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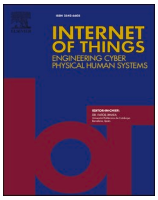

LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring

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ABSTRACT

This study proposes a smart long-range (LoRa) sensing node to timely collect the air quality information and update it on the cloud. The developed long-range wide area network (LoRaWAN)-based Internet of Things (IoT) air quality monitoring system (AQMS), hereafter called LoRaWAN-IoT-AQMS, was deployed in an outdoor environment to validate its reliability and effectiveness. The system is composed of multiple sensors (NO_2, SO_2, CO_2, CO, $PM_{2.5}$, temperature, and humidity), Arduino microcontroller, LoRa shield, LoRaWAN gateway, and The Thing Network (TTN) IoT platform. The LoRaWAN-IoT-AQMS is a standalone system powered continuously by a rechargeable battery with a photovoltaic solar panel via a solar charger shield for sustainable operation. Our system simultaneously gathers the considered air quality information by using the smart sensing unit. Then, the system transmits the information through the gateway to the TTN platform, which is integrated with the ThingSpeak IoT server. This action updates the collected data and displays these data on a developed Web-based dashboard and a Graphical User Interface (GUI) that uses the Virtuino mobile application. Thus, the displayed information can be easily accessed by users via their smartphones. The results obtained by the developed LoRaWAN-IoT-AQMS are validated by comparing them with experimental results based on the high-technology Aeroqual air quality monitoring devices. Our system can reliably monitor various air quality indicators and efficiently transmit the information in real time over the Internet.

Introduction

The quality of inhaled air in recent years has greatly deteriorated compared with that in the last few decades due to uncontrollable pollution. Although people know the effects of inhaling polluted air, this concern is often ignored because information is generally lacking with respect to the surrounding air and levels of air quality. The importance of surrounding air quality has increased during the COVID-19 pandemic, suggesting that air quality index (AQI) should be urgently measured in real time. Although several systems have been proposed in the literature to monitor air quality, most of them adopt the new Internet of Things (IoT) technology to provide real-time information about the surroundings. Air is one of the major needs of human beings, and a breathable atmosphere is one of the crucial factors that render Earth inhabitable and distinct from other planets in the solar system [1]. Therefore, the importance of maintaining a certain level of air quality in the environment should be comprehensively elucidated. Undoubtedly, improving the air

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quality has a positive impact on human health [2]. When the air quality is poor, public health and the economy are adversely impacted [3]. Furthermore, the intensification of deforestation, urbanization, and industry activities has widely affected our living environment, especially air. This issue has become a main concern in addressing the health of humankind [4, 5]. The vast impact of the aforementioned activities brings disadvantages to human beings, which eventually may cause death. Society needs to be alerted about the surrounding environment, enabling individuals to take precautionary steps at any time. Living in the 21st century suggests that everything is fast-paced, the machinery is technologically advanced, and the world's population is continuously growing; air pollution has become an ever-growing problem [6]. Air pollution is expected to deteriorate the environment and drastically affect human health.

Air quality refers to the air condition in the atmosphere, and its measurement indicates how clean or harmful it is for humans to inhale air. The monitoring of air quality also shows how much harmful substances are present in air. Air quality is an important factor of the urban environment, with a possible impact on public health, especially in walking areas where the public actively utilizes the public space for day-to-day events, mobility, leisure, and recreation. Good outdoor air quality is essential to the wellness of human beings. On the average, a person can inhale approximately 13,000 liters of air every day, but the existence of contaminants in air can adversely harm an individual's health. Understanding the expectations of users for acoustic and aeronautical efficiency is a great reward for public space management [7]. As for the consistency of environmental conditions, it is dictated by natural processes, such as dust storms, forest fires, and everyday human activities.

Monitoring systems are generally used to regularly observe and routinely collect data, and they have been widely used in this modern era being affected by various environmental phenomena and conditions. Good monitoring systems can help to notify users about abnormal conditions and trigger alerts as a warning. Several air quality monitoring systems (AQMSs) are reported in the literature for monitoring pollution. According to the United States Environmental Protection Agency (USEPA), the six common air pollutants are particulate matter (PM), ground-level ozone (O_3), CO, SO_2, NO_2, and lead [8]. These pollutants must be monitored measured and continuously to alert the society of how healthy the breathable air is.

With the emergence of the Internet of Things (IoT) paradigm to characterize the interconnection of various devices with respect to their pervasive accessibility and body-build intelligence, a new era of environmental monitoring has also started [9]. A wide range of communication technologies is used to connect smart devices with Internet connectivity and sensing nodes to monitor various environmental conditions. IoT is a new technological concept that envisages a world where everyday objects are equipped with microcontrollers, digital communication transceivers, and appropriate protocol stacks, enabling machines to communicate with one another while users become an integral part of the Internet. IoT supports the growth of several applications by using the theoretically massive amount and diversity of data collected by devices, subsequently providing different services for the people and communities. A wide variety of IoT applications exist to date, including smart cities, smart homes, smart streets, air and water quality monitoring systems, and healthcare applications. More interestingly, IoT has redesigned the route in which users usually communicate with applications, subsequently supplying them with advanced networking and intermediate interfaces with socializing capabilities.

Low power wide area network (LPWAN) technologies have competitive features, including wide-area connectivity for low-power and low-data rate devices not provided by legacy wireless technologies. LPWANs interconnect many inexpensive and simple devices and enable direct wireless interconnections among end-devices and gateways in geographic areas of up to tens of square kilometers. Among the existing LPWAN technologies, long-range (LoRa) modulation technology can achieve wide coverage areas, low power consumption, and robustness to interferences. In chirp spread spectral modulation, the chirps modulated with different spreading factors behave quasi-orthogonally. The selection of LoRa as a representative for LPWAN is based on its suitable connectivity, low energy consumption, and license-free frequency spectrum. In particular, its low energy consumption coupled with long-distance communication enables LoRa to be one of the potential LPWAN technologies for IoT applications. LoRa is a physical layer in which the upper layers are defined by open-standard long-range wide area networking (LoRaWAN) [10]. LoRaWAN provides a medium-access control mechanism, enabling many end-devices to communicate with a gateway via LoRa modulation. LoRa/LoRaWAN technology targets key IoT requirements, such as bidirectional communication, end-to-end security, mobility, and localization services. Moreover, the technology is robust to interference.

The aforementioned features of LoRa/LoRaWAN technology are considered for developing an IoT-based air quality monitoring in this study. Here, the different air quality parameters and their consequences on air pollution levels are investigated. The proposed LoRaWAN-based IoT AQMS (LoRaWAN-IoT-AQMS) is composed of several sensors for monitoring different air quality indicators (NO_2, SO_2, CO_2, CO, $PM_{2.5}$, temperature, and humidity). An integrated algorithm based on the Arduino Uno microcontroller is used to combine the collected data as a single packet of multiple payloads to be transmitted using the LoRa shield to the LoRaWAN gateway, and then the information is updated in real time on the The Thing Network (TTN) IoT server. LoRaWAN enables the sensing nodes to transmit the information as small packets with low energy consumption to the gateway, which is far away for many kilometers, in a single hop. The public can access the transmitted data via a graphical user interface (GUI) using Virtuino mobile applications on their smartphones or through a Web-based ThingSpeak dashboard.

Motivations and problem statement

Living in the era of globalization, every country tends to compete globally to produce high-quality and reliable goods and services, some of them even exporting goods while providing dependable service. Living in a fast-paced life has indirectly allowed humans to work continuously without taking a break. However, the appreciation towards high air quality is often ignored. Nowadays, a huge number of large factories are continuously being built worldwide. Although national economies have been developed steadily, factories release massive amounts of unwanted gasses and toxic gasses to the surrounding air, consequently causing air pollution and harming human health. Air pollution is caused by the Earth's atmosphere of PM, hazardous materials, and biological molecules created by human activities. The effects of air pollution are alarming, causing global warming, acid rain, heart and respiratory problems, and eutrophication. Excessive usage of vehicles also contributes to air pollution with the emission of carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon monoxide (CO), $PM_{2.5}$, and nitrogen dioxide (NO_2). Vehicles produce air pollution during their life cycle, including the emissions during vehicle service and the processing of fuel [11]. These harmful gasses not only affect human health but also cause greenhouse effect and global warming in cases of severe air pollution.

Inventive and extensible techniques are being used to identify hazardous air pollutants [8]. However, most existing AQMSs detect only $PM_{2.5}$, but they cannot detect several other air pollutants. Current methods of $PM_{2.5}$ rate measurement require a comprehensive and lengthy-term assessment of air contaminants using highly advanced air monitoring stations. Nonetheless, fixed monitoring stations can only detect air pollution within a given area, suggesting the need of utilizing dispersion models. The actual data collected from these stations are then used to extrapolate pollutant rates around the world. This pollution measurement method requires expensive equipment that needs to be stationed at key locations. However, harmful air pollution can hardly be measured and determined on time because of the complex process. Furthermore, the hardware and maintenance of the aforementioned monitoring stations entail a hefty cost, preventing constant monitoring and the further installation of similar systems in other areas [12, 13].

Although many systems for air quality monitoring have been proposed in the literature, most of them lack the new IoT technologies to provide real-time information about the surroundings. The conventional systems are also limited in terms of the lack of supported wireless technologies, air quality parameters, microcontroller processing capabilities, and accessibility of collected information by the public.

This study proposes a new, cost-effective LoRaWAN-based IoT AQMS with a user-friendly interface. Our proposed scheme has several advantages over the existing systems in terms of the following: (i) wide range connectivity with low power consumption via the LoRa radio interface, (ii) data collection reliability with the use of multiple air quality sensors in a single multi-sensing smart unit, (iii) operation sustainability by using a solar panel with a solar charger shield to power-on the sensing unit, and (iv) real-time data access via Web-based and mobile-based GUI.

Research contributions

A LoRaWAN-based IoT AQMS is designed and fabricated with a low-cost, portable, smart sensing unit using an Arduino-based LoRa node to collect information from several air indicators. Then, the collected data are updated on the cloud via a LoRaWAN gateway. Users can monitor various air quality parameters and their impact in the form of air pollution levels to help update the surrounding air quality. Users can also use their smart mobile phones to check the status of surrounding air by using Virtuino applications or the ThingSpeak dashboard via a public channel. If any drastic changes are noticed in the monitored air, then the user can immediately call the responsible agencies.

The objectives and contributions of this study can be summarized as follows:

An IoT-based AQMS is designed and fabricated to measure environmental parameters, including $PM_{2.5}$, CO_2, CO, SO_2, NO_2, temperature, and humidity.

A new algorithm based on Arduino IDE is implemented to gather information from multiple air quality sensors and send it as a single packet of multiple payloads over the LoRaWAN gateway to the TTN platform.

The ThingSpeak IoT server is integrated with the TTN platform as a means of posting the gathered air quality statistics in real time via the Internet.

A ThingSpeak public channel dashboard and a Virtuino GUI linked to an IoT server are developed, enabling users to access air quality information anytime and anywhere.

The rest of this paper is organized as follows. Section II describes the background and related studies. Section III presents the adopted methods and materials. Section IV discusses the system development, verification, and testing. The results and performance evaluation are discussed in Section V. Finally, the conclusion is drawn in Section VI.

Related works

Dynamism, dependency, and uncertainty are the main characteristics of a good air quality system. The central idea for solving air pollution issues is the scientific representation of the internal structure of air mass distribution and its relationship to demonstrate the complex nature of air quality [14]. Air quality monitoring is an essential step in understanding the factors affecting air quality, and findings can help to inform engineering and policy decisions to improve air quality [15]. Various pollutants abound globally, including CO, nitrogen oxides, SO_2, microbial materials, volatile organic compounds, O_3, and hydrocarbons [16]. If environmental quality continues to deteriorate, then the costs of addressing the emissions problem in most industrialized countries will steadily increase [17]. According to the World Bank, the ten “worst cities” globally are all developed countries with high particulate pollutant rates. Developing nations usually aim for rapid economic growth, but energy conservation remains to be a “luxury” they cannot afford. Furthermore, air pollution is simply one of many public health issues that demand attention. Air quality indicators are currently based on the pollution levels of O_3, $PM_{2.5}$ and PM_{10}, SO_2, NO_2, and CO. For example, the AQI is a color-coded indicator of air quality data, and they are updated on a daily basis to show people how healthy or polluted the air is. Subsequently, information is provided on how clean or harmful the environment is and what the associated health consequences may be.

Air quality trends is created by EPA based on measurements from monitoring across the USA. EPA estimates nationwide levels of emission of ambient air pollutants using actual monitored measurements or engineering calculations of the amounts and types of pollutants produced by different sources such as vehicles and factories. Many factors are involved in the estimation of emission, including industrial activity levels, developments of technologies, consumption of fuel, vehicles and different engines operation, and all activities that produce air pollution. Emissions data is developed with inputs from various air agencies and industry. EPA tracks a range of emissions information such as how much pollutant is emitted from each pollution source. The AQI is EPA's index for reporting the quality of air and it can be considered as a yardstick that runs from 0 to 500. The higher the value of AQI, the greater air pollution level and the greater concern of the health. For example, an AQI value less or equal to 50 signifies good air quality, while an AQI value more than 300 denotes hazardous air quality. AQI value of 100 normally corresponds to a concentration of an ambient air which equals the level of the short-term national ambient air quality standard for public health protection. AQI values that are equal or less than 100 are generally satisfactory level of air quality. Unhealthy level of air quality occurs when AQI values are greater than 100: initially for certain sensitive groups of people, then for all people as AQI values get higher. The AQI is categorized into six categories with different color and each of it corresponds to a different health concern level. The category's color allows people to quickly determine whether the surrounding air quality is reaching unhealthy levels.

The AQI sets a value between 0 and 500 for environmental agencies to alert the people about how the air is contaminated. The higher the AQI, the poorer the air quality. Cities and states track and forecast the air quality by using the AQI. Meanwhile, USEPA has used AQI based on the flowchart in Fig. 1 and developed a method for specific pollutant concentrations as follows:

$$AQI = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} \times (C - C_{low}) + I_{low}, \tag{1}$$

where I is the AQI, C is the pollutant concentration, C_{low} is the concentration breakpoint (i.e., $\leq C$), C_{high} is the concentration breakpoint (i.e., $\geq C$), I_{low} is the index breakpoint corresponding to C_{low}, and I_{high} is the index breakpoint corresponding *to* C_{high}. The pollutant breakpoint of USEPA also defines all of the abovementioned parameters.

Many of the studies in the reviewed literature have investigated AQMSs from different perspectives. Various systems have focused

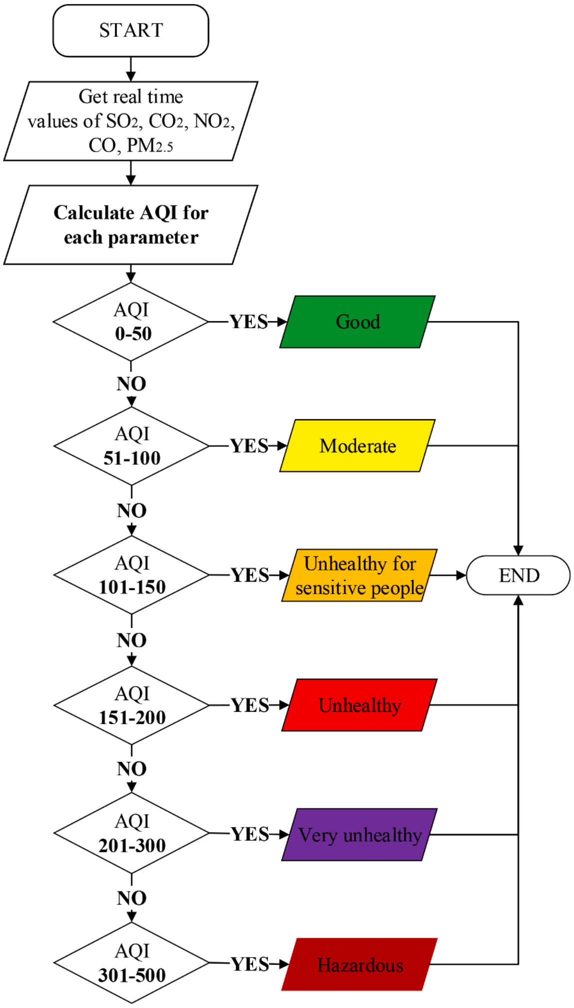


Fig. 1. AQI indicators [18].

on air quality parameters, such as $PM_{2.5}$, PM_{10}, CO_2, CO, SO_2, NO_2, temperature, and humidity, to represent invisible liquid or solid matter accumulated in the Earth's atmosphere. With the emerging concept of IoT, environment monitoring has become widely accepted as an IoT application. However, most existing systems are limited in terms of the lack of air quality parameters, unutilized communication technologies, low cost effectiveness, or data inaccessibility by the public. Given this context, Ref. [19] developed a self-sustainable air quality monitor for use in urban areas by utilizing the wireless sensor network (WSN) technology, in which only two sensors were used to monitor CO and PM. However, several parameters have a direct impact on air quality monitoring.

Ref. [20] presented a real-time standalone AQMS that could handle various parameters, such as $PM_{2.5}$, CO, CO_2, temperature, humidity, and air pressure, but ignored PM_{10} and NO_2. Furthermore, the sensing node was connected to the gateway via wires; thus, it is limited in terms of complexity and utilization of new wireless technologies. Ref. [21] proposed a standard solution based on the IoT technology by using the NodeMCU microcontroller. The main focus was on pollutant gasses (CO and NO_2) and temperature and humidity, but PMs were ignored. Their system utilized Wi-Fi, a short-range wireless communication technology.

Ref. [22] developed an AQMS based on IEEE/ISO/IEC 21,451 standards by using the GSM wireless communication module. The developed system could monitor the real-time measurement of air pollutant gasses, such as CO_2, CO, NO_2, and SO_2. The system did not include air temperature, humidity, pressure, and PM. In general, air quality monitoring that ignores the concentrations of all air parameters is incomplete. In addition, their system lacked the IoT concept, and the communication based on the GSM model is not cost-effective because of the SMS charges. By contrast, the proposed system utilizes the IoT concept and uses seven sensors to monitor various air quality parameters in real time over the Internet.

New research areas on smartphone-based air pollution monitoring have emerged with the advancement of wireless sensing [23]. The authors designed the first sensing model to deploy high-volume corridors on public transport infrastructures such as buses. Many of the applications could use dust or PM sensors, but the low-cost sensors obtained inaccurate and non-sensitive findings, particularly when the temperatures and humidity varied [24]. Oftentimes, the sensors would fail to properly record data and provide the time-stamps required to synchronize the data collected by other sensors. Many of these studies (e.g., Ref. [25]) obtained measurements in a stationary environment over long periods. However, wired stationary sensors are inappropriate for remote health monitoring, as real-time connectivity and feedback are often needed for users to travel around in the environment. Furthermore, the validation of those systems in an indoor environment is insufficient in proving their efficiency. From a different perspective, remote sensing using satellites can help to obtain coarse-grained surface air quality information. Even by using a single satellite, remote sensing can easily and effectively cover a large area. However, the building and maintenance of these stations usually require a large amount of money and human resources. By contrast, our IoT-based AQMS focuses on data transmission reliability with the compensation of LoRa/LoRaWAN technologies operating in the free spectral frequency (i.e., 920–923 MHz in Malaysia) to wirelessly transmit the collected data from the sensors to the gateway in real time. The public can also easily access the IoT platform. In this manner, the high-cost constraint of building and maintaining satellite-based AQMSs to ensure data accuracy and accessibility can be solved.

A Raspberry Pi-based AQMS has been proposed in the literature [20, 26-28]. Raspberry Pi may have been selected because it can support different operating systems, such as Raspbian, Raspbmc, Pidora, and Windows 10, and others. The Raspberry Pi-based AQMSs are also inexpensive and have a small size, hence their portability. Compared with Arduino, Pi operates almost 40 times faster in terms of clock speed. However, Pi is a powerful hardware and requires a continuous power supply, which means difficulty in operating the battery. Users also have to install programs prior to executing actions. Different from the operation of Arduino, Pi needs to be shut down properly before switching off the power to prevent the operating system and the application from being corrupted; otherwise, the microprocessor may be damaged. Pi is also more expensive compared with other microcontrollers, such as NodeMCU and Arduino, and thus not economical when implementing many nodes in the same network.

All of the aforementioned Pi-based AQMS used Wi-Fi as the main wireless interface, which is only suitable for short-range communication. By contrast, the proposed system utilizes Arduino with a LoRa shield for LoRa data transmission. In addition, the node in our system is suitable for continuous operation. A standalone photovoltaic (PV) provides the required power prior to switching on all sensors and the Arduino.

AQMSs that utilize various sensors, microcontrollers, and communication technologies are widely discussed in the literature. However, to the best of our knowledge, none of the reviewed studies have considered the multi-criteria approach that we implemented in our system. In terms of sensor selection, our proposed scheme uses six sensors, namely, gas sensors (MQ135, MQ136, MQ9, and MiCS-4514), a temperature and humidity sensor (DHT11), and a dust sensor. All sensors are implemented on a single wireless node for data transfer across several kilometers in a line-of-sight environment and up to 2 km in an environment with obstacles. In terms of microcontroller selection, the low-cost and energy-efficient Arduino Uno microcontroller (0.25 W) is utilized to overcome the limited number of ports of NodeMCU and the high power consumption and cost of Pi (2.4 W). Our system exploits one of the most recent LPWAN technologies for communication technology, namely, LoRa for the PHY layer and LoRaWAN for the MAC layer. A license-free sub-gigahertz radio frequency with a much lower energy consumption, higher security, lower data rate for data transmission, and wider coverage is also provided.

Our system can overcome the constraints of short-range communication technologies (ZigBee, Bluetooth, and Wi-Fi) and wired-based approaches utilized in most existing AQMSs. The proposed system also can solve the problem of add-on subscription charges for cellular services in systems based on GSM, GPRS, 3 G, LTE, and NB-IoT. In terms of the sustainable operation of the system, our LoRaWAN-IoT-AQMS is powered by a standalone PV system that uses an attached solar cell with an Arduino-based solar charger and a lithium-ion rechargeable battery. In terms of the utilization of the IoT concept, real-time data monitoring, and data security, the proposed scheme is an IoT-based system. Real-time information and secure end-to-end encryption are provided between sensors and IoT platforms. All of the selected software and IoT platforms are open access technologies, thus enabling data access by the public and facilitating free data storage in the cloud for further data analysis. Different from WSN-based systems, our system has a star-of-stars

Table 1

Summary of Related Studies.

Reference	Parameters	AQI	Techniques	Micro-controller	Communication Interface	IoT Server	GUI	System Prototype	Outdoor Implementation	Validation	Solar-powered
[29]	$PM_{2.5}$	X	Machine Learning	Raspberry Pi/ NodeMCU/PC	Wi-Fi	√	X	√	X	X	X
[30]	CO_2, CO, NO_2, temperature, humidity	X	MIT App Inventor/ Android	NodeMCU	Wi-Fi	√	√	√	X	X	X
[31]	CO_2, TVOC, temperature, humidity	X	IAQ, InfluxDB, Freeboard.io	ESP32	Wi-Fi	√	√	√	X	X	X
[32]	Temperature, humidity, CO_2, CO, PM_{10}, LPG	√	IAQ, Neural Network, Blockchain, dataset	Arduino UNO	Wired serial port	X	X	X	X	X	X
[33]	Temperature, humidity, CO	X	IAQ, Fuzzy Logic, Ventilation Control	Arduino	Wired serial port	X	X	√	X	X	X
[34]	Temperature, humidity, CO, CO_2, smoke, $PM_{2.5}$	X	Duct AQM, DJI RoboMaster mobile robot	Arduino Uno	Mesh LoRa	X	X	√	√	X	X
[35]	CO_2, $PM_{2.5}$	X	IAQ, LoRaWAN	ARM	LoRa	√	√	√	X	X	X
[36]	$PM_{2.5}$, PM_{10}, CO_2, temperature, humidity	√	EnMoS Web dashboard	Raspberry Pi zero	LoRa	√	X	√	√	X	X
[37]	CO, CO_2	X	IAQ, Fuzzy Logic, MATLAB simulation	Arduino Uno	Wi-Fi	X	√	√	X	X	X
LoRaWAN-IoT-AQMS	NO_2, SO_2, CO_2, CO, $PM_{2.5}$, temperature, humidity	√	LoRaWAN, TTN, ThingSpeak, Virtuino	Arduino Uno	LoRa/LoRaWAN	√	√	√	√	√	√

topology that allows sensor nodes to communicate directly with any nearby LoRaWAN gateway. The received data are forwarded to the open-source TTN server, which is integrated into both ThingSpeak and Virtuino mobile applications. The system components have been selected according to the best features and cost. A user-friendly interface, which includes a Web-based dashboard that uses ThingSpeak public/private channel and Virtuino GUI on smartphones, is also considered. In contrast to LAB instruments, our proposed system can be implemented and tested in a real environment and validated under different practical scenarios. Table 1 compares key features of selected recent studies on IoT air quality monitoring systems with the proposed the proposed LoRaWAN-IoT-AQMS. For the sake of paper readability, we have listed the useful abbreviations and notations used in this paper in Table 2.

Methods and materials

Research methodology

This section presents the research materials and methods adopted in this study. The flowchart is shown in Fig. 2.

The overall methodology approach was adopted. In the early phases, issues about the existing systems were investigated while comprehensively reviewing the topics related to the AQMS. After determining the detected issues from the reviewed studies, an AQMS with the capability of integrating the LPWAN networks with IoT concepts and smart sensing was built by selecting materials appropriate for the air quality monitoring sensing unit and the network and cloud. All of the hardware and components used in the construction of the system were identified. The modeling phase was followed by system design, hardware installation and software development, system fabrication, prototyping, and GUI integration. The system design was divided into two parts: design of the system enclosure and design of the multi-sensing unit. Thereafter, the testing and verification phase focused on enhancement and optimization to achieve the expected result through several tests. If a test fails due to some coding errors or other issues, then the testing process is repeated to reduce the errors until the AQMS can obtain the expected result for meeting the objectives. For the wiring and installation of sensors on the Arduino and the related hardware and software integration, the components were tested individually, followed by the entire LoRa-based smart sensing unit. A prototype cover for the AQMS was designed before system finalization to enable the airflow to come in contact with all sensors. Then, coding was performed according to the selected sensor libraries, the IoT platform, and the configured LoRa parameters. Finally, the practical deployment of the developed system was conducted, followed by data collection, results analysis, and system validation.

Research materials

The components of the proposed AQMS were selected according to their capability to be integrated into a single multi-sensing unit. We reviewed a number of market-available AQMS to gain insights into the required components. Material selection is a key step in designing any physical object. The comprehensive collection of the best materials for the product begins with identifying the properties and costs of the applicant's products. The selection of appropriate materials is one of the key elements of a successful system. In this section, we describe the selected hardware and software components to implement our system:

The system modules include the following components:

- Dragino Outdoor LoRaWAN Gateway
- Dragino LoRa shield
- MQ135 sensor
- MQ9 sensor

Table 2
Notations and terminology.

Term/Symbol	Description	Term/Symbol	Description
AQMS	Air Quality Monitoring System	GSM	Global System for Mobile Communications
IoT	Internet of Things	GPRS	Global Packet for Radio Services
TTN	The Things Network	3G	Third Generation
LPWAN	Low Power Wide Area Networks	LTE	Long-Term Evolution
LoRa	Long Range	NB-IoT	Narrowband Internet of Things
LoRaWAN	Long Range Wide Area Network	SMS	Short Message Service
WSN	Wireless Sensor Network	AC	Alternate Current
NO_2	Nitrogen dioxide	DC	Direct Current
SO_2	Sulfur dioxide	CSS	Chirp Spread Spectrum
CO_2	Carbon dioxide	PV	Photovoltaic
CO	Carbon monoxide	MAC	Media Access Control
$PM_{2.5}$ & PM_{10}	Particulate Matter	IDE	Integrated Development Environment
O_3	ozone	API	Application Programming Interface
DHT	Digital Temperature and Humidity	PLC	Power Line Communication
AQI	Air Quality Index	GUI	Graphical User Interface
TVOC	Total Volatile Organic Compound	IAQ	Indoor Air Quality
LPG	Liquefied Petroleum Gas	EnMoS	Environmental Monitoring System

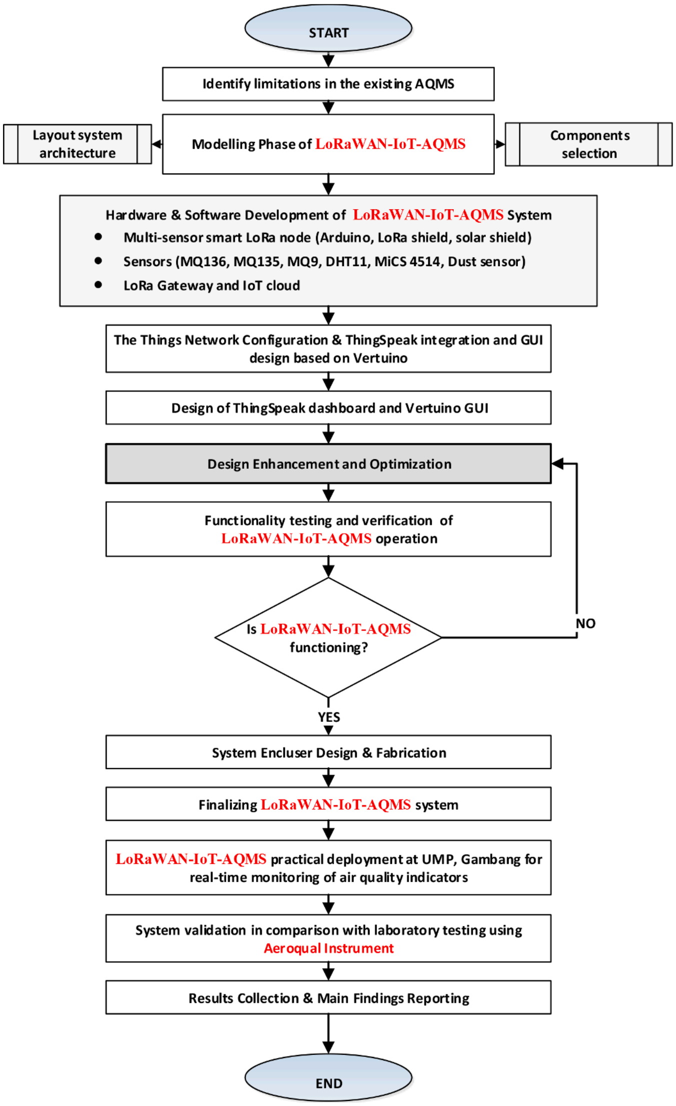


Fig. 2. Flowchart of the research activities.

- PMS3003 sensor
- MQ136 sensor
- MiCS-4514 sensor
- DHT11 temperature and humidity sensor
- 3.7 V lithium-ion battery
- PV solar panel
- Arduino-based solar charger shield
- Junction box, boards, wires, and terminals

As for the software components, they include the following:

- Fritzing software
- Arduino IDE software
- The Things Network
- ThingSpeak IoT Server
- Virtuino mobile application

After the device selection, the LoRaWAN-IoT-AQMS for air quality monitoring was designed and fabricated, and the system was ultimately installed.

System architecture

Fig. 3 presents the overall system architecture of our AQMS. The system consists of the following five main parts: (i) a PV system to provide the required energy for switching on and running the system; (ii) several sensors positioned in an outdoor environment for measuring the different air quality indicators, (iii) a LoRa/LoRaWAN network that consists of the Arduino Uno microcontroller, LoRa shield, solar charger shield, and LoRaWAN gateway; (iv) an IoT server with TTN platform and ThingSpeak server integration; and (v) a user application that consists of the ThingSpeak web-based dashboard and Virtuino mobile application. The PV system consists of a mini-polycrystalline solar panel PV panel with a rechargeable battery and an Arduino-based solar charger shield. The solar panel is placed on the system enclosure for harvesting sunlight and producing the required power for the multi-sensing LoRa node. The solar charger shield (ver. 2.2) is attached with Arduino Uno R3 for receiving the generated electricity from the panel to charge the 3.7 V lithium-ion rechargeable battery at daytime for use at nighttime. The microcontroller is a compact integrated circuit comprising the microprocessor and memory and related circuits, which regulates all or some of the functions of an electrical device or the equipment

The selected sensors (DHT11, MQ135, MQ136, MiCS 4514, MQ9, and dust sensor) sense the air parameters composed of temperature, humidity, CO_2, SO_2, NO_2, CO, and $PM_{2.5}$. The six sensors measure the air quality parameters and transfer the information to the multi-sensing smart node that utilizes a LoRa shield to forward the collected data to the LoRaWAN gateway. Arduino is used to gather the data from various sensors. The data are periodically transmitted as a payload stream to the LoRaWAN gateway over the 915 MHz Dragino LoRa radio. The data are updated on the open-source TTN platform after defining the gateway and configuring the LoRaWAN-IoT-AQMS application on the TTN console. Then, the air quality information is displayed simultaneously on the integrated TTN and ThingSpeak IoT platform on PC/laptops. The information is also linked to the Virtuino mobile application and can be accessed via smartphones.

System operation mechanism

Fig. 3 shows the overall system architecture and the general workflow of the proposed AQMS. The PV solar panel is connected to the sensors' circuit to power up the system. Once the system is powered, each sensor detects its corresponding pollutant gas. The LoRa node gathers the data from each sensor and forwards them to the gateway. Once the LoRaWAN gateway receives the information from the LoRa node, the streams of payloads are uploaded onto the TTN server, which is integrated with the ThingSpeak IoT platform and Virtuino mobile applications. Then, the information is published either on a Web-based dashboard or a mobile-based GUI, from which the users can easily observe the air quality indicators over the Internet. The system coding development includes the Arduino IDE-based algorithm for packetizing, encoding, and decoding the collected data and managing the transmission and receiving times. Several parameters, such as the time interval of data collection, packet size, number of payloads, and the configured LoRa radio parameters, need to be configured during the transmitting/receiving process. The system's operational workflow is shown in Fig. 4.

Development of lorawan-iot-aqms

Monitoring system design

The LoRa node consisting of the Arduino Uno and LoRa shield is the core unit of the proposed system. Sensors are used to track various air parameters, such as PM2.5, PM_{10}, CO, CO_2, SO_2, NO_2, temperature, and relative humidity. The sensors are connected to the Arduino Uno microcontroller, which is attached with a LoRa shield in the junction box. Fig. 5 shows the preliminary design of the circuit consisting of the six sensors and the Arduino Uno with the Fritzing software. The LoRa interface continuously transmits the data

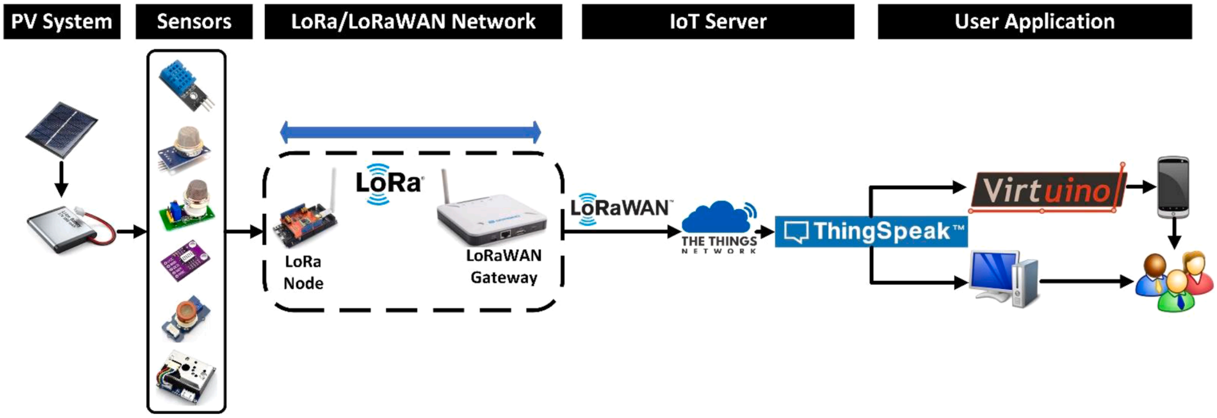


Fig. 3. Overall system architecture.

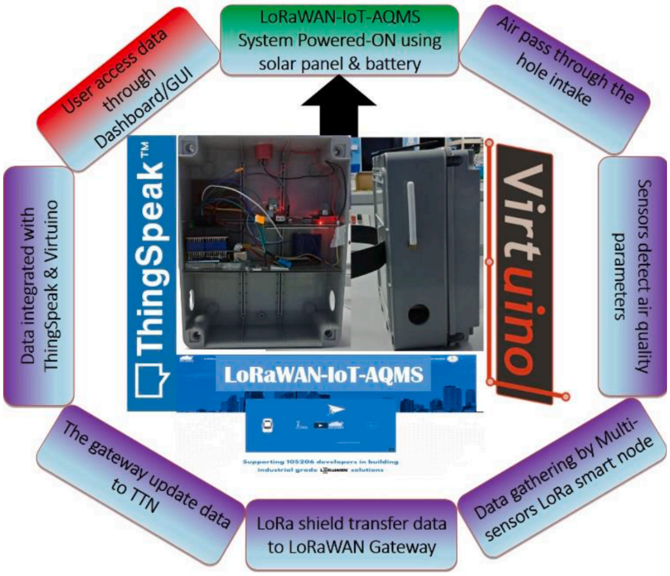


Fig. 4. LoRaWAN-IoT-AQMS operational procedure.

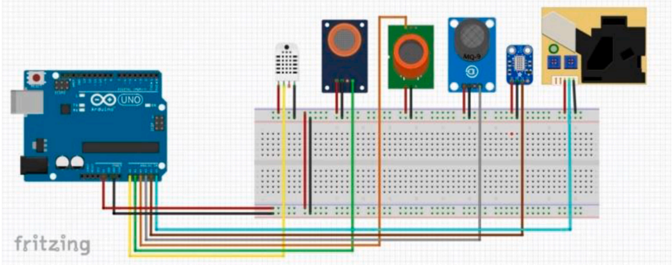


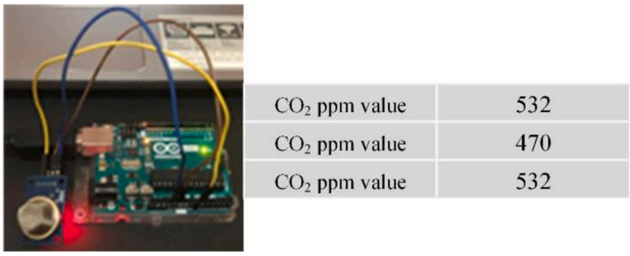
Fig. 5. Circuit design.

sensed by the sensors to the cloud via the LoRaWAN gateway. The dust sensor monitors $PM_{2.5}$, i.e., the smoke and dust found in our atmosphere, while DHT11 reads the temperature and humidity. MQ9 and MQ135 (analog sensors) measure CO and CO_2. MiCS-4514 detects NO_2, and MQ136 detects SO_2. In addition, a 3.7 V lithium-ion battery acts as a power source for the system. The solar panel with a charger shield charges the battery. The sensor system is encased by a waterproof junction box.

Prior to constructing the multi-sensing smart LoRa node, each sensor is tested and calibrated individually using Arduino. The connections of the sensors with Arduino Uno and the sample readings are shown in Figs. 6-10. The calibration test is applied individually to each sensor. The first three readings given by each sensor are shown in the tables beside each sensor label.

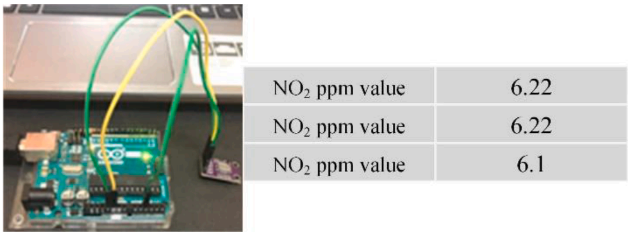
Fig. 7., 8., 9.

The network management consists of three stages of network activity: network establishment phase, configuration phase, and data collection phase. During network establishment, the gateway is connected to the Internet via an access point. The TTN console is an active gateway for receiving the transmitted data from the LoRa nodes. The LoRaWAN gateway and nodes exchange messages to establish a connection in a star topology. Each node initiates a connection link with all nearby gateways, and each gateway responds to



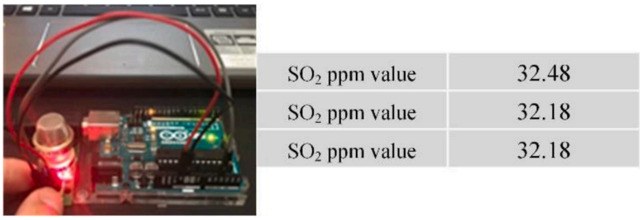
CO_2 ppm value	532
CO_2 ppm value	470
CO_2 ppm value	532

Fig. 6. Calibration of MQ-135 sensor for CO_2.



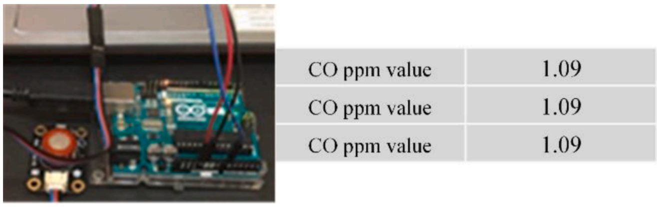
NO_2 ppm value	6.22
NO_2 ppm value	6.22
NO_2 ppm value	6.1

Fig. 7. Calibration of MiCS-4514 sensor for NO_2.



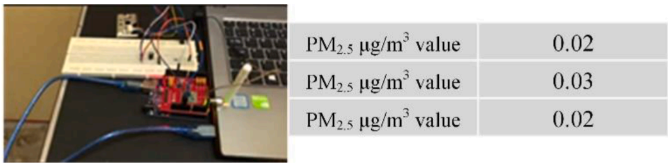
SO_2 ppm value	32.48
SO_2 ppm value	32.18
SO_2 ppm value	32.18

Fig. 8. Calibration of MQ 136 sensor for SO_2.



CO ppm value	1.09
CO ppm value	1.09
CO ppm value	1.09

Fig. 9. Calibration of MQ 9 sensor for CO.



$PM_{2.5}$ µg/m^3 value	0.02
$PM_{2.5}$ µg/m^3 value	0.03
$PM_{2.5}$ µg/m^3 value	0.02

Fig. 10. Calibration of dust sensor for $PM_{2.5}$.

all connection requests from the nodes within its coverage. At the configuration stage, a configuration command transmitted by the gateway triggers the network. Nodes update the required information (i.e., device EUI, application EUI, device address, network session key, and application session key) via the gateway. The system enters the data collection phase when the configuration process is completed. Once all sensor nodes have collected the required data, the nodes transmit these data from the surrounding environment and send them as streams of payloads to the gateway. Then, the data are displayed on the TTN, IoT ThingSpeak cloud, and Virtuino applications. The main function of the gateway is to monitor wireless sensor nodes and capture sensor data, thus enabling data forwarding to the Internet. The sensing data collected by the sensor nodes provide details on the monitored temperature, relative humidity, CO_2, NO_2, SO_2, CO, and $PM_{2.5}$.

System enclosure design

In the stage, a junction box is designed to encase all the developed smart sensing node components. A number of aspects are taken into account while designing and modeling the proposed AQMS.

i All of the related electronic devices are selected on the basis of the system requirements. The code is developed according to the expected operation of the system.
ii A junction box is selected in a manner that all devices can be arranged properly in its structure.

A target product needs to be completely specified (with accurate measurements) before it can be sufficiently designed and modeled. Specification plays a key role in this initiative. Therefore, the requirements are considered prior to the design process. We visualized our entire sketch using a more practical image; that is, we designed the cover measurements and the key components of the air quality monitor, thus enabling us to uncover and install the integrated monitoring system. The main cover of the sensing node is a junction box made from PVC. This material was selected for the project because of its weatherproof characteristics. The finalized high-quality box has a strong flame-retardant, good insulation, anti-corrosive, waterproof, and dust-proof specification; it also has strong impact resistance, high tensile strength, and scratch resistance, and it entails low cost.

The weatherproof junction box with a wide-space configuration allowed us to encase all components of the smart node inside its structure. The monitoring device includes six gas sensors, Arduino Uno board, LoRa shield, solar charger shield, PV solar panel, and a battery within the junction box. As the junction box is weatherproof, the sensors are protected from water and strong wind. Fig. 11 shows the sides of the junction box with two holes. These holes allow air to flow inward and outward from the junction box. With this air movement concept, the sensors encased by the junction box should be exposed to external air to be able to easily record the values of air parameters during monitoring. The sensors and the other electrical components are also protected from water and strong wind. The LoRa shield's antenna is placed outside the junction box to ensure a highly efficient signal transmission from the LoRa node to the LoRa gateway. In terms of manufacturing, holes with a diameter of 28 mm are drilled on the junction box by using a driller. The junction box has a hole on top for the placement of the PV solar panel. After holes are drilled, a small net is used to cover these holes to ensure that no water droplets or insects can enter the junction box, thereby preventing unnecessary incidents.

Hardware installation

The hardware installation phase is implemented upon completion of the design and modeling phase. As stated previously, the sensors are individually tested for coding verification and calibration purposes. In all test platforms, a breadboard and the Arduino connected to a PC via a serial monitor port are utilized. Then, the design and fabrication of the system's enclosure is finalized. As shown in Fig. 12, the junction box with all of its encased components take the form of a portable LoRaWAN-IoT-AQMS. Portability implies easy implementation in a real environment. A donut board with wire connectors is used to affix the electrical installation and ultimately lower the chances of a short circuit. The solar panel is fixed on top of the enclosure at a slight inclination angle to ensure that maximum sunlight radiation can reach the solar panel, allowing the battery charging process to be efficiently completed. A belt clip is used to allow users to affix the system on any outdoor support. Reliable readings can be obtained by placing the box at a high position, thus allowing all air parameters to be read sufficiently. The other reason for placing the box at a high place is to avoid vandalism and losing the electronic components due to burglary.

The system is enhanced and optimized to solve errors caused by hardware or software issues while ensuring system functionality. The sensor's placement inside the enclosure comes in contact only with the airflow, thus providing correct data readers of the air indicators. The data acquired by the sensor are transferred wirelessly via the LoRa node to the LoRaWAN gateway, which uploads the data onto the TTN server. The TTN console is integrated into the ThingSpeak platform, and the readings are displayed on the users' computers and smartphones. Users can view the graphs of each parameter through ThingSpeak, and the graphs are updated regularly. All readings are real-time readings. The same graph also appears in the Virtuino smartphone application. The completed interior view of the LoRaWAN-IoT-AQMS is shown in Fig. 12. The top view consists of a solar panel, and the whole circuit is encased by the junction box and a lamppost or pole can support the box, as shown in Fig. 13.

Software development

Program design plays an important role in ensuring that the whole system will operate properly. All materials are selected on the basis of suitability, i.e., the monitoring system should have superior performance. In ensuring that all electronic components (sensor, battery, solar charger shield, and LoRa node) are functional, the Arduino microcontroller is used for testing in the initial stages of system development. Prior to the coding, we reviewed the literature to learn about each component specification and the required libraries for them to work smoothly in congruence with other components. The foundation of the air quality parameters and monitoring system is also investigated to provide a strong background when making decisions during software development. Before configuring all sensors as a multi-sensing unit, each of them is tested using its coding library to verify its functionality. If the first sensor

(a) Top view (b) Side view

Fig. 11. Junction box design.

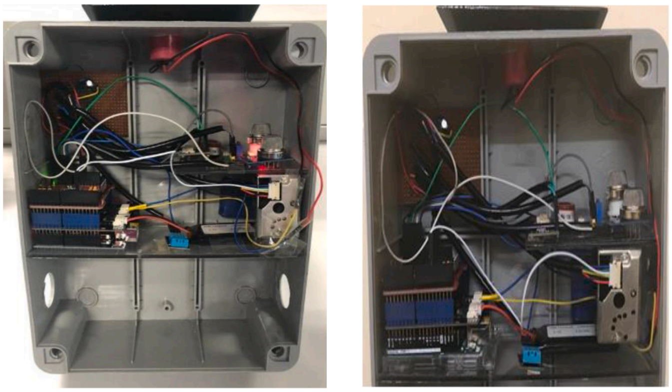
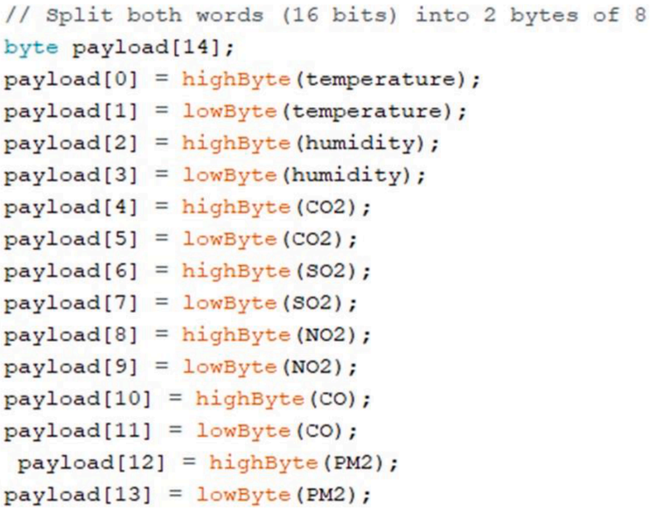


Fig. 12. Interior view of the finalized system prototype.

Fig. 13. Exterior view of the finalized system prototype.

is functioning suitably, then reading will appear on the Arduino IDE serial monitor. Then, other sensors are added in sequence to the Arduino Uno to ensure they will function as expected. Upon configuring the six sensors, the Arduino Uno runs and processes the collected data supplied by these sensors. The air quality values of the surrounding area are displayed on the serial monitor of the Arduino IDE.

One of the core contributions of this work is the software development of the portable LoRaWAN-IoT-AQMS, which can be



```
// Split both words (16 bits) into 2 bytes of 8
byte payload[14];
payload[0] = highByte(temperature);
payload[1] = lowByte(temperature);
payload[2] = highByte(humidity);
payload[3] = lowByte(humidity);
payload[4] = highByte(CO2);
payload[5] = lowByte(CO2);
payload[6] = highByte(SO2);
payload[7] = lowByte(SO2);
payload[8] = highByte(NO2);
payload[9] = lowByte(NO2);
payload[10] = highByte(CO);
payload[11] = lowByte(CO);
 payload[12] = highByte(PM2);
payload[13] = lowByte(PM2);
```

Fig. 14. Packet payload structure.

implemented in an outdoor environment to continuously monitor air quality indicators and wirelessly update the data in real time over the Internet anytime and anywhere. This development, including the one for the new algorithm (Algorithm 1) for data acquisition from the six sensors and the related data encoding, allows for the periodic transmission of a single packet of multiple payloads over LoRa to the TTN server. However, several configuration keys for the TTN console need to be defined in the Arduino sketch. In this manner, the node can be connected to the TTN server through any available gateway. Several coding schemes have been considered. Ultimately, with the adopted coding, our system can successfully send and upload the readings obtained from the sensors to the TTN server. Fig. 14 shows an example of a code used to compose 14 payloads as a single packet for transmission to the TTN server every ten seconds. The data received by the TTN server are decrypted and displayed as hexadecimal representations of decrypted "binary data," every two digits being one "byte" similar to those being sent by the sensor node. For the TTN application data, a payload decoder transforms the characters in bytes (hexadecimal units) as human-readable fields, as shown in Fig. 15.

The received uplink payload, which consists of 14 bytes (2 bytes for each sensor reading), is decoded into seven sensor readings for the considered quality parameters (NO_2, SO_2, CO_2, CO, $PM_{2.5}$, temperature, and humidity) to display the obtained data from the utilized sensors. Nevertheless, the TTN dashboard is not user-friendly without data visualization support. Consequently, as part of software development, the TTN platform is integrated into ThingSpeak IoT server and then linked to a Web-based dashboard and smartphone GUI based on the Virtuino mobile application.

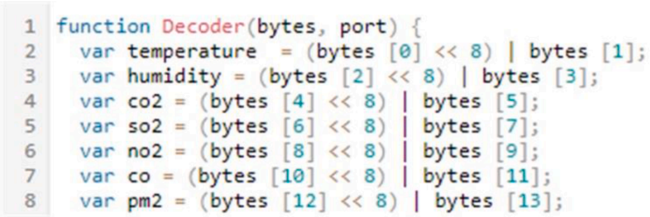
Our channel is created for ThingSpeak by using channel ID, write API key, and read API key to allow the channel to obtain data from the TTN console and display them in predefined visualize gage charts or widgets. ThingSpeak is an IoT analytics platform service that allows the aggregation, visualization, and analysis of live data streams. After the data are transmitted to ThingSpeak from the AQMS device, instant visualizations of real live data can be displayed without coding. The ThingSpeak API is also considered for connecting the device to the IoT platform. Moreover, ThingSpeak allows the building of applications based on the data collected by the sensors; it provides real-time data collection, data processing, and simple visualizations for users. A channel is created, and all data are published and accessed by the ThingSpeak API using a write key.

Subsequently, a read key is used to access the channel data if they are considered private data. The channels can also be made available to the public, in which case no read key is required. Seven visualization widgets are created to display the air quality indicators. The developed channel supports private and public viewing, mainly to control channel privacy. API keys are used to forward the data to the other devices and share data accessibility.

Virtuino is an HMI platform for IoT applications. All data from the ThingSpeak IoT platform are displayed in the applications upon adding the channel and API keys of the platform. Different types of charts, graphs, and indicators can be viewed using the applications. The readings indicate whether the sensors for the parameters have obtained normal or unusual values. The application allows users to more easily access and track variations in air conditions. Virtuino is a free and open-source smartphone application that can be downloaded from the Google Play store. Once the application is downloaded, users can link the interface to the selected IoT platform. Furthermore, by using Virtuino, users can monitor the air situation through their smartphone. The process can be described as follows. First, the Virtuino application is connected to ThingSpeak via a channel ID and read key of ThingSpeak. Second, widgets (charts, analog instruments, text, and indicators) are selected as a means of representing each parameter (temperature, humidity, $PM_{2.5}$, CO_2, CO, SO_2, and NO_2). The indicators are set to three colors according to the air pollution level: green for normal, yellow for not normal, and red for dangerous. Charts are created for all the pollutants, and fluctuations representing real-time data are shown for each parameter. The details of the integrated dashboard and GUI and their use in LoRaWAN-IoT-AQMS are presented in the next section. Upon completing the hardware and software development, the system is run in a real environment to verify its functionalities and validate its effectiveness. As the LoRaWAN-IoT-AQMS is meant to be used outdoors, it is tested in this study under three conditions: exposure to cigarette smoke, exposure to vehicle exhaust smoke, and exposure to burned coal smoke. The test results are then used to measure the pollutant gasses, mainly NO_2, SO_2, and CO. Our proposed LoRaWAN-IoT-AQMS uses sensors that can measure particular gasses.

Results and validation

The data collected from the different sensors provide substantial information about AQI. As an index, AQI defines how healthy the surrounding air is according to certain standards, criteria, and thresholds. The air status in AQI can be categorized on the basis of specific conditions and several indicators, as shown in Table 3. The stages indicate how clean and serious the air pollution is according to the AQI standards. Our monitoring system can define different levels of air quality based on the AQI. If the AQI score is in the range of 0–50, then the air quality is in "good" condition. If the air quality is in the range of 51–100, the condition is "moderate." If the



```
function Decoder(bytes, port) {
  var temperature  = (bytes [0] << 8) | bytes [1];
  var humidity = (bytes [2] << 8) | bytes [3];
  var co2 = (bytes [4] << 8) | bytes [5];
  var so2 = (bytes [6] << 8) | bytes [7];
  var no2 = (bytes [8] << 8) | bytes [9];
  var co = (bytes [10] << 8) | bytes [11];
  var pm2 = (bytes [12] << 8) | bytes [13];
```

Fig. 15. TTN payload decoder function.

Table 3
USEPA AQI standard breakpoint [18].

$PM_{2.5}$(μg/m^3)	CO (ppm)	SO_2 (ppb)	NO_2 (ppb)	AQI	AQI
C_{Low} -C_{high} (avg)	C_{Low} -C_{high} (avg)	C_{Low} -C_{high} (avg)	C_{Low} -C_{high} (avg)	I_{low}-I_{high}	Category
0.0–12.0 (24-hr)	0.0–4.4 (8-hr)	0–35 (1-hr)	0.0–53.0 (1-hr)	0–50	Good
12.1–35.4 (24-hr)	4.5–9.4 (8-hr)	36–75 (1-hr)	54–100 (1-hr)	51–100	Moderate
35.5–55.4 (24-hr)	9.5–12.4 (8-hr)	76–185 (1-hr)	101–360 (1-hr)	101–150	Unhealthy for sensitive Groups
55.5–150.4 (24-hr)	12.5–15.4 (24-hr)	186–304 (1-hr)	361–649 (1-hr)	151–200	Unhealthy
150.5–250.4 (24-hr)	15.5–30.4 (8-hr)	305–604 (24-hr)	650–1249 (1-hr)	201–300	Very Unhealthy
250.5–350.4 (24-hr)	30.5–40.4 (8-hr)	605–804 (24-hr)	1250–1649 (1-hr)	301–400	Hazardous
350.5–500.4 (24-hr)	40.5–50.4 (8-hr)	805–1004 (24-hr)	1650–2049 (1-hr)	401–500	

surrounding air has a core of 101–150, the air condition is “unhealthy for sensitive people.” The range of 151–200 indicates that the surrounding air is “unhealthy.” “Very unhealthy” represents the air quality scores of 201–300. Lastly, “hazardous” is displayed when the air surrounding is in a critical stage, and the corresponding AQI score is 301–500.

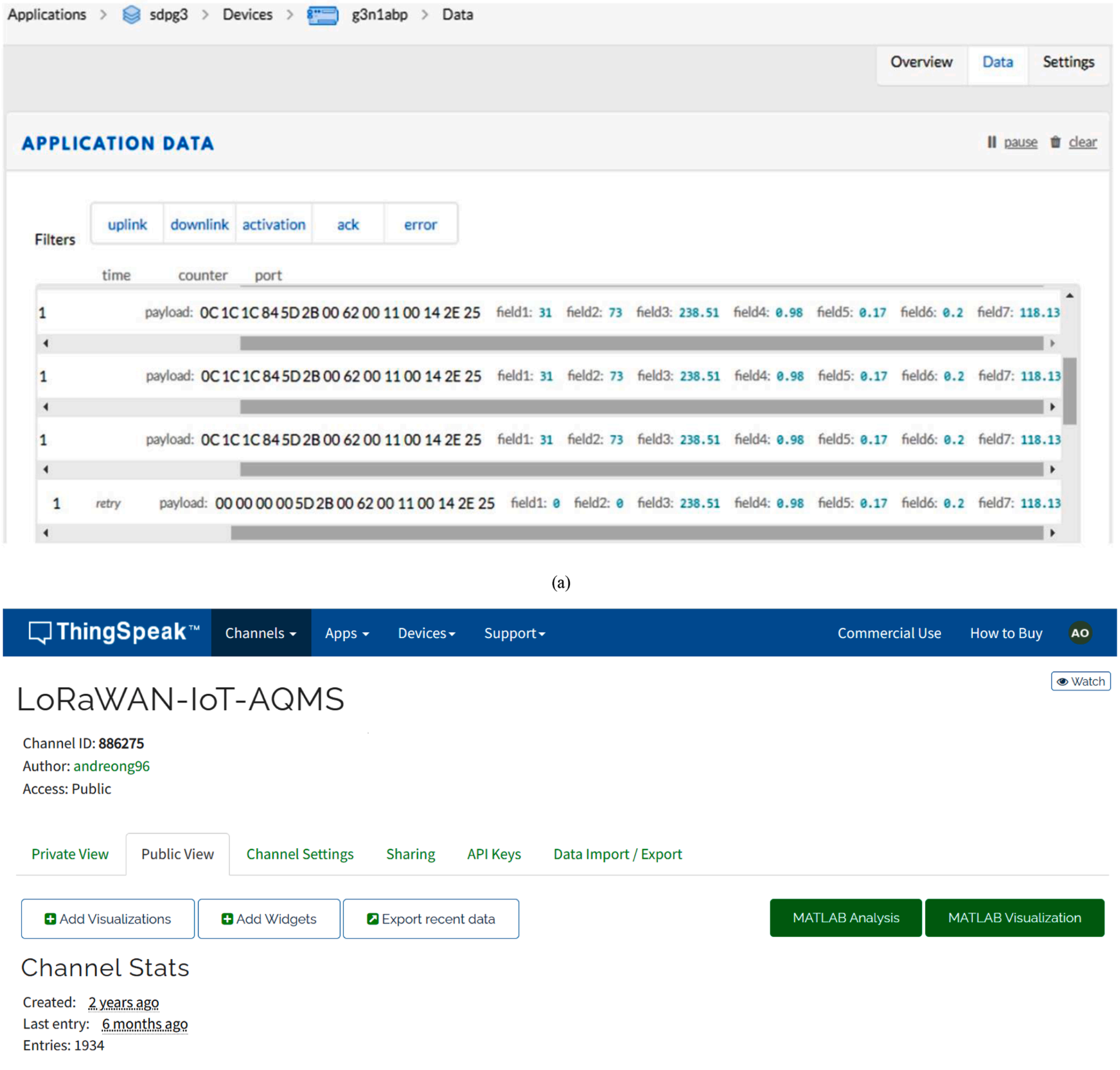
System functionality testing

This section discusses the experimental results and validation of the proposed LoRaWAN-IoT-AQMS. System testing is conducted numerous times to prevent obtaining the wrong data. Aeroqual, a reliable air monitoring equipment used to detect air quality, is used to compare all of the data gathered by the AQMS. The system is run for a few hours to regularly gather the scores of the surrounding air quality. The system is continuously run by a rechargeable lithium-ion battery. Once the battery is fully charged, it supplies power to all of the sensors, microcontroller, LoRa shield, and solar charger shield. The installed solar panel charges the battery to prevent the power from decreasing. At daytime, the solar panel charges the battery and supplies power to the system. At nighttime, the fully charged battery powers the system to obtain timely information. The sensors transmit the detected information to the LoRa node, which includes the microcontroller, solar charger shield, and LoRa shield. As mentioned previously, the proposed system is tested in multiple stages prior to deployment in a real outdoor environment. The results, discussions, and validations of the LoRaWAN-IoT-AQMS are presented in this section. The data measured by the utilized sensors (NO_2, SO_2, CO_2, CO, $PM_{2.5}$, temperature, and humidity sensor) are updated on the cloud. The air quality scores measured by the six sensors can be observed simultaneously using the TTN, ThingSpeak, and Virtuino applications.

The information about air quality parameters can be checked in real time on the TTN server as soon as the power of the LoRa sensing node is switched on. The device, channel, and network configuration keys and IDs are defined previously in the software development phase. Instantaneous sensor readings are shown in Fig. 16 which also shows the public view of the designed ThingSpeak channel. Users only need to know the channel ID for the AQMS to check the data. The different fields represent the selected air parameters, and the data are updated every 10 s. These presented results were obtained during the fabrication of LoRaWAN-IoT-AQMS at the Universiti Malaysia Pahang (UMP) Campus. The seven fields of the TTN console represent the following fields: Field 1 for temperature (31 °C), Field 2 for humidity (73%), Field 3 for CO_2 (238.51 ppm), Field 4 for SO_2 (0.98 ppm = 980 ppb), Field 5 for NO_2 (0.17 ppb), Field 6 for CO (0.20 ppm), and Field 7 for $PM_{2.5}$ (118.13 μg/m^3).

The results displayed on the TTN platform are not suitable for public access because the information requires private keys that have been configured beforehand for security purposes; however, only system developers and management offices adopt this type of secured platform. In our proposed scheme, the data obtained from each sensor (field) are synchronized and displayed as ThingSpeak charts in real time, as shown in Fig. 17. The chart format can present the time data more effectively, and the data can be stored on the cloud. The air quality level can be determined from the graph’s fluctuations (low and high values) for each parameter, considering that the air condition may vigorously change. Using ThingSpeak as the IoT platform entails several advantages. First, the IoT platform can be easily configured and matched with the TTN server and the connected sensors. The information can be easily transmitted from TTN language to ThingSpeak with IoT protocols. Second, ThingSpeak can be used to visualize the real-time data in the format of a gage, numerical values, indicators, or graphs. Third, ThingSpeak can show the historical trend of a selected period (minutes, hours, days, and months) in graph format. Fourth, ThingSpeak supports MATLAB analysis and visualization of the data, enabling the collected data to be further analyzed. Finally, users can access the information publicly shared over the Internet via the ThingSpeak channel anytime and anywhere using a channel name or a channel ID.

In addition, with our proposed scheme, users can use their smartphones to access the Virtuino GUI developed specifically for our system. Virtuino is a mobile application that is compatible with the Android operating system for mobile phones, and it can be downloaded from the Google Play Store as “Virtuino.” After some investigation and testing of several applications, we selected this application to build our dashboard. Our system GUI was developed using Virtuino because of its simplicity and user-friendliness in



```
1        payload: 0C 1C 1C 84 5D 2B 00 62 00 11 00 14 2E 25  field1: 31 field2: 73 field3: 238.51 field4: 0.98 field5: 0.17 field6: 0.2 field7: 118.13
1        payload: 0C 1C 1C 84 5D 2B 00 62 00 11 00 14 2E 25  field1: 31 field2: 73 field3: 238.51 field4: 0.98 field5: 0.17 field6: 0.2 field7: 118.13
1        payload: 0C 1C 1C 84 5D 2B 00 62 00 11 00 14 2E 25  field1: 31 field2: 73 field3: 238.51 field4: 0.98 field5: 0.17 field6: 0.2 field7: 118.13
1 retry  payload: 00 00 00 00 5D 2B 00 62 00 11 00 14 2E 25  field1: 0 field2: 0 field3: 238.51 field4: 0.98 field5: 0.17 field6: 0.2 field7: 118.13
```

(a)

LoRaWAN-IoT-AQMS

Channel ID: 886275
Author: andreong96
Access: Public

Channel Stats

Created: 2 years ago
Last entry: 6 months ago
Entries: 1934

(b)

Fig. 16. (a) Result of TTN, (b) Public view of ThingSpeak channel.

terms of viewing and overall use, and It can be synchronized with the ThingSpeak cloud server. The air quality parameters displayed in ThingSpeak are synchronized with the developed Virtuino GUI. All of the data are displayed simultaneously on multiple platforms, including the TTN website, ThingSpeak IoT platform, and the Virtuino smartphone application. In linking the Virtuino to ThingSpeak, the channel ID and API read keys of ThingSpeak need to be added, as shown in Fig. 18.

Furthermore, a widget is created for each sensor to synchronously transmit the data from the ThingSpeak and TTN servers to Virtuino. The graphs, indicators, and parameter labels in Virtuino need to be configured manually during software development. For Virtuino, every user can use this application because it is an open-source and user-friendly application.

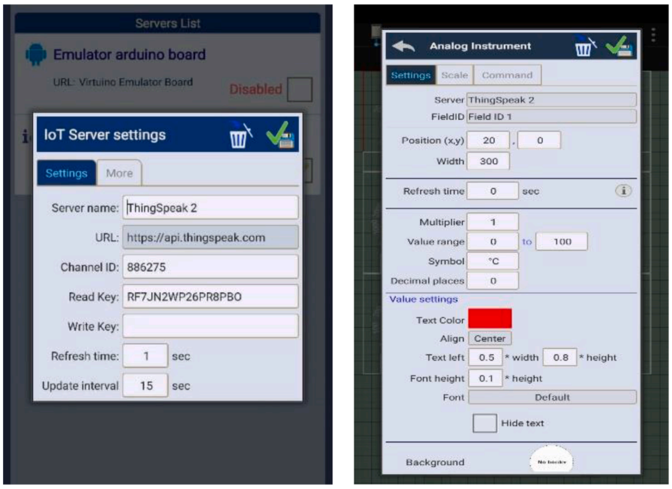
Knowing how to run the system to monitor various air parameters can be easily explained. The displayed data on Virtuino also allow users to easily comprehend and understand the information. As mentioned previously, the scales and ranges of each parameter are defined according to a specific AQI score range. Four levels with different colors are shown for each parameter, namely, “good” in green, “moderate” in yellow, “unhealthy for sensitive people” in orange, and “unhealthy” and “hazardous” in varying colors of red. Thus, the data collected by all sensors can be easily monitored, with each indicator pertaining to a particular AQI score, as shown in Fig. 19.

(a) (b) (c) (d) (e) (f) (g)

Fig. 17. ThingSpeak public channel view with a dashboard for various sensor data in dynamic graphs with time: (a) Temperature, (b) Humidity, (c) CO_2, (d) SO_2, (e) NO_2, (f) CO, and ((g) $PM_{2.5}$.

Performance evaluation

Prior to the implementation of the system in a real environment, performance evaluation is conducted to ensure system stability. The four main constraints considered during the development of our prototype kit are as follows: multi-sensing nature, sustainable



IoT Server settings

Settings | More

Server name: ThingSpeak 2
URL: https://api.thingspeak.com
Channel ID: 886275
Read Key: RF7JN2WP26PR8PBO
Write Key:
Refresh time: 1 sec
Update interval 15 sec

Analog Instrument

Settings | Scale | Command

Server ThingSpeak 2
FieldID Field ID 1
Position (x,y) 20 , 0
Width 300
Refresh time 0 sec
Multiplier 1
Value range 0 to 100
Symbol °C
Decimal places 0

Value settings

Text Color 🟥
Align Center
Text left 0.5 * width 0.8 * height
Font height 0.1 * height
Font Default
☐ Hide text
Background No border

Fig. 18. Process of linking Virtuino to the ThingSpeak IoT platform.

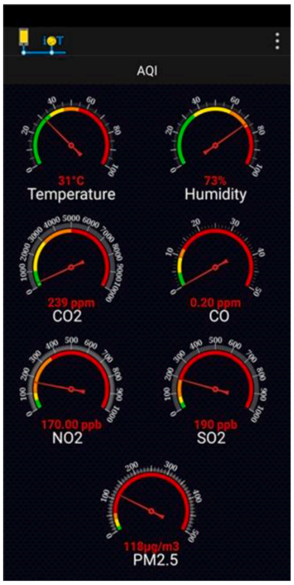


Fig. 19. Virtuino GUI of LoRaWAN-IoT-AQMS.

operation, data transmission, and cost-effectiveness. The proposed LoRaWAN-IoT-AQMS has been designed and fabricated, with the aim of solving the four issues. A dedicated smart LoRa node is built with a PV system; this served as the main concern for ensuring sustainable operation. Then, the six sensors are evaluated. A 3D-printed node enclosure is fabricated to allow for a more compact and affordable system. Collectively, the abovementioned features can help to improve system performance. In addition, the proper selection of IoT servers allows for the information to be more accessible to the public, further providing a suitable solution for problems associated with AQI monitoring. Market-available AQMSs have utilized a variety of communication technologies to build data pipelines, including short- and long-range communication interfaces. In our study, the selection of LoRa/LoRaWAN technology is based on a comprehensive survey and comparison of all LPWAN technologies and their application in IoT. The LoRaWAN gateway used in the testing and validation phases can promote a line-of-sight linking radius of 10 km. However, in an outdoor environment with some obstacles, the radius is closer at 2 km. Moreover, most of the existing systems exploit the LoRa interface without the LoRaWAN MAC protocol, which could have allowed for the smooth forwarding of data to the TTN server. By considering all of the aforementioned aspects, we confidently decided that the LoRa/LoRaWAN smart nodes and gateway are the best candidate for building the IoT-based outdoor AQMS. Furthermore, our system benefits from the open-source nature of hardware and software provided by the manufacturers and developers of LoRa Alliance and TTN.

Data collection in several operation scenarios for air quality monitoring is also performed. Our system provides open access to the collected data and demonstrates usefulness of data acquisition based on our analysis. Fig. 20 shows the average of collected entries for

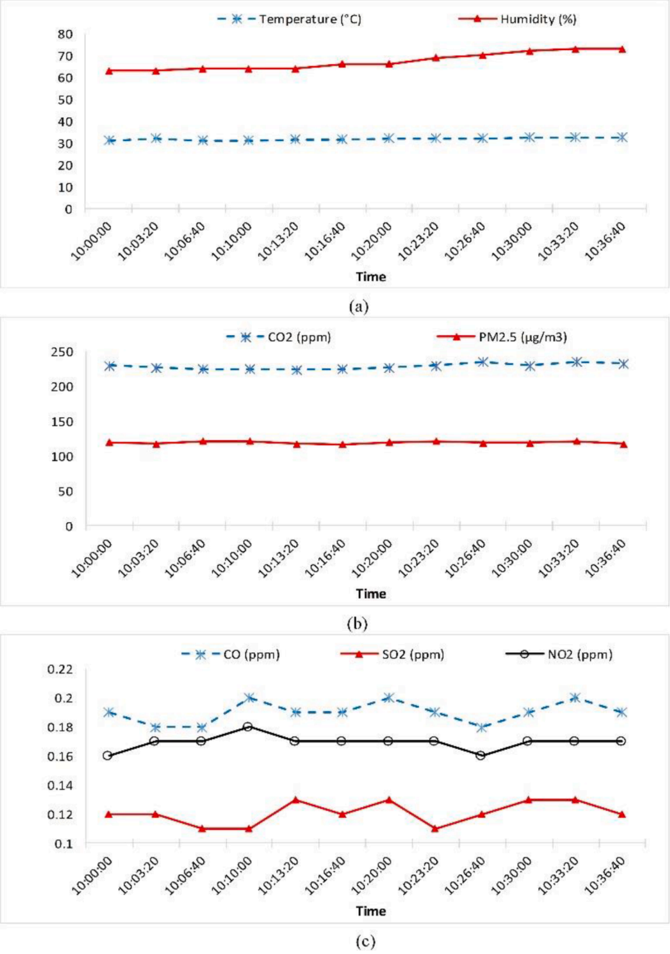


Fig. 20. Average air quality parameters at varying times: (a) temperature and humidity, (b) CO_2 and $PM_{2.5}$, (c) CO, SO_2, and NO_2.

a fresh air scenario in which our system has run continuously for more than half an hour. The data are stored in the ThingSpeak server and exported for analysis. Each point represents the average of 20 readings of the surrounding air condition from the sensors, and the data are updated every 10 s on the cloud. The obtained results show the stability of the developed LoRaWAN-IoT-AQMS for the different air parameters. The system can successfully monitor the temperature, humidity, CO_2, CO, NO_2, SO_2, and $PM_{2.5}$ data and transmit them from the LoRaWAN network to the IoT server. At the same time, the information is instantaneously displayed on the ThingSpeak public channel and the Virtuino mobile GUI.

Outdoor air refers to the air outside buildings, from the ground level to several miles above the Earth's surface. More importantly, outdoor air is a valuable resource for the current and future generations because it provides essential gasses to sustain life, and it shields the Earth from harmful radiation. However, outdoor air quality is also affected by pollutants, mainly smoke from the vehicle exhaust, illegal burning activities, and much more. In this study, our AQMS is implemented and tested in three different scenarios. The LoRaWAN-IoT-AQMS is exposed to a cloud of smoke produced from burning charcoal, smoke from vehicle exhaust, and cigarette smoke.

Coal is one of the relatively inexpensive sources of fuel for generating and converting the material to useful energy. However, the processing and use of coal affect the atmosphere. Principal emissions resulting from coal combustions are as follows:

- SO_2 cause acidic rain and respiration illnesses;
- NO_2 produces smog and causes respiratory illnesses;
- PMs cause haze, smog, and lung disease, and respiratory illnesses;
- CO_2 is one of the greenhouse gasses produced from fossil fuel combustion; and

Residues, such as ash, are created when power plants burn coal.

In the first scenario, the coal was burned in a box to trap the smoke obtained from the burning coal. Then, our system was used to monitor the pollutant content in the smoke released by the coal. The data collected by the different sensors were updated in real time on the cloud over the gateway. In the second scenario, we treated the smoke generated by vehicles as a main source of air pollutants (e.g., the exhaust of cars is the main source of CO_2, and the most common type of pollutant these days). In this study, the carbon-capturing process required the data acquisition of unwanted carbon in the air. However, other toxic chemicals are emitted by car exhaust, and they all damage the environment. Aside from CO, the other pollutants released from vehicle exhaust are SO_2, NO_2, PM, benzene, formaldehyde, and polycyclic hydrocarbons. In the last scenario, the air with cigarette smoke was tested using the developed system. Smoke from cigarettes contains harmful pollutants that cause environmental pollution. Hence, cigarette smoke was also considered in the testing of the LoRaWAN-IoT-AQMS. Cigarettes contain formaldehyde, lead, cyanide, ethanol, nicotine, hydrogen cyanide, methanol, tar, and vinyl chloride. Given these components, cigarette smoke emits benzene, arsenic, aluminum, acetone, CO_2, cadmium, ammonia, butane, CO, and chloroform.

Table 4 shows a comparison of the data obtained from coal, cigarette, and vehicle smoke and the normal air data for a selected period. The data from each scenario were updated on the IoT servers for access in real time via ThingSpeak dynamic graphs and Virtuino GUI, and the AQI indicators were also made accessible to public users (Fig. 21). In all three scenarios, the data collected from the sensors represent a specific color based on the definition of air quality and the standard level of each parameter. Widgets were adopted to allow users and experts to observe the air condition, and colors were used to represent the different levels of air cleanliness. The CO_2, CO, NO_2, SO_2, and $PM_{2.5}$ concentrations could be clearly defined and monitored by public users even if they do not have in-depth knowledge about these parameters.

Validation of results

The readings from the AQMS as obtained by the TTN, ThingSpeak, and Virtuino platforms needed to be validated for proving the reliability and efficiency of our system. Data validation, an element of quality assurance, was implemented to ensure the accurate and reliable collection of environmental data. In general, measured data of known and acceptable quality can help users to comply with regulations, assess health effects, and develop optimal strategies to cope with environmental pollution situations. Here, data validation was conducted to prevent the inaccurate data from being included in the data collection prior to storage in the system. Data validation generally serves as the final screening phase before the data are used for decision making. Here, we compared the collected data during a specific testing period with practical experimental data obtained using the Aeroqual Portable Monitor kit.

The instruments were selected on the basis of their availability in the campus laboratory. All of the instruments have powerful features, which include but not limited to the following:

(i) Interchangeable sensor heads;
(ii) Zero calibration;
(iii) Field-replaceable long-life lithium battery;
(iv) Minimum, maximum, and average readings;
(v) Suitable measurement units (ppm or mg/m^3);
(vi) Use of location and monitor ID; and
(vii) High and low values alarms.

Aeroqual monitors have sensors encased in interchangeable “sensor heads” attached to a monitor base. Swapping the sensor heads only took seconds and could be implemented in the field; furthermore, no configuration or recalibration was required. Fig. 22 shows the sensor head and the Aeroqual Portable Monitor Base. The Aeroqual monitor was placed alongside the LoRaWAN-IoT-AQMS apparatus. The monitoring location was in CARIFF Block-T, UMP, Gambang where no primary pollutant sources could be observed nearby. The LoRaWAN-IoT-AQMS and Aeroqual monitors were only slightly separated, and minor differences in the pollution concentrations were anticipated. The Aeroqual monitor was programmed to deliver real-time readings of the average concentrations of CO_2, SO_2, CO, $PM_{2.5}$, and NO_2 in the surrounding air. The real-time data of the Aeroqual monitor was then compared with the real-time data of the LoRaWAN-IoT-AQMS. During this process, the differences in the obtained readings from both systems were used to indicate the accuracy of our proposed system.

For the data validation process of LoRaWAN-IoT-AQMS, the data obtained from its six sensors were compared with the data from the Aeroqual air monitor. The ambient hourly temperature range during testing was from 24 °C to 26 °C. The vast majority of the hourly relative humidity measurements were between 55% and 60%. This monitoring process was adopted for all parameters in the LoRaWAN-IoT-AQMS, namely, temperature, humidity, CO, CO_2, NO_2, SO_2, and $PM_{2.5}$. Certain differences in the results were observed, which may be attributed to the wind direction and speed. Wind may disturb the pollutant concentrations in air. Besides, variations may also arise due to the slight distance between the AQMS and Aeroqual air monitor. In this study, the minor errors were neglected because the wind speed and direction could not be controlled, and the slight distance between the AQMS and Aeroqual was necessary.

Data samples were collected for every sensor. As our system could send information to the cloud every 10 s, we selected 10 s as our base period and observed 11 readings from each parameter for comparison. First, in the data validation, temperature was tested. Figs. 23(a) and (b) show the comparative results obtained from both systems. The temperature data from LoRaWAN-IoT-AQMS and Aeroqual differ slightly in the range of ± 1 °C, but the trend shown in both graphs is almost the same. Through this analysis, the temperature is validated as a parameter, and the temperature sensor (DHT 11) in our system can be used to accurately monitor the ambient air temperature. The same sensor was used to monitor humidity. The readings of our system differed slightly in the range of $\pm 2\%$. Both curves in the graph are consistent, and our system can collect the ambient air humidity percentage in real time.

Figs. 23(c) and (d) show the comparative results of CO_2 and CO, respectively. Slight differences were observed in the CO_2 readings

Table 4
Data obtained from coal smoke, vehicle smoke, and cigarette smoke.

Parameters	Normal air	Coal smoke	Vehicle smoke	Cigarette smoke
Temperature (°C)	24	30	31.8	25
Humidity%	51	59.6	63	58
CO_2 (ppm)	301.1	641	447	258
SO_2 (ppm)	0.13	2.31	38.33	0.36
CO (ppm)	37.65	60.53	1.73	8.7
NO_2 (ppm)	0.15	44.15	50.65	3.2
$PM_{2.5}$(μg/m^3)	66	120	110	71

Algorithm 1
Air quality monitoring algorithm.

```
Require: Monitor air quality indicators
Ensure: Realtime monitoring ($NO_2$, $SO_2$, $CO_2$, CO, $PM_{2.5}$, temperature, and humidity)
Install LoRaWAN Gateway & connect to the Internet
Register the Gateway in the TTN Console (GW ID, Frequency Plan, router, GW key)
Create LoRaWAN-IoT-AQMS Application in the TTN Console (App. ID, App. EUI, TTN—Handler)
Register LoRa Node under LoRaWAN-IoT-AQMS Application (Dev. ID, Dev. EUI, App Key, App EUI)
Define Device Activation Method (ABP)
Get Network Session Key & App Session Key & Device Address
Define Libraries for multi-sensor smart LoRa node & TTN
Define LoRa-Node pin mapping// For sensors & LoRa connection
Set LoRa configuration parameters
$NO_2 \leftarrow$ Nitrogen Dioxide ➲ MiCS-4514 sensor
$SO_2 \leftarrow$ Sulfur dioxide ➲ MQ136 Sensor
$CO_2 \leftarrow$ Carbon Dioxide ➲ MQ-135 sensor
$CO \leftarrow$ Carbon Monoxide ➲ MQ 9 sensor
$PM_{2.5} \leftarrow$ Particulate Matter 2.5 ➲ Dust sensor
$H \leftarrow$ Humidity value ➲ DHT11 sensor
$T \leftarrow$ Temperature value ➲ DHT11 sensor
Initialize WQMS-LoRaWAN ➲ System Powered ON at $t = 0$
for each round, do
    Get $NO_2$, $SO_2$, $CO_2$, $CO$, $PM_{2.5}$, $T$, $H$
    Multiply each reading by 100 ➲ Represent each sensor by 2 words
    Split both words (16 bits) into 2 Payload of 8 bits
    Encode all Payloads into ONE packet of 8 bytes
    Establish a connection between LoRa Node & LoRaWAN GW
    Update status of sensors in TTN Server (online)
    Send data to LoRaWAN GW
    Upload data to TTN Server over the Internet
    Decode the received Payloads to retrieve original sensors readings
    Integrate data into ThingSpeak Web-based dashboard
    Synchronize data with Virtuino mobile App. using Smartphone
end for
User monitors all sensors data in real-time remotely via ThingSpeak & Virtuino App
END
```

at ±7 ppm between the LoRaWAN-IoT-AQMS and Aeroqual data acquired every 10 s. Overall, the trend of both graphs is almost the same. The CO readings for both systems are almost identical and consistent in most cases regardless of time. The CO_2 (MQ135) and CO (MQ9) sensors are validated, as they can work efficiently in the proposed system when monitoring the CO_2 and CO concentrations in ambient air.

The data validation tests for NO_2, SO_2, and $PM_{2.5}$ were conducted for a defined period for each sensor (Fig. 24). The graph in Fig. 24 (a) shows the NO_2 data. The use of NO_2 as a parameter is validated, and the NO_2 sensor (MiCS-4514) LoRaWAN-IoT-AQMS can be used to monitor NO_2 concentration in ambient air. The comparative results of SO_2 are shown in Fig. 24(b). Overall, the trend in both graphs is almost the same. The analysis indicates that our system can correctly measure SO_2 by using the MQ136 sensor, and the data can be updated in real time on the IoT server. $PM_{2.5}$ is a primary pollutant in the air along with other contributors, such as NO_2 and SO_2. The data validation test results for $PM_{2.5}$ is shown in Fig. 24(c). The $PM_{2.5}$ data from the LoRaWAN-IoT-AQMS collected using the dust sensor were compared with the data obtained from Aeroqual. The values differ in the range of ±10 μg/m^3. Overall, the trend in both graphs is consistent regardless of time.

The outdoor LoRaWAN-IoT-AQMS was designed as a standalone device requiring a PV solar panel and a lithium-ion chargeable battery. The PV solar panel was placed on top of the junction box at a slight inclination to ensure maximum sunlight exposure. The PV solar panel harnessed energy from the sunlight, and the collected energy was then utilized to charge the lithium-ion battery. A type of renewable energy, solar energy as an external power source benefits the environment. According to the test, the required time for fully charging the battery via the PV solar panels is 6 h.

(a) (b) (c) (d)

Fig. 21. Virtuino GUI for LoRaWAN-IoT-AQMS measurements: (a) normal air (b); coal smoke; (c) vehicle smoke; and (d) cigarette smoke.

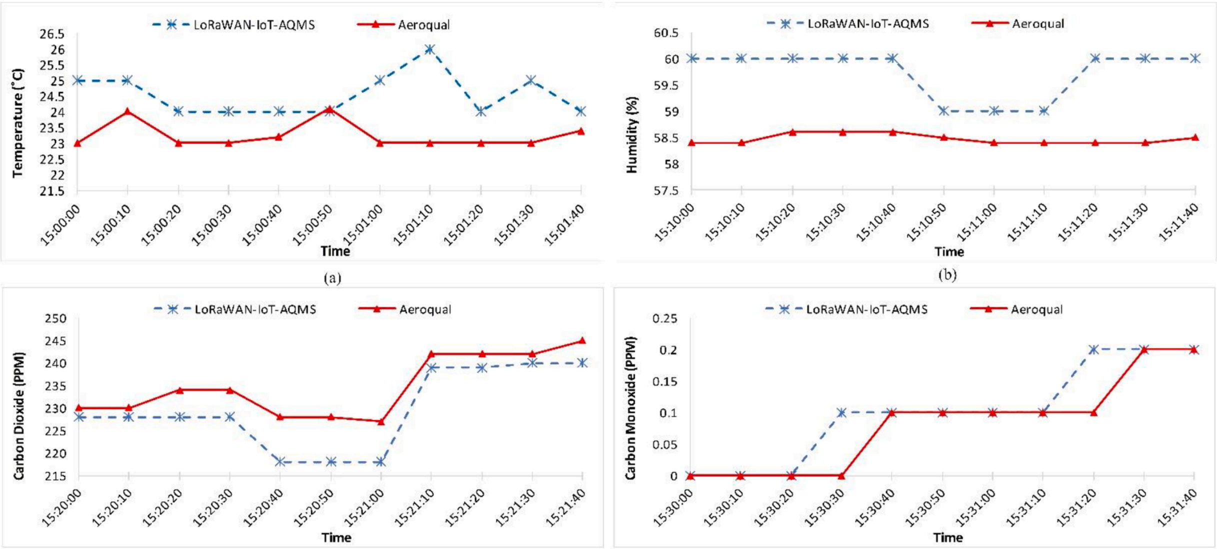
Fig. 22. Aeroqual portable monitor.

Conclusion and future work

An outdoor AQMS based on IoT with LoRa/LoRaWAN support was developed in this study. The LoRaWAN-IoT-AQMS apparatus monitored the concentrations of NO_2, CO, SO_2, CO_2, PM, temperature, and humidity. The system was powered by a PV system for standalone operation. LoRa was utilized because of its autonomous networking architecture, simplicity, low cost, low power, low data transmission rate, wide range connectivity, and open standard specification. An air intake hole was used to ensure that readings could be transmitted throughout the system and allow data gathering to be implemented with high efficiency. The data about the air quality indicators were successfully uploaded onto the TTN and ThingSpeak, and the information could be easily accessed via the Virtuino mobile application.

The developed dashboard and GUI served as an interactive tool for the users to observe air pollutant information on their smartphones. The data collected from LoRaWAN-IoT-AQMS were validated on the basis of the readings of Aeroqual, an air quality monitoring instrument. Overall, the measurement of the LoRaWAN-IoT-AQMS produced accurate results for ambient air quality monitoring.

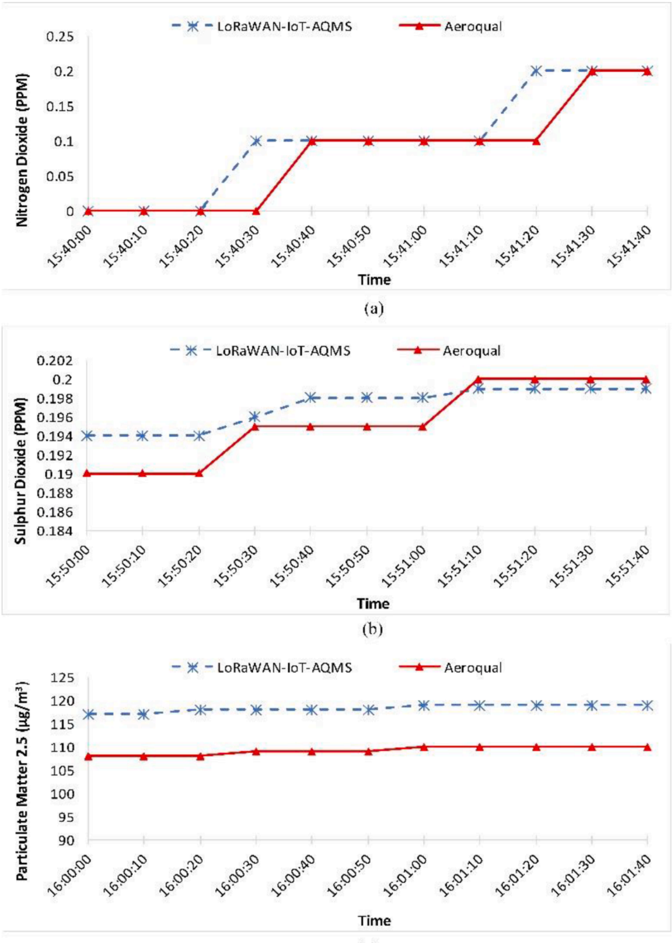
The objectives proposed at the beginning of this study have been achieved successfully. However, more work is needed. In the current study, our aim was to utilize LoRa-based nodes to monitor the surroundings and increase the people's awareness of air quality



(a) (b)

(c) (d)

Fig. 23. Comparison of LoRaWAN-IoT-AQMS and Aeroqual measurements: (a) temperature, (b) humidity, (c) CO_2, and (d) CO.



(a)

(b)

(c)

Fig. 24. Comparison of LoRaWAN-IoT-AQMS and Aeroqual measurements: (a) NO_2, (b) SO_2, and (c) $PM_{2.5}$.

by improving the accessibility of collected data. This study focused on the development and implementation of the developed sensing node for air quality monitoring. The system's functionality and effectiveness were proven by a number of testing scenarios while gaining richer insights.

Researchers may also utilize more sensors when deploying other AQIs as a means of improving data accuracy. From a methodological perspective, new performance metrics for the LoRaWAN network prior can enhance the analytic results. The impact of air quality on healthcare, especially during the COVID-19 pandemic, is another potential field of investigation. Among the limitations of our system that need to be considered for future improvement is the sensing node keeps sending data every 10 s to the cloud which may generate a huge amount of network traffic. This issue can be solved by utilizing some optimization techniques that can minimize the data traffic and make it limited to the important information updates. Also, a prediction technique can be utilized to predict the future air quality index based on the collected data during a pre-defined period. In the future, an adequate number of fabricated nodes may be deployed as a LoRaWAN network, allowing the public to access much more information.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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