Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Development and Verification of an IoT-Enabled Air Quality Monitoring System Based on Petri Nets

Yi-Nan Lin
Ming Chi University of Technology
Sheng-Kuan Wang
Ming Chi University of Technology
Gwo-Jen Chiou
National Formosa University
Cheng-Ying Yang
University of Taipei
Victor R. L. Shen (rlshen@mail.ntpu.edu.tw)
National Taipei University https://orcid.org/0000-0001-8194-3446
Zhi Yang Su
Ming Chi University of Technology

Research Article

Keywords: Long Range (LoRa) technology, low power consumption network, Internet of Things (IoT), environmental parameters monitoring, LoRaWAN, Azure cloud database.

Posted Date: July 12th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-627459/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Development and Verification of an IoT-enabled Air Quality Monitoring System Based on Petri Nets

Yi-Nan Lin (Member, IEICE)
Department of Electronic Engineering
Ming Chi University of Technology
84, Gongzhuan Rd., Taishan District, New Taipei City 243, Taiwan, ROC.
Email: jnlin@mail.mcut.edu.tw

Sheng-Kuan Wang (Member, IEEE)
Department of Electrical Engineering
Ming Chi University of Technology
84, Gongzhuan Rd., Taishan Dist., New Taipei 243, Taiwan, ROC.
Email: skwang@mail.mcut.edu.tw

Gwo-Jen Chiou (Member, IEEE)
Department of Electrical Engineering
National Formosa University
Huwei Township 632, Yunlin County, Taiwan, ROC.
Email: chuogj@nfu.edu.tw

Cheng-Ying Yang (Member, IEEE)
Department of Computer Science
University of Taipei
1, Ai-Kao W. Rd., Taipei City 100, Taiwan
Email: cyang@utaipei.edu.tw

Victor R.L Shen (Fellow, IET; Senior Member, IEEE, ACM and IEICE)
Department of Computer Science and Information Engineering
National Taipei University
151, University Rd., Sanxia District, New Taipei City 237, Taiwan, ROC.
Email: rlshen@mail.ntpu.edu.tw
and
Department of Information Management
Chaoyang University of Technology
168, Jifeng E. Rd., Wufeng District, Taichung City 413, Taiwan, ROC.
and

Zhi Yang Su
Department of Electronic Engineering
Ming Chi University of Technology
84, Gongzhuan Rd., Taishan District, New Taipei City 243, Taiwan, ROC.
Email: a29945365@gmail.com

Corresponding Author -- Victor R.L. Shen
Department of Computer Science and Information Engineering
National Taipei University
New Taipei City, 237 Taiwan, ROC.

Acknowledgments: This work was supported by the Ministry of Science and Technology, Taiwan, under grants MOST 107-2221-E-845- 001-MY3 and MOST 107-2221-E-845- 002-MY3.

Subject Area: Smart Air Quality Monitoring System **Reference No.**:

Abstract

An IoT (Internet of Things) system for monitoring campus environmental parameters was successfully developed in this study. Various sensors were adopted in the front of IoT system for sensing air pollutants. The architecture of LongRange (LoRa) in Class C uses low-power and long-distance transmission technologies, which has been set up on the large campus, so that the terminal equipment can reach a balance between downlink latency and battery life, making it the best transmission communication protocol. In addition, this monitoring system uses the Petri net software tool to build a correct IoT platform based on the fundamental working processes, and to demonstrate the feasibility of the IoT system through simulation-based verification. Finally, the experimental results have shown that the IoT system for monitoring the campus environmental parameters achieves the goal of an acceptable data transmission success rate of more than 95%. Thus, it can facilitate the air quality trends for policy making as well as the hazardous prediction and prevention.

Keywords Long Range (LoRa) technology; low power consumption network; Internet of Things (IoT); environmental parameters monitoring; LoRaWAN; Azure cloud database.

1 Introduction

Currently, a morning exercise has become the energy source of people's daily vitality. Many people prefer to take jogging early in the morning. With regards to the air quality, the degree of pollution is increasing rapidly. In addition, due to climate change, the weather in spring, summer, autumn and winter has varied significantly, especially, in summer and winter. According to the statistics of Central Weather Bureau in Taiwan, the average relative humidity reaches as high as 70% in summer [1]. With the influence of humidity, the actual temperature and the temperature felt by human body may be different even though the heat index and the wind chill index have been taken into consideration. Therefore, it motivates us to present this system, in which the temperature and the air quality can be viewed as a basis to release reference standards, providing the outdoor air quality on campus to determine whether it is suitable for holding the outdoor activities or not [2-3]. Furthermore, most campuses have many departmental and dormitory buildings, which usually occupy a large area.

Since Ming Chi University of Technology (MCUT) has a tradition of morning jogging, students need to gather up and run around the sports field at 6:30 in the morning. Thus, the temperature and the air quality must be viewed as reference standards, enabling teachers to determine whether the morning jogging is required or not. Many department buildings, faculty and student dormitories are distributed on campus. The air detection locations were set up in the 2nd Education Building and the 5th student dormitory to simultaneously monitor air pollutants, such as suspended particles (particulate matters, PM 2.5), carbon monoxide, and carbon dioxide, which are harmful to our health, reminding teachers and students to be always aware of such air pollutants. In the previous monitoring system, the problems such as low data transmission success rate and high system maintenance cost have ever caused, which need to be solved.

In this study, the LongRange (LoRa) communication technology was used to implement the IoT platform. By selecting the LoRaWAN in Class *C*, the data latency can be minimized. Users can always pay attention to whether the datasets are returned. Thus, the terminal equipment can reach a balance between downlink latency and battery life. Various sensors were installed in different areas of the campus. The indoor detection items include temperature, humidity, suspended particles (e. g. particulate matters, PM 2.5), carbon monoxide, and carbon dioxide, while the outdoor detection items include temperature, humidity, wind speed, suspended particles, and ultraviolet light. In addition, the actual temperature is found from the humidity and wind speed datasets collected.

Communication with the gateway was done through signal requirements to implement low-power and long-range applications. It is in line with Class *C* for the LoRaWAN architecture, forming a two-way communication. In other words, through this type of instant messaging, the back end uses software applications such as *C#*, Azure, ASP.NET, and IIS to realize the construction of a campus air quality monitoring system.

The gateway uses an industrial computer to write the *C#* Windows Forms application to analyze the datasets from different detection stations and upload them to the Microsoft Azure cloud database system every hour, ensuring that the datasets are completely stored. The server uses ASP.NET to develop web programs to publish datasets and to integrate with the Google Map API to locate different detection stations. Users can search for the environmental quality and further carry out data analysis and evaluation through the website.

The remainder of this paper is organized as follows: The works related to IoT platform and LoRa wireless transmission technology are discussed in Section 2. Section 3 focuses on the proposed hardware and software systems. Experimental results and performance evaluation are presented in Section 4. Finally, Section 5 describes our remarkable conclusion.

2 Literature Review

This Section first introduces the communication and transmission characteristics of IoT architecture with its network layers. Furthermore, the working principle of the wireless transmission technologies and Petri net definitions are presented.

2.1 Current IoT Architecture

IoT technology allows all common objects with independent functions to connect to an interoperable network. To realize IoT applications, more than 500 megabytes of objects may be required. Moreover, the use of wireless radio frequency technology to connect objects to communicate with each other becomes an integral part of IoT. The current IoT platform is divided into three layers, namely, application layer, network layer and perception layer.

2.1.1 Application Layer

The application layer is responsible for the overall analysis and processing of the recovered datasets, through performing some algorithms until all datasets are generated. Usually, the application layer is related to the hardware devices for big data analysis, data receiving and sending center, server, and storage, such as smart home, smart transportation, urban management, urban safety, environmental monitoring, and management of agricultural, fishery and pasture farms, and so on.

2.1.2 Network Layer

The network layer is responsible for transmitting and receiving information through the wired or wireless methods. Usually, the network layer is connected to hardware devices that are related to the Internet, local networks, mobile networks, and wireless networks, such as LAN, 2G/3G/4G, Wi-Fi, ZigBee, BlueTooth and RFID technologies.

2.1.3 Perception Layer (i.e. Physical Layer)

The perception layer is responsible for sensing the surrounding environment and collecting datasets. Usually, the perception layer is related to sensors, monitoring and storage devices such as IPCam, LightSensor, temperature sensor, RFID card and reader, and so on.

2.2 LPWAN

According to the definition from WiKi [4], Low-Power Wide-Area Network (LPWAN) [5-6], also known as Low-Power Network (LPN), is a type of architecture applied to IoT. This architecture realizes a low-transmission and long-range wireless network. To achieve the design concept of low power consumption, the technology adopted by the LPWAN architecture is basically the sub-GHz frequency band, thereby fulfilling the definition required by LPWAN. According to the white paper [7] proposed by the LoRa® Alliance, the main characteristics of LPWAN are shown as follows:

1. Long battery life (usually more than 10 years, while supporting smart measurement applications).
2. Wide-area connection that enables the out-of-the-box features.
3. Low-cost chips and networks.
4. Limited data throughput.

In other words, LPWAN has the characteristics of extremely low power consumption, long transmission range (usually *km* level) and low price. However, it has the problem of data load. In fact, LPWAN eliminates the shortcomings of the existing short-range cellular network technology. Shortening the transmission range means that the wide area network can be realized at lower equipment cost while having better power consumption. These features can clearly explain the potential of LPWAN technology. The transmission range and power consumption of the current mainstream network for IoT, such as ZigBee, BlueTooth, Wi-Fi, RFID, 2G/3G/4G mobile networks, and so on, are not as good as those in the LPWAN architecture. Thus, the terminal devices of IoT do not usually require the transmission of a huge number of datasets.

Since the need of LPWAN architecture comes from the development of IoT, LPWAN was developed after the establishment of IoT. Before the beginning of 2013, the term LPWAN did not exist. Now, it has become one of the technologies that exhibit the fastest growth in the development of IoT. The IoT market demonstrates the incredible potential of LPWAN technology. Machina Research [6] predicted that there would be 3.6 billion LPWAN connections by 2024, which would grow substantially from today's number.

The data transmission rate and transmission range of the IoT technologies are divided into two categories, namely, one category in unauthorized frequency band such as LoRa, and the other category in authorized frequency band such as EC-GSM, LTE Cat-m, and NB-IoT.

The transmission range of ZigBee, BlueTooth and Wi-Fi technologies is the shortest one in the unauthorized frequency band, while the transmission range of LoRa and UNB technologies is the longest one. Moreover, based on the power consumption and the data transmission rate of each technology [7], UNB technology exhibits the best power-saving performance, while LoRa technology shows low power consumption and moderate data transmission rate [8-11].

2.3 LoRa

LoRa is an emerging wireless technology designed specifically for LPWAN, providing long-range, low-speed, and low-power consumption wireless communication, which is considered as the most promising technology for realizing IoT applications. LoRa defines the physical layer communication lines. Many traditional communication systems use Frequency-Shift Keying (FSK) modulation as the physical layer, which can achieve low-power modulation. It is designed and patented by Semtech Corporation, which uses proprietary spread spectrum technology in the sub-GHZ ISM band. Bidirectional transmission uses Chirp

Spread Spectrum (CSS), which is a sinusoidal signal of spread spectrum (SS) modulation that increases or decreases with time. LoRa allows six spreading spectrum factors (SF7 to SF12) and three different bandwidths (125 kHz, 250 kHz, 500 kHz). It is assumed that the higher spreading spectrum allows longer transmission range, but lower transmission speed (rate), and vice versa. The transmission rate of LoRa is from 300 bps to 50 kbps, and the maximum load length of each data is 243 bytes [12-13].

LoRa-Alliance formulated communication protocol and system architecture based on LoRa in 2015, which was named as LoRaWAN™. According to the MAC layer protocol, power consumption level, LoRa® modulation and ISM bands in different regions around the world, this communication protocol and network architecture have a great impact on the node battery life, network capacity, service quality, and various application services. Based on the Open System Interconnection Reference Model (OSI), LoRa represents the physical layer, and LoRaWAN™ represents the data connection layer and the network layer [14-15].

Many of the established network architectures still belong to the *mesh* network, in which each node sends messages of other node to increase the network communication range. However, it increases the operation complexity and shortens the battery life. In contrast, the *star* topology can realize long-range connection and make the battery more power-saving. The LoRaWAN™ architecture can be divided into end nodes, gateway, network server and application server. In terms of architecture, the end-devices are not connected to a specific gateway and the datasets are all received by multiple gateways. Gateway sends control signals and end-device messages to the cloud, and simultaneously decodes multiple signals. The connection can be made through 3G, 4G or Ethernet, and the application server presents the results to all users [15].

Asynchronous communication data transmission protocol is used in the LoRaWAN™ architecture. This protocol is based on the Aloha system transmission method. In a mesh network or synchronous network, nodes must be woken up to synchronize with the network and to receive messages at any time. In such a mode, a lot of energy will be consumed, resulting in shortening the battery life. To achieve a long-range star topology, the gateway must have large capacity, which uses multi-channel modulator-demodulator (MoDem) to receive messages of end-devices from all directions. However, the key factors include the transmission rate, the effective load length of datasets, and how long it takes to send the datasets. The LoRaWAN ™ is a spread-spectrum technology that uses different spreading spectrum factors, and the transmission rate changes accordingly [15].

There are three communication protocols defined for different services under the LoRaWAN™ protocol. The terminal equipment achieves a balance between the downlink communication latency and the battery life, which is divided into Class *A*, Class *B*, and Class *C* [13-15]. Class *C* device allows bidirectional communication with maximal receiving slots. The receiving window is open at almost all the time and is only closed during transmission.

Class *A* terminal device is power saving; however, its data transmission rate is low, which may easily delay. On the contrary, Class *C* device has high power consumption. Since its receiving port is always open, it is in the best immediacy. Class *B* has the characteristics of signal synchronization. As a result, there is no need to continuously open the window for receiving signals like Class *C*, and there is no problem in transmission efficiency like Class *A*. Each type of device can be applied to different scenarios.

2.4 Petri Net

Petri Net (*PN*) is a well-known graphical and mathematical model, which is characterized as concurrent, asynchronous, nondeterministic, stochastic, distributed, parallel, fuzzy, and so on. People like using it to model and analyze various systems, different from flowcharts, block diagrams, and neural networks. The formal *PN* mathematical formula includes five elements, namely, $PN = (P, T, F, W, M_o)$. The formal *PN* mathematical definitions are listed in Tables 1 and 2. *PN* theory has been widely applied in the distributed and parallel systems. A *PN* model belongs to a directed graph including those elements such as place, transition, and the directed arc connecting a place to a transition. A *PN* model owns parallel and concurrent modeling features, and it is also applied in the areas of system construction, property checking, systematic modularization, and so on [16-17].

Table 1 Formal PN mathematical definitions

Place (*P*)	$P = \{p_1, p_2, ..., p_n\}$, $n > 0$. A finite set of places.
Transition (*T*)	$T = \{t_1, t_2, ..., t_m\}$, $m > 0$. A finite set of transitions.
Flow (*F*)	$F \subseteq (P \times T) \cup (T \times P)$. A finite set of arcs (i.e. flow relation).
Weight (*W*)	$W: F \rightarrow \{1, 2, 3, \ldots\}$. Weight function.
M_o	$M_0: P \rightarrow \{0, 1, 2, \ldots\}$. An initial marking.

Table 2 PN Notations

Elements	Petri Net symbols
Place(*P*)	○
Transition(*T*)	—
Arc	→
Token	●

2.4.1 WoPeD

Workflow-Petri-net-Designer (WoPeD) is adopted as a software simulation tool; and the *PN* model is used to modularize, simulate, and analyze the proposed approach and to help us get the experimental results [18]. WoPeD is an open-source software system developed by the Cooperative State University Karlsruhe under the GNU Lesser General Public License (LGPL), which serves as an easy-to-use system for simulating and analyzing the monitoring processes modeled by workflow nets. In the WoPeD simulation, the analysis results are divided into two parts, namely, Wizard and Expert. Wizard part presents the Workflow net property and the Soundness. Expert part presents the Structural analysis and the Soundness. The proposed monitoring system has used this software tool; and the block diagram was converted into the *PN* model for property analysis, which would verify its applicability and integrity.

3 Proposed Approach and Simulation Results

This Section is divided into five parts to present the system architecture, hardware components, software architecture and tools, packet transmission specification, and system verification.

3.1 System Architecture

Fig. 1 shows the proposed system architecture. Three detection stations were set up on campus. Different sensors were used and classified as indoor and outdoor ones, such as PMS5003T, MQ7, DS-CO2-20, GUVA-S12SD, and JL-FS2.

Indoor sensors were used to detect temperature, humidity, suspended particulates, carbon monoxide, carbon dioxide; while outdoor sensors were used to detect temperature, humidity, wind speed, apparent temperature, suspended particulates, and ultraviolet light, serving as an analysis basis. For data transmission, LoRa 915 MHz was used as the communication protocol, which is a transmission module LRM001 developed by Liyatech. The REVQ704 industrial computer developed by Avalue Technology was used as a Gateway. The C# Windows Forms program was installed to analyze the datasets collected from different detection stations. The datasets were uploaded to Microsoft Azure SQL Server every hour. Finally, the ASP.NET technology was adopted by the server to publish web pages which were integrated with the Google Map API to locate different detection stations, providing graphical interface to users.

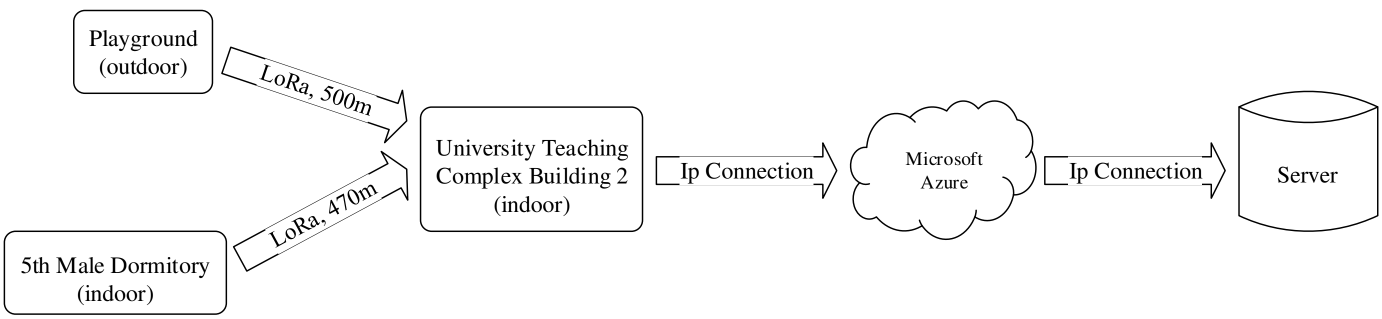

Fig. 1 System architecture

3.2 Hardware Components

The hardware devices and components are included in the following: Arduino Mega2560 Rev3 [19], XH-M401, PMS5003T [20], MQ-7 [21], GUVA-S12SD [22], JL-FS2 [23], DS-CO2-20 [24], LRM001 [25], RN2903 [26-27], and Q7-REV07. The entire hardware components are divided into the transmitting end and the receiving end. The transmitting end combines the corresponding sensors depending on the monitoring scenarios.

The indoor detection station is composed of the Arduino Mega2560 Rev3 development board and Liyatech LRM001; and integrates the voltage stabilizing modules including PMS5003T, MQ7, DS-CO2-20, and XH-M401. The UART and ADC provided by Arduino are used as a communication channel to integrate the datasets of the above sensors, to define the packet specification hexadecimal string, and to transmit the UART protocol to the LRM001 module. The LoRa communication technology is utilized to upload the datasets to the receiving end.

The outdoor detection station is also composed of the Arduino development board and LRM001; and integrates the voltage stabilizing modules including PMS5003T, GUVA-S12SD, JL-FS2, and XH-M401. The datasets are transmitted to LRM001 via UART and ADC, and the packet datasets are sent to the receiving end. The receiving end is an industrial computer REVQ704, which is set as the system gateway. Since Arduino Mega2560 can be connected to the sensors, it becomes one of the detection stations, which has a Mini PCI-E slot to connect the LRM001 and the UART communication at the same time, collecting all datasets into the installed C# Windows Forms program.

3.3 Software Architecture and Tools

The program of the corresponding environment was installed at the detection station, and the LoRa transmission mechanism was adopted to return it to the C# Windows Forms software application (App) [28]. Then all datasets were analyzed and published. The results can be obtained from the screen of the App to debug in the future. The results were uploaded to Microsoft Azure SQL Database and saved as a table with different settings. The effective datasets were then loaded using the Web Application of ASP.NET technology via the server [29]. In addition, the webpage was issued by IIS Service [30], enabling a connection to the server by using a physical network path, forming the interactive interface presented by the system in the end, and providing to the public with complete data analysis.

3.3.1 IIS

Internet Information Services (IIS) allows Microsoft to provide the basic services for Internet users. It belongs to the management platform for developing and managing web application services. This system includes the Windows Process Activation Service (WPAS), which enables the website to use protocols other than HTTP and HTTPS, and to integrate request management from IIS and ASP.NET. IIS includes the important functions of applications and web server in Windows Server 2008 (IIS7.0) and Windows Server 2008 R2 (IIS7.5). Therefore, IIS provides a graphical management interface to simplify the complexity in response to various management needs [30].

3.3.2 Microsoft Azure SQL Database

Cloud computing is a network-based computing method that can transfer hardware and software resources to servers, storage, databases, and so on. It is established under the concept of virtualization, scalability, and Pay-As-You-Go. There are three cloud services, including infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS) [31].

Microsoft Azure is a public cloud service (PCS) platform launched by Microsoft. At first, it only provides basic cloud services with IaaS; and abundant services such as IaaS, PaaS, and SaaS are provided, allowing users to create services by using different methods. Azure categorizes services into those groups including computing service, application service, data management, analysis service, network service, and so on, which are provided according to users' needs. This system uses Azure data management to build a database system in Azure SQL Database [32]. The gateway connects to the database system through the network and accesses the datasets in the database system, completing the cloud automation function.

3.3.3 SQL Server Management Studio

SQL Server Management Studio (SSMS) is a graphical integrated environment that forms SQL infrastructure. It is applicable to SQL Server and Azure Database, providing the configuration and management of SQL Server. Users can quickly deploy, search, or upgrade the data layer used by applications. Through either edge computer or cloud computer, users can access the management function by connecting to the database engine [33].

3.4 Packet Transmission Specification

The data transmission is customized according to a specific protocol. This system uses LoRa as the communication link. According to the description of the RN2903 command manual, the packet transmission is defined by hexadecimal method. Arduino Mega 2560 integrates the sensor datasets, with the command "radio tx", the detection station code, the detection item abbreviation and the detection value added in front of the datasets. After receiving the command, LRM001 sends it to the gateway for analysis.

3.5 System Verification

Fig. 2 shows the block diagram of our proposed air quality monitoring system, from which the Petri Net model was derived, as shown in Fig. 3. The interpretations of places and transitions are all listed in Table 3 and Table 4, respectively. The place marking vector represents a current state in the monitoring system. The transition firing vector represents all processes that need to be changed under the current conditions, and the arc represents the connection between a place and a transition. For the net statistics shown in Fig. 4, there are 14 Places, 18 Transitions, and 36 Arcs in total; and for the semantical analysis, there are no errors made in the Workflow net property with Soundness.

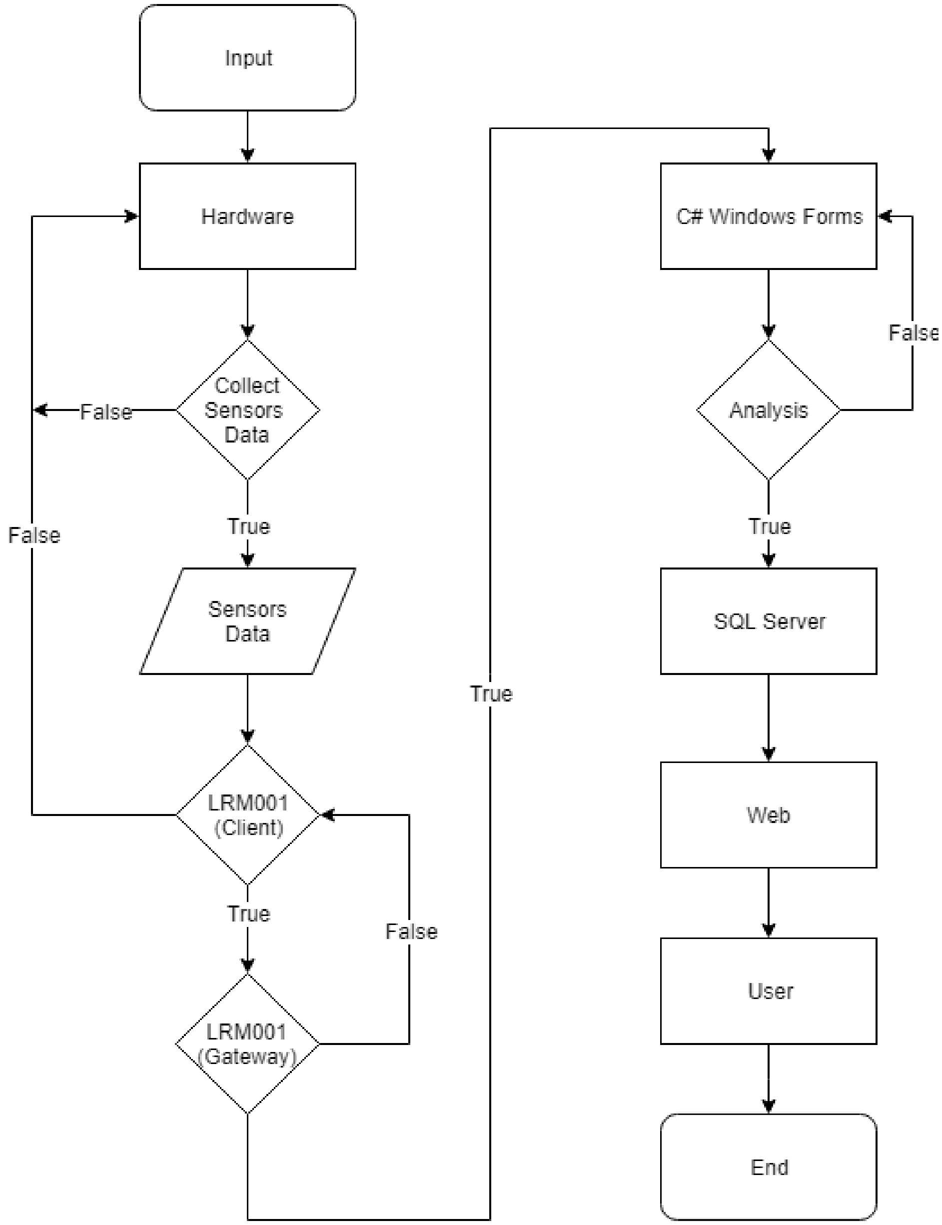

Fig. 2 Block diagram of our proposed monitoring system

As shown in Fig. 3, *p1* is like an Input port and a token is inserted in *p1*. When Start system (*t1*) is completed, the token moves to Hardware (*p2*). *p2* enters the next step, namely, Start hardware tools (*t2*); and *t2* enters the gathering of sensor datasets (*p3*) when finished. If sensor datasets have problems, it returns to Hardware (*p2*) via Return and check hardware (*t3*). If there is no abnormality in the gathering of sensor datasets (*p3*), it moves to Sensor Datasets (*p4*) via Send (*t4*). LRM001 Client (*p5*) determines whether the datasets can be transmitted to the LRM001 Gateway (*p6*) via LoRa communication mechanism. If there is an error, the token will return to *p5* via Return and check LRM001 Client (*t8*); and the next LRM001 Gateway (*p6*) will send the datasets to C# Windows Forms (*p7*) and Analysis Data (*p8*), which are filtered into valid information and stored in Azure SQL Server (*p9*). ASP.NET Web Form (*p11*) runs on the server side and presents the Cloud datasets to the Web (*p12*). Provide users (*p13*) to use, and finally complete the entire system operations (*p14*). The semantical analysis and net statistics are shown in Fig. 4. The simulation results are shown in Fig. 5.

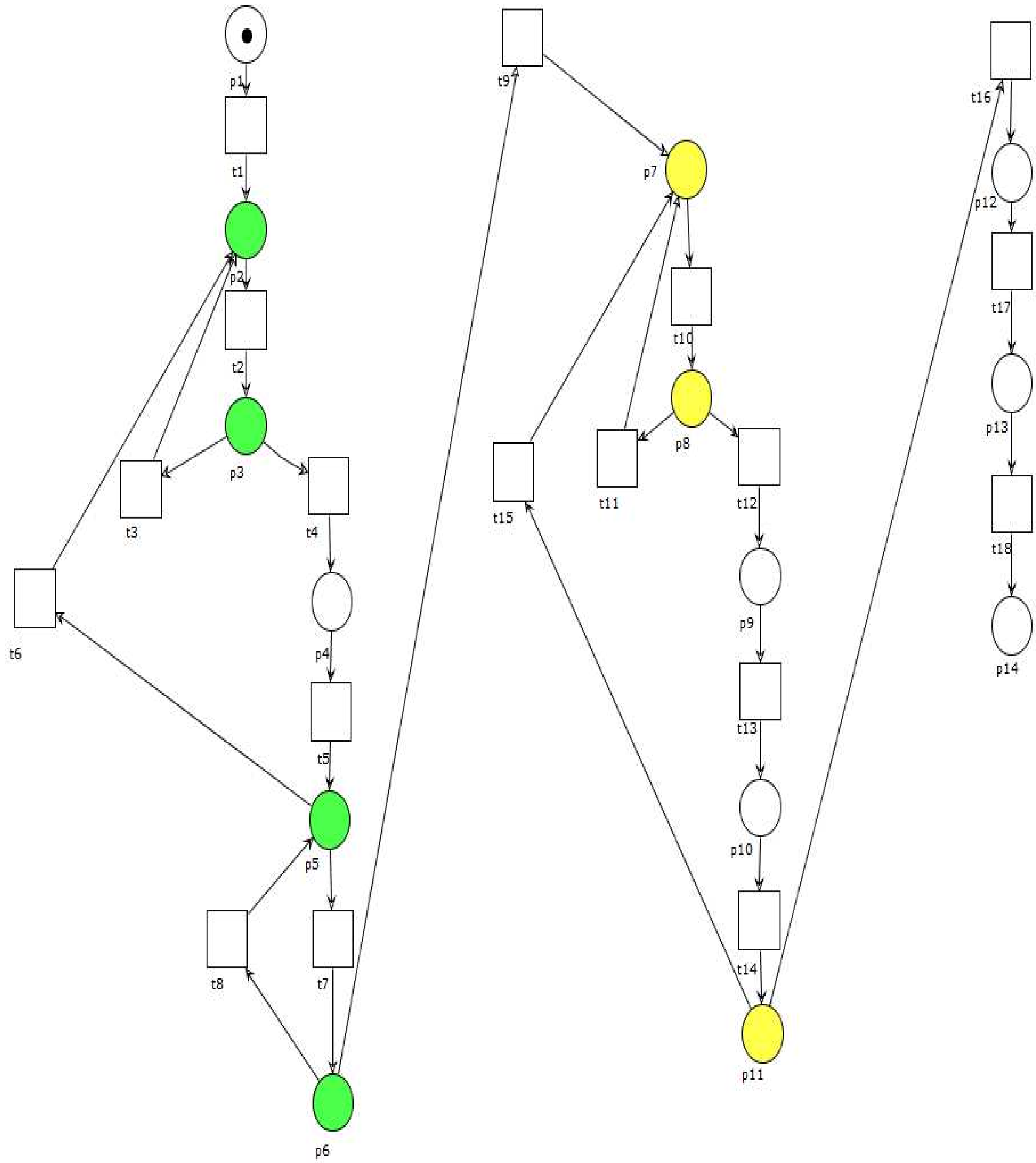

Fig. 3 Petri Net model of the proposed monitoring system

Table 3 Interpretation of places

Places	Interpretation	Places	Interpretation
p1	Input token	*p8*	Analysis Data
p2	Hardware	*p9*	Azure SQL Server
p3	The gathering of sensors data	*p10*	The analysis data
p4	Sensors Data	*p11*	ASP.NET Web Form
p5	LRM001(Client)	*p12*	Web
p6	LRM001(Gateway)	*p13*	Users
p7	C# Windows Forms	*p14*	The End

Table 4 Interpretation of transitions

Transitions	Interpretation	Transitions	Interpretation
t1	Start system	*t10*	Use Windows Forms
t2	Start hardware tools	*t11*	Return to Windows Forms
t3	Return and check hardware	*t12*	Get data
t4	Send P4	*t13*	Store data to Azure SQL Server
t5	Send data to LRM001(Client)	*t14*	Send data to web application
t6	Return and check hardware	*t15*	Return to web application
t7	Send data to LRM001(Gateway)	*t16*	Use server data
t8	Return and check LRM001(Client)	*t17*	User search web
t9	Send data to windows application	*t18*	End system

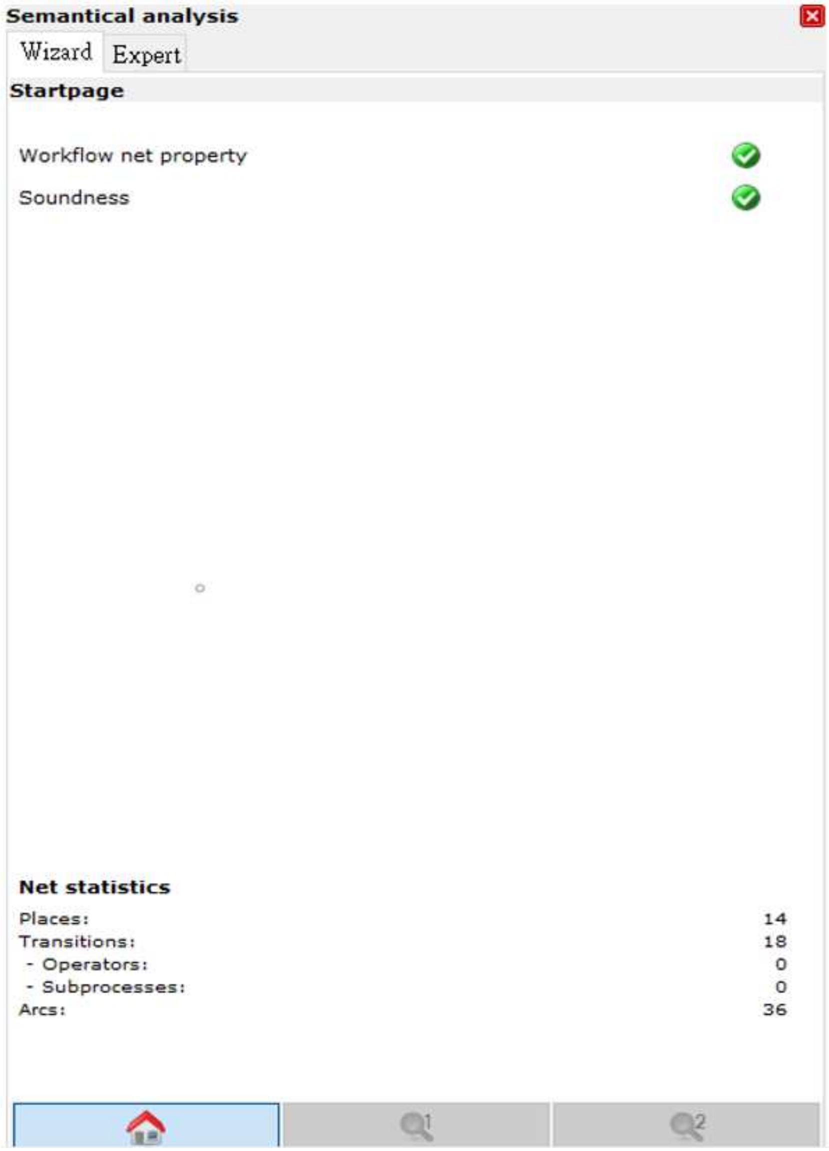

Fig. 4 PN semantical analysis

Fig. 5 Simulation results.

In summary, by using the WoPeD simulation tool, the PN model can be qualitatively analyzed. The PN model shown in Fig. 3 has one source place and one sink place. According to simulation results shown in Fig. 5, the IoT monitoring system is proved to be totally correct. In other words, the connections from places to transitions and vice versa do not have deadlocks at all. Since there are no deadlocks, the system is safe. The PN model has been utilized to verify and analyze the proposed IoT monitoring system, enhancing its applicability and integrity. Thus, the developed IoT monitoring system is ensured to be safe and correct [16-17].

4 Experimental Results and Performance Evaluation

This Section describes how the system uses the LoRa communication technology to develop the campus environmental monitoring system. The hardware and software requirements stated in Section 3 were used to carry out the IoT system development, leading to the creation of a complete monitoring system. This Section is divided into hardware information, software design and testing, and system performance evaluation.

4.1 Hardware Information

The required hardware information has been described in Section 3. Table 5 shows the summary of all hardware components and the datasets collected by the detection stations.

Table 5 Summary of air detection station information

Location	Hardware	Datasets
Playground (Outdoor)	1. LRM001 2. Arduino Mega 2560 3. PMS5003T 4. JL-FS2 5. GUVA-S12SD 6. Lithium Battery 7. XH-M40111	1. Temperature 2. Humidity 3. Particulate Matter 4. Apparent Temperature 5. Wind Speed 6. Ultraviolet Light
Fifth Dormitory (Indoor)	1. LRM001 2. Arduino Mega 2560 3. PMS5003T 4. MQ-7 5. DSC-CO2-20 6. Lithium Battery 7. XH-M40111	1. Temperature 2. Humidity 3. Particulate Matter 4. Carbon Monoxide 5. Carbon Dioxide
Second Education Building (Indoor)	1. Q7-REV07 2. LRM001 3. PMS5003T 4. MQ-7 5. DSC-CO2-20	1. Temperature 2. Humidity 3. Particulate Matter 4. Carbon Monoxide 5. Carbon Dioxide

4.2 Software Design and Testing

In this study, three detection stations were set up in the air quality monitoring system. As shown in Fig. 6, the gateway runs the C# Windows Forms software application (App), which opens the UART communication protocol at both ends. It connects the first end to the REVQ704's own Arduino, and sets COM1 and 9600 Baud, while the second end communicates with the LRM001 of the Mini PCI-E slot, which sets COM4 and 57600 Baud. The Start button is pressed to start the communication mechanism, which sends the command to complete the LRM001 command configuration.

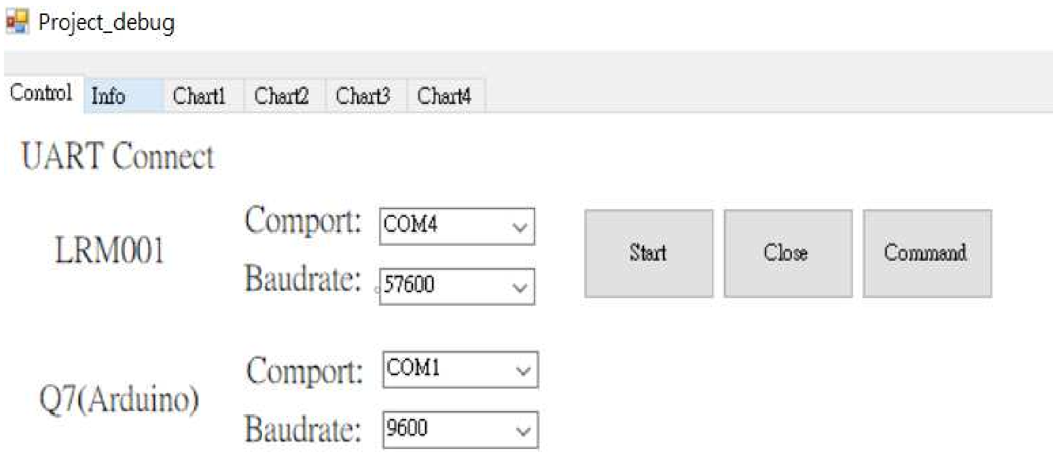

Fig. 6 UART connection

A command was sent to the LRM001, and the RN2903 chip returned the corresponding reply. As shown in Fig. 7, the command is successful. If there is a command error, the communication will stop.

- sys reset
- mac pause
- radio set freq 915100000
- radio set pwr 20
- radio set bw 250
- radio set wdt 5000

Fig. 7 RN2903 response

As shown in Tables 6, 7, and 8, after opening the gateway software App, it receives the values of the sensors from three detection stations. As stated in Section 3.4, the header for different locations is identified and the effective hexadecimal value of each string is obtained to get the average value of each item based on the number of datasets received per hour. In addition, every day at 00:00, the 24-hour datasets in the cloud database system for the previous day are cleared automatically.

Apparent temperature (AT) is calculated based on temperature (T), relative humidity (RH), water pressure (e) and wind speed (V) according to formulas (4-1) and (4-2) [31].

$$\mathrm{e} = \frac{RH}{100} \times 6.105 \times exp\left(\frac{17.27 \times T}{237.7 + T}\right) \tag{4-1}$$

$$\mathrm{AT} = \mathrm{T} + 0.33 \times \mathrm{e} - 0.7 \times \mathrm{V} - 4 \tag{4-2}$$

Comfort level (THI) is calculated based on temperature (T) and relative humidity (RH) according to formula (4-3).

$$\mathrm{TH1} = \mathrm{T} - 0.55 \times \frac{1 - GH}{100} \times (T - 14) \tag{4-3}$$

Table 6 User interface in App-1

Fifth dormitory

Temperature :	28	℃	
Humidity :	66.6	%	
THI :	26		Comfortable
PM1.0 :	27	$\mu g/m^3$	
PM2.5 :	45	$\mu g/m^3$	unhealthy
PM10 :	53	$\mu g/m^3$	
CO :	0.1	ppm	
CO2 :	595	ppm	

Table 7 User interface in App -2

Playground

Temperature :	34.5	℃	
Humidity :	49.5	%	
Wind speed :	1	m/s	
Apparent Temperature :	36.6		Sultry
PM1.0 :	29	$\mu g/m^3$	
PM2.5 :	44	$\mu g/m^3$	unhealthy
PM10 :	56	$\mu g/m^3$	
UV :	6		

Table 8 User interface in App-3

Second educational building

Temperature :	28.9	℃	
Humidity :	67.7	%	
THI :	26		Comfortable
PM1.0 :	29	μg/m^3	
PM2.5 :	44	μg/m^3	unhealthy
PM10 :	56	μg/m^3	
CO :	0.1	ppm	
CO2 :	601	ppm	

The hourly average value is connected to the Microsoft Azure through the network. The intelligently correlated cloud database service is to store each effective sensing value in the corresponding table. This system uses SSMS to connect with the Azure SQL Database to create a table for each detection item, helping the gateway and the server to carry out an access. In addition, users can use this tool to access the cloud database and issue those commands such as add, modify, delete, and search. Fig. 8 shows the apparent temperature datasets in the sports field.

After the C# Windows Forms analysis of the gateway is completed, the valid datasets are uploaded to the cloud database system through the network. The C# Web Application of the system was installed in the host at the Department of Electronic Engineering. By adopting the IIS service technology, a terminal server webpage was built. Physical network location can be used to enter the homepage of the campus environmental monitoring network.

Taking the detection station on the playground (i. e. sports field) as an example, and clicking the icon, the server receives the commands which lead to the playground information webpage. There are some options at the top for visiting the webpage of other detection station or returning to the homepage of the map. Various sensing information, such as apparent temperature, PM2.5 and ultraviolet light, is all listed in the middle to inform users of the current statuses, as shown in Fig. 8.

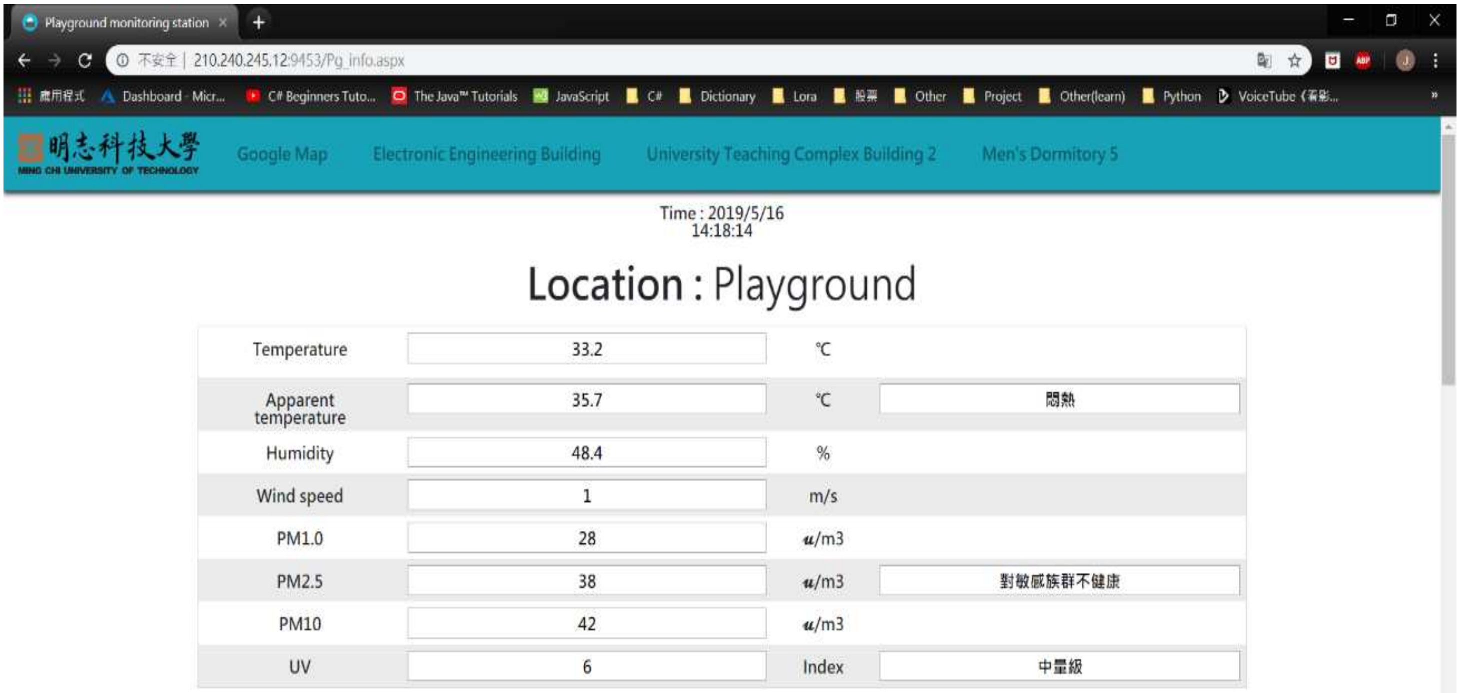

Fig. 8 Detection information on the playground

Figs. 9, 10, and 11 show the values of relative humidity, wind speed, temperature, and apparent temperature [34] detected by the monitoring station on the playground, respectively. By comparing the temperature with the apparent temperature in Fig. 11, the temperature can reach as high as 32 degrees or more during the daytime. However, by taking into consideration the humidity and the wind speed, the apparent temperature is higher than the hourly temperature during the daytime. Therefore, using the apparent temperature as a reference standard instead of the heat index or the wind chill index is more accurate.

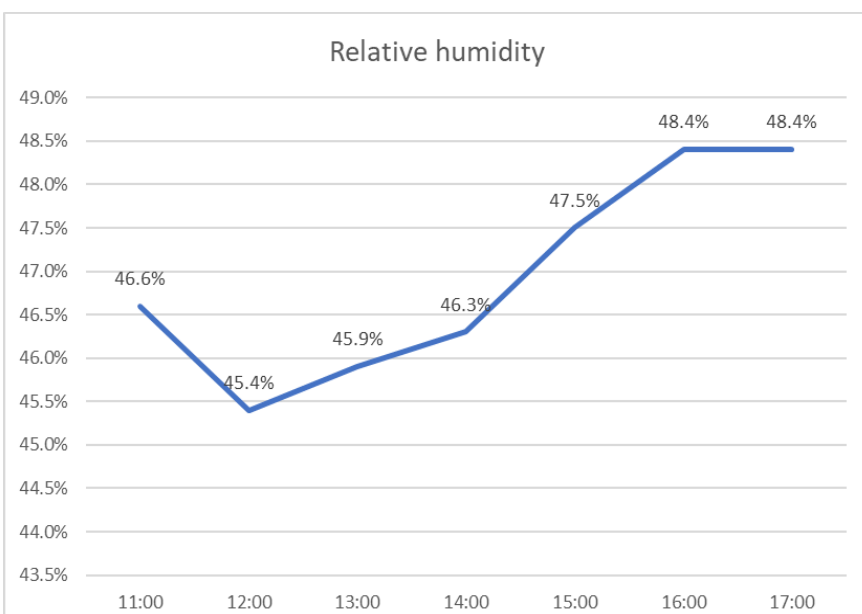

Fig. 9 Relative humidity on the playground

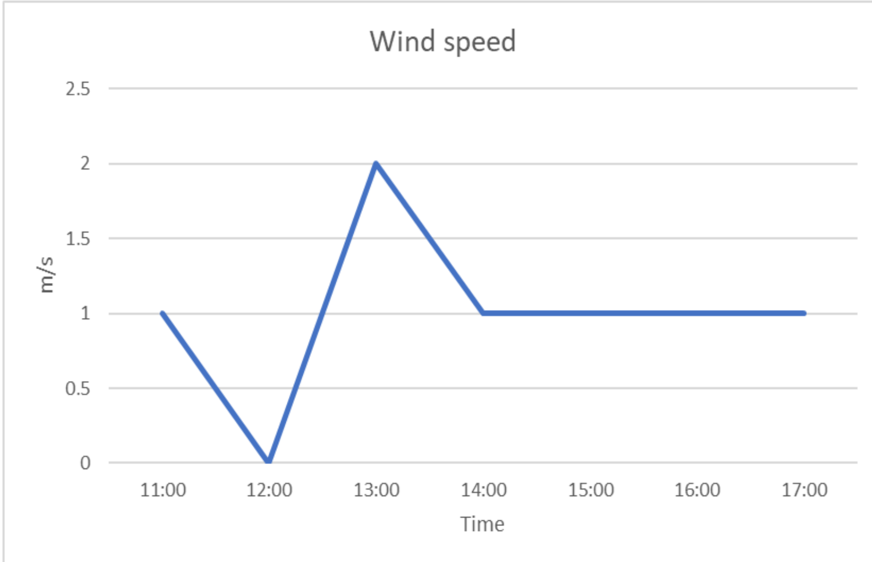

Fig. 10 Wind speed on the playground

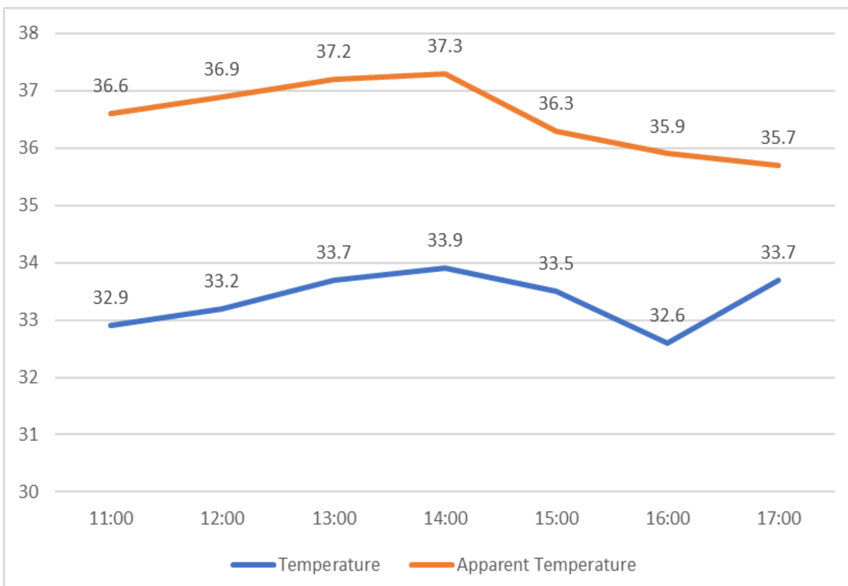

Fig. 11 Temperature and apparent temperature on the playground

Fig. 12 shows the graph of PM1.0, PM2.5, and PM10 measured during the daytime. Each detection item can be identified according to the legend provided. With the information bar provided at the top of the webpage, the current air quality analysis results can be obtained. Fig. 13 shows the graph of UV measurement, indicating that the UV is strong during the daytime, and its value reaches maximum at noon.

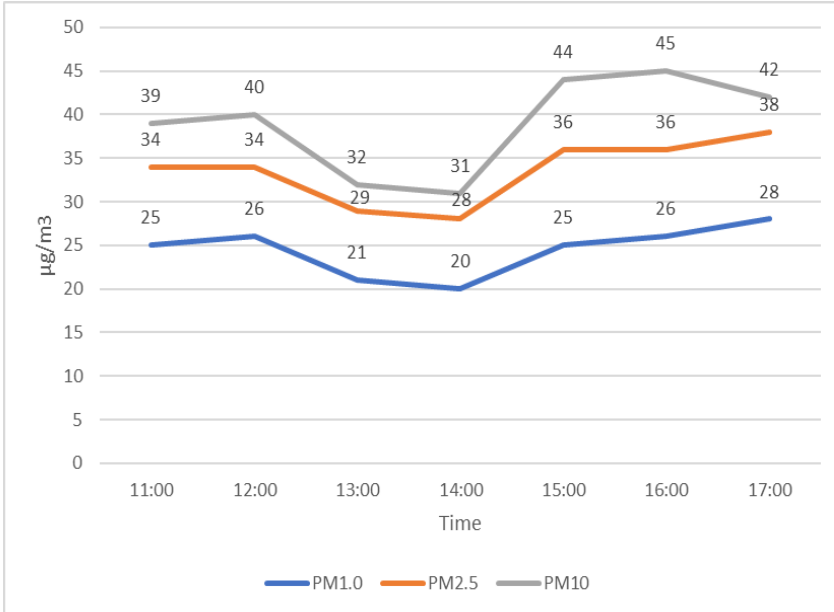

Fig. 12 Particulate matters measurement on the playground

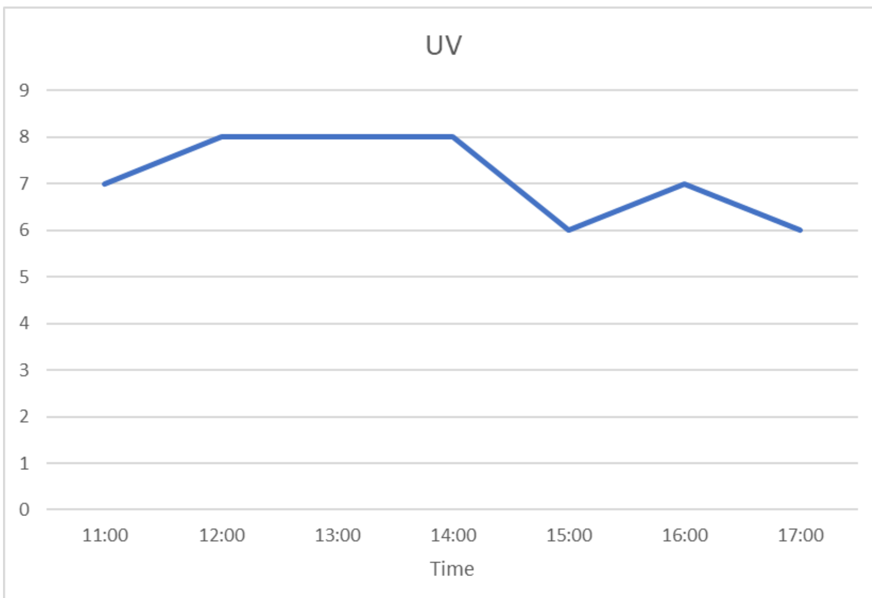

Fig. 13 UV measurement on the playground

4.3 Performance Evaluation

Finally, the success rate of packet transmission in this system was tested. A total of 3000 pieces of dataset were sent from the front-end device to the gateway, with a time interval of 5 seconds, as shown in Fig. 14. The distances between each station and the gateway were recorded in Table 9. In addition, the LoRa 915 MHz communication transmission results were used to serve as an important basis for the future system development. With LoRa 915 MHz adopted as the communication transmission, despite the presence of several obstacles, the success rate remains at 95% or more.

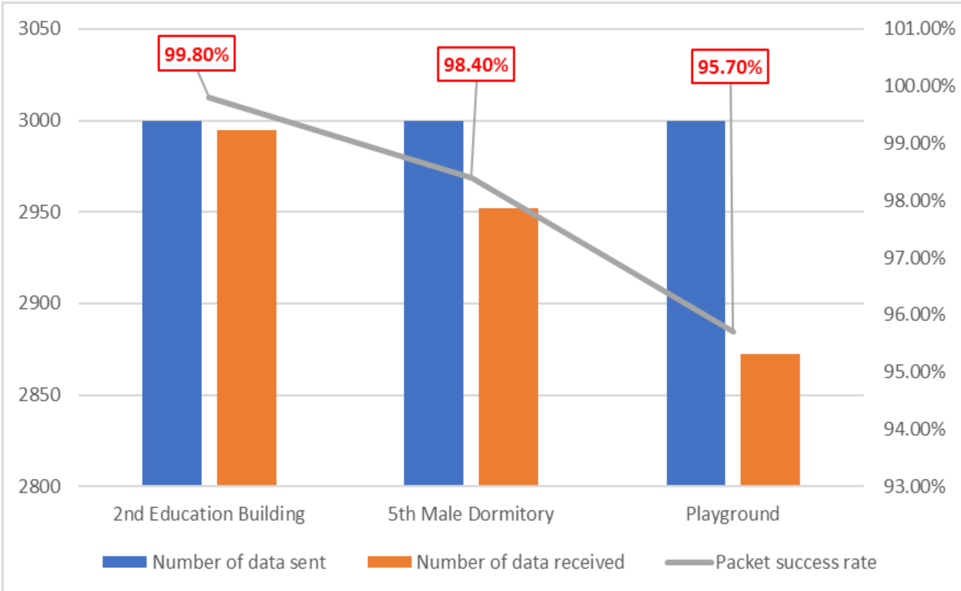

Fig. 14 System packet test

Table 9 System packet transmission success rate

Location	Tested distance	Number of datasets sent	Number of datasets received	Packet success rate
2nd Education Building	0m	3000	2995	99.8%
5th Male Dormitory	470±5m	3000	2952	98.4%
Playground	500±10m	3000	2872	95.7%

4.3.1 Advantages of Cloud Database over Traditional Database

Cloud computing is to allocate computing resources according to demands through the network, and those computing resources include server, database system, storage space, platform, architecture, and applications. Cloud computing supports pay-per-use, meaning that users only need to pay the prices as needed. In the following, the advantages of a cloud database system are all discussed. The feature comparison between cloud database system and traditional database system is shown in Table 10.

Table 10 Comparison between cloud database and traditional database

Items	Cloud database	Traditional database
Hardware equipment	Aggregated server mode	Single server mode
Hardware equipment cost	No hardware installation required	Cost ranges from hundreds of thousands to million dollars
Operating system	Users can use different operating systems such as Windows, Apple (iOS) or Android simultaneously.	Must work under the same system architecture.
Server cost	Maintained by cloud platform supplier	Hiring of maintenance personnel is required.
System platform maintenance	Platform supplier and equipment supplier are the same, which favors the maintenance operation.	Software supplier and hardware supplier are different, which may lead to responsibility issues. Additional cost is required for software update.
Software cost	Low cost, free or rental	High cost, and hardware equipment needs maintenance.
Data management	Easy to manage and high data security	Hiring of special personnel for management is required. There are risks of data loss or infection by viruses.
Computing method	Computing methods are distributed and synchronized.	Computing methods are independent.
Resource sharing	All users can easily access the data.	Users must be in the same domain or datasets need to be shared via portable hard drive.
Resource storage location	Less; requires multiple hardware devices.	More; can be added indefinitely if capacity is big enough.

In this study, the Azure cloud database system was used. When building this system, the advantages stated above indeed have been noticed, namely, low cost and high data security. When building a traditional database system, users may worry about the failure of the database equipment. However, when using the cloud database system, such a worry can be eliminated.

4.3.2 Functional Comparison

To fully support the claim that our proposed approach is more feasible and acceptable than other existing ones, we have made a functional comparison among different approaches including ours, Po-Ying Wu [9], and Yu-Sheng Lin [10]. The results of functional comparison are shown in Table 11.

Table 11 Results of functional comparison

Functions / Approaches	Short downlink latency	Low power consumption	Data visualization	User-friendly interface	Fast data transmission	Low system maintenance cost
Our proposed	V	V	V	V	V	V
Po-Ying Wu [9]		V	V	V		
Yu-Sheng Lin [10]		V	V	V		

"V" denotes "Yes" or "Available".

5 Conclusion

The campus environmental parameters monitoring system has been successfully developed. Three detection stations were set up to monitor different items according to the needs at each location. A variety of sensors are used to measure the substances that are harmful to people's health, allowing users to easily access the status of various environmental parameters on campus from the school's website. In the end, the Petri net simulation software tool was used to analyze and verify the integrity of the proposed IoT system.

The contributions of this study are presented as follows：

1. The environmental parameters on campus can be viewed from the university website. Users can access the status of environmental parameters in various regions at MCUT, such as temperature, humidity, wind speed, UV light and air quality (e.g. PM1.0, PM2.5, and PM10). Based on the monitored temperature, humidity and wind speed, the apparent temperature can be found, which is closer to the temperature experienced by users.
2. The LoRa technology with the characteristics of low-power consumption and long-range wireless communication was adopted to replace the traditional wireless communication technology such as Wi-Fi, ZigBee, and BlueTooth.
3. The most suitable protocol among Classes *A*, *B*, and *C* was determined. By selecting the LoRaWAN in Class *C*, the data latency is minimized. Users always pay attention to whether the datasets are returned. The terminal equipment can reach a balance between downlink latency and battery life.
4. A more stable way of storing datasets was used. The Azure cloud database system was used to completely store the datasets, making the maintenance of IoT platform become easy.

5. The datasets from experimental results are stable so that the wireless communication with LoRa can maintain a packet transmission success rate of more than 95% in the long-range transmission region with multiple obstacles.

Although this system has been already completed, further improvements are still needed to reach the practical application and commercialization. In the future, this project will focus on improving and expanding the system functions. The system will be expanded to six detection stations, realizing a star topology of network connection to create a multi-point gateway. In this case, if the gateway encounters a failure, it will not affect the entire system operation. Furthermore, when communicating with the server, it will be distributed anywhere depending on the distance. The gateway with shorter distance will be set for returning datasets to the server.

Acknowledgements

This work was supported by the Ministry of Science and Technology, Taiwan, ROC, under grants MOST107-2221-E-845- 001-MY3 and MOST 107-2221-E-845- 002-MY3.

REFERENCES

1. Syu, Y.-J., Jhang, B.-S. (2015). Taiwan's somatosensory temperature preliminary analysis. *Procs. of Central Meteorological Administration's 104-year Seminar on Weather Analysis and Forecasting*. (Visited on 2019/11/23).
2. Sobin, C. C. (2020). A survey on architecture, protocols and challenges in IoT. *Wireless Personal Communications*, 112, 1383-1429.
3. Ahmed, M. I., Kannan, G. (2021). Secure end-to-end communications and data analytics in IoT integrated application using IBM Watson IoT platform. *Wireless Personal Communications*, Online.
4. WIKIPEDIA, LPWAN. [Online]. Available: https://en.wikipedia.org/wiki/LPWAN. (Visited on 2019/1/23)
5. LPWA Technologies-unlock new IoT market potential. *LoRa Alliance. 2015*. (Visited on 2019/1/23).
6. Khalil, A., Mbarek, N., Togni, O. (2021). A self-optimizing QoS-based access for IoT environments. *Wireless Personal Communications*, Online.
7. Mobile experts White Paper for LoRa Alliance-Where does LoRa fit in the big picture. *LoRa Alliance*, *2015*.
8. Mikhaylov, K., Petaejaejaervi, J., Haenninen, T. (2016). Analysis of capacity and scalability of the LoRa low power wide area network technology. *European Wireless 2016*.
9. Wu, P.-Y. (2019). Development of LoRa-based IoT platform. *Master's Thesis, Department of Electronic Engineering, I-Shou University,* https://hdl.handle.net/11296/66m549 [Online].
10. Lin, Y.-S. (2018). The implementation of a campus air monitoring system using LoRa network. *Master's Thesis, Department of Information Engineering, Tunghai University,* https://hdl.handle.net/11296/h48a65 [Online].

11. Khanna, A., Kaur, S. (2020). Internet of Things (IoT), applications and challenges: A comprehensive review. *Wireless Personal Communications*, 114, 1687-1762.
12. Raza, U., Kulkarni, P., Sooriyabandara, M. (2017). Low power wide area networks: An overview. *IEEE Communications Surveys & Tutorials*, 19(2), 855–873.
13. Ayele, E. D., Hakkenberg, C., Meijers, J. P., Zhang, K., Meratnia, N., Havinga, P. J.M. (2017). Performance analysis of LoRa radio for an indoor IoT application. *Procs. of 2017 International Conference on Internet of Things for the Global Community (IoTGC)*, 1–8.
14. LoRa world coverage [Online]. Available: www.lora-alliance.org/ (Visited on 2018/8/20).
15. LoRaWAN™ what is it? - A technical overview of LoRa and LoRaWAN™, *LoRa Alliance, 2015*.
16. Shen, V. R.L., Yang, C.-Y., Shen, R.-K., Chen, Y.-C. (2018). Application of Petri nets to deadlock avoidance in iPad-like manufacturing systems. *Journal of Intelligent Manufacturing*, 29(6) 1363-1378.
17. Shen, R.-K., Lin, Y.-N., Juang, T. T.-Y., Shen, V. R.L., Lim, S. Y. (2018). Automatic detection of video shot boundary in social media using a hybrid approach of HLFPN and keypoint matching. *IEEE Transactions on Computational Social Systems*, 5(1), 210-219.
18. WoPeD Website [Online], https://woped.dhbw-karlsruhe.de/, as of Aug. 23, 2019.
19. Arduino-Mage-2560-Rev3 [Online]. Available: https://store.arduino.cc/usa/arduino-mega-2560-rev3%20 (Visited on 2018/8/20).
20. PMS5003T User Manual. PLANTOWER, 2016.
21. MQ-7 User Manual. SparkFun Electronics, 2012.
22. GUVA-S12SD User Manual. Roithner Lasertechnik, 2011.
23. JL-FS2 User Manual. EKT, 2012.
24. DS-CO2-20 User Manual. PLANTOWER, 2017.
25. LRM001-915 User Manual. Liyatech, 2018.
26. RN2903 LoRa™ Technology Module Command Reference User's Guide. MICROCHIP, 2015.
27. RN2903 Low-Power Long Range LoRa Technology Transceiver Module. MICROCHIP, 2015.
28. C# programming manual [Online]. Available: https://docs.microsoft.com/zh-tw/dotnet/csharp/programming-guide/ (Visited on 2018/8/20).
29. Web development (ASP.NET) [Online]. Available: https://dotnet.microsoft.com/apps/aspnet (Visited on 2018/9/30).
30. Introduction to IIS Architectures [Online]. Available: https://docs.microsoft.com/en-us/iis/get-started/introduction-to-iis/introduction-to-iis-architecture (Visited on 2018/10/10).
31. Chanal, P. M., Kakkasageri, M. S. (2020). Security and privacy in IoT: A survey. *Wireless Personal Communications*, 115, 1667-1693.
32. What is the Azure SQL Database service [Online]. Available:

https://docs.microsoft.com/zh-tw/azure/sql-database/sql-database-technical-overview (Visited on 2019/12/15).
33. Transact-SQL syntax conventions (Transact-SQL) [Online]. Available: https://docs.microsoft.com/zh-tw/sql/t-sql/language-elements/transact-sql-syntax-conventions-transact-sql?view=sql-server-2017 (Visited on 2019/12/11).
34. What is apparent temperature? https://zh.wikipedia.org/wiki/%E9%AB%94%E6%84%9F%E6%BA%AB%E5%BA%A6 (Visited on 2019/12/15).

Publisher's Note Springer Nature remains neutral with regards to jurisdictional claims in published maps and institutional affiliations.