition, we also examined the required memory usage of each algorithm during runtime (see Equation (3)).

$$RMSE = \sqrt{\frac{1}{N}\sum\nolimits_{k=1}^{N}\left[y(k) - \hat{y}\,(k)\right]^2} \tag{3}$$

where $y(k)$ is a predicted value for k, and $\hat{y}(k)$ is an observed value. For our experiments, $\hat{y}(k)$ is the real value sensed by each sensor for k and $y(k)$ is the result calculated dynamically by EMA and SMA.

Table 2 summarizes the performance evaluation with respect to each metric. The results demonstrate that the proposed CIAQI (based on EMA) is the most adaptive to the changes of real-time air-quality, despite smoothing outliers well over other schemes: AVG and SMA. Furthermore, since the proposed CIAQI requires a smaller memory usage for the computation than others, it is the most suitable for a comprehensive real-time indoor air-quality level indicator for an IoT-based small, low-cost air-quality monitoring system.

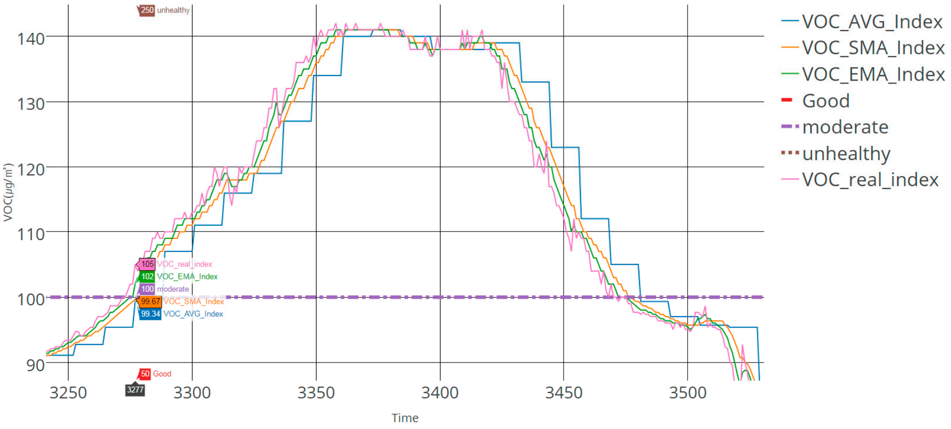

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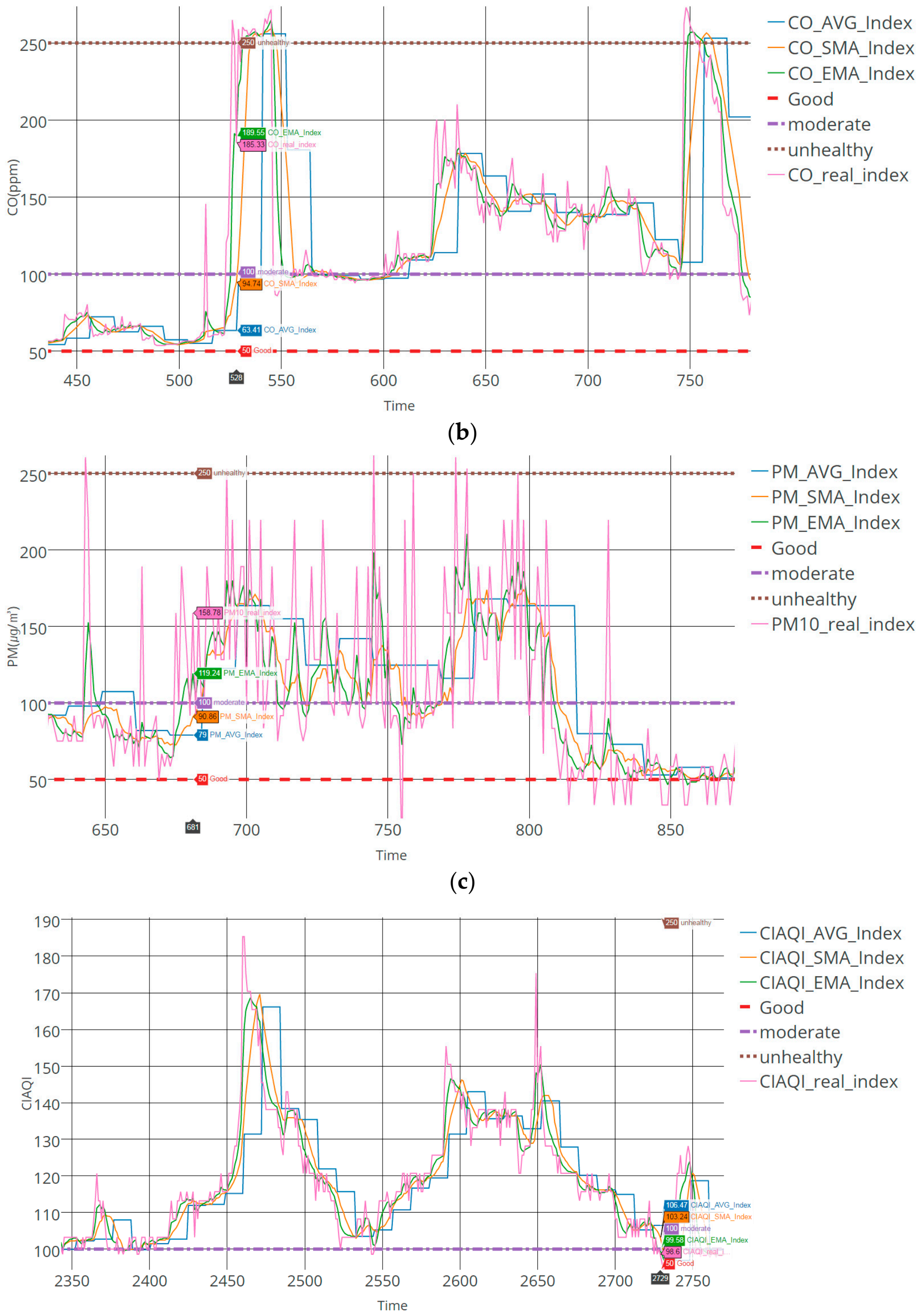
Figure 9. *Cont.*



(**b**)

(**c**)

(**d**)

Figure 9. IAQI per sensor and CIAQI. (**a**) VOC value and Index; (**b**) CO value and Index; (**c**) PM value and Index; (**d**) CIAQI comparison with different methods.

Table 2. Evaluation results.

	VOC			**CO**			**PM_{10}**			**CIAQI**		
Smoothing method	AVG 12	SMA 12	EMA 0.3	AVG 12	SMA 12	EMA 0.3	AVG 12	SMA 12	EMA 0.3	AVG 12	SMA 12	EMA 0.3
RMSE	1.6785	3.2993	1.2296	8.8225	11.0439	5.7809	18.2461	19.3337	14.7557	13.7972	16.3289	10.8457
Variability	0.9963	0.9857	0.9980	0.9118	0.8619	0.9621	0.7758	0.7510	0.8549	0.7798	0.7194	0.8762
Memory usage	180 bytes	180 bytes	30 bytes	180 bytes	180 bytes	30 bytes	180 bytes	180 bytes	30 bytes	180 bytes	180 bytes	30 bytes

6. Conclusions

In this paper, deriving from the experiments based on the developed tiny air-quality monitoring system, we first demonstrated that the general CAQI representation for ambient air-quality is not directly suitable for an air-quality monitoring system. To address the problems, we redefined the level category table for a comprehensive indoor air-quality level indicator and enhanced the real-time ability of CIAQI by using exponential moving average (EMA). Through additional experiments, we compared the proposed CIAQI with section average (AVG) used in ambient AQI and simple moving average (SMA), which uses a sliding window. The results suggest that the proposed CIAQI (based on EMA) is the most adaptive to the change of real-time air-quality, despite smoothing outliers well over other schemes: AVG and SMA. Furthermore, since the proposed CIAQI requires a smaller memory usage for the computation than others, it is the most suitable for a comprehensive real-time indoor air-quality level indicator for an IoT-based small, low-cost air-quality monitoring system.

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Author Contributions: All authors contributed to the development of the idea and experiments reported in this paper. More specifically, the first version of this paper was written by the corresponding author, Kwang-Il Hwang, while several technical experiments of this paper were led by the first author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AQI	Air-Quality Index
IoT	Internet of Things
VOC	Volatile Organic Compound
PM	Particulate matters
CO	Carbon Oxide
BP	Break Point
CAQI	Comprehensive Air-Quality Index
CIAQI	Comprehensive Indoor Air-Quality Indicator
EMA	Exponential Moving Average
SMA	Simple Moving Average
AVG	Average
RMSE	Root Mean Square Error

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