The IoT Based Environmental Sensing Platform

by

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

I would like to dedicate this thesis to my family and friends

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Acronyms

ABP	Activating By Personalization
ABS	Acrylonitrile Butadiene Styrene
ADR	Adaptive Data Rate
API	Application Programming Interface
BLE	Bluetooth Low Energy
CR	Code Rate
DBPSK	Differential Encoding Binary Phase-Shift Keying
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communications Technology
IMU	Inertial Measurement Unit

IoT	Internet of Things
ISM	Industrial, Scientific, and Medical
ISO	International Organization for Standardization
ISP	In-System Programming
LPP	Lowe Power Payload
LPWAN	Low-Power Wide-Area Network
LTE	Long-Term Evolution
MAC	Media Access Control
MCU	Microcontroller Unit
NB-IoT	Narrowband Internet of Things
NFC	Near-Field Communication
OSI	Open Systems Interconnection
OTAA	Over The Air Activation
PC	Polycarbonate
PHY	Physical
PMU	Power Management Unit
PZT	Piezoelectric Transducer

RFID	Radio-Frequency Identification
RSSI	Received Signal Strength Indicator
SC-FDMA	Single Carrier Frequency Division Multiple Access
SF	Spreading Factor
SoC	System on Chip
SRAM	Static Random-Access Memory
TPH	Temperature Pressure Humidity
TTN	The Things Network
VOC	Volatile Organic Compounds
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor Network

Abstract

Environmental monitoring defined as using sensors to detect the condition of the ambient environment has attracted an upsurge of research interests. It can be applied in many fields such as weather prediction, outdoor asset monitoring, structural health monitoring, etc. IoT technologies act as an essential tool to realize the wireless connection between weather stations and the real-time data collection from environmental sensing nodes. One of the ultimate objectives of environmental monitoring is to deploy sensing devices over a large area to obtain enough data samples automatically for condition analysis and management. However, current weather stations are constrained by their high energy consumption, bulky size, limited accessibility, and high cost, which impedes the wide deployment of environmental sensing devices. The purpose of this thesis is to develop a new environmental sensing platform by adopting IoT technologies which could overcome many challenging design problems in this field. There are two main contributions of this thesis.

The first contribution is the development of an ultra-low energy consumption anemometer. There are different ways to measure the wind speed, using such as ultrasonic sensors and hot-film resistors. However, the energy consumptions of those anemometers are relatively high, and extra power lines need to be connected to power the anemometer. A novel method to measure the wind speed and direction is developed which uses a 6-axis accelerometer to measure the change of the acceleration induced by the wind force and then to calculate the corresponding wind speed. The power consumption of the proposed anemometer is only 3.42 mW, which is significantly smaller than other anemometers, thus batteries can be used as the energy source to power the proposed anemometer instead of the power line. The new design can make an anemometer to be a standalone device powered by a battery only, which increases the deployment flexibility of the sensor node. The proposed anemometer has low energy consumption and compact size which also allows it to be easily integrated to be

part of an environmental sensing platform.

The second contribution of this work is the development of an IoT based environmental sensing platform which consists of wireless sensor nodes, a communication network, data visualization and storage cloud. The environmental sensing platform has the ability of collect, send, present, and store various environmental parameters and it has the advantages of easy deployment, real-time accessibility, low deployment and maintenance cost. The sensing device in the environmental platform is a true standalone device which has wireless connection and can be powered by using a solar panel. The data gathered by the sensor node can be transmitted to a data visualization platform named Cayenne in real time, and the user can easily access the collected data from sensors deployed in different areas.

This thesis has introduced and successfully demonstrated a number of novel methods for environmental monitoring applications. An environmental sensing platform has been developed with improved performance in terms of such as reducing the energy consumption of the device, increasing the deployment flexibility of the end device, and improving the connectivity of the sensor node. The proposed environmental sensing platform is of great importance to future research and industry applications.

Chapter 1 Introduction

1.1 Background: Internet of Things

The Internet of Things (IoT) is a concept first introduced by Kevin Ashton at Procter & Gamble (P&G) in 1999 who viewed Radio-Frequency Identification (RFID) as an essential technology to the Internet of Things [1]. With the rapid development of advanced communication technologies in the last two decades, different short-range and long-range communication protocols such as RFID, Wi-Fi, Bluetooth, Bluetooth Low Energy (BLE), Zigbee, LoRaWAN, and Narrow Band Internet of Things (NB-IoT) have been widely used to connect a vast number of devices. Nowadays, The Internet of Things has become one of the hottest emerging technologies which could fundamentally change the way how people interact with things. IoT can be defined as things and sensors being connected to the Internet to achieve the interchange of data and message to realize smart control and management [2]. The Machine-to-Machine (M2M) traffic volume in the U.S. has a 250 % growth in 2011, and 45 % of the total internet traffic flows will be constituted by M2M communications by 2022 [3-7]. IoT has become national strategies of some countries[8].

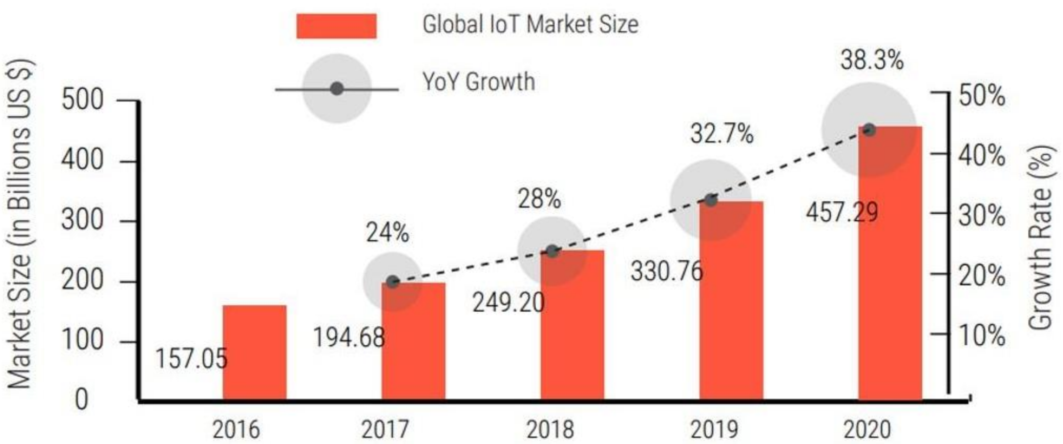

Fig. 1- 1 The global IoT market growth [9].

Different technologies such as information and communications technology (ICT), wireless sensor network (WSN), radio-frequency identification (RFID), system on chip (SoC), machine learning, big data, and cloud computing contribute to the development of IoT. Some latest communication methods like LoRaWAN and NB-IoT were specially designed for machine-type communication with low energy consumption, wide coverage, and strong robustness against noise. It provides reliable channels for things to be connected to the Internet. The wireless sensor network (WSN) is a large number of sensors connected to form a network. The sensors can provide useful information about the ambient environment or the conditions of the monitored devices. RFID is a foundational technology for IoT, which is widely used in logistics, retailing, and supply chain to identify, track and monitor objects attached with RFID tags. To realize smart control and management, we need to process and analyze the gathered data by using machine learning algorithms.

IoT architecture can generally be viewed as a centralized architecture, where a heterogeneous and dense set of devices deployed over a wide area generate a large amount of data delivered by using suitable communication technologies to a control center [10]. Then, the data will be stored and processed for further decision making, smart control, and other purposes. A key characteristic of an IoT architecture is its capability of integrating different devices, systems, and technologies into the same existed centralized platform to support the progressive evolution of the IoT. Also, for a centralized network, the data should be transferred by using a reliable channel to reduce the latency and packet errors to provide reliable information in time. There are other design criteria that need to be concerned, such as security, real-time interaction, interoperability, and energy consumption to improve the overall performance of the centralized platform.

Since it is very challenging to design a centralized platform consisting of millions of devices deployed over a wide range, and some researchers propose new decentralized

IoT architectures based on blockchain or fog computing. By adopting the blockchain technology, it provides the access control policies to improve the mobility, accessibility, scalability, security, and the transparency of IoT platforms [11]. Instead of transmitting the data to the cloud to be further processed, the fog computing allows to do the calculation and make decisions in local to avoid generating a huge volume of data to be transmitted and reduce the latency [12].

The International Standards Organization (ISO) developed the Open Systems Interconnection (OSI) model to divide network communication into seven layers which are the physical layer, the data link layer, the network layer, the transport layer, the session layer, the presentation layer, and the application layer [13]. The IoT model is very similar to the communication model, and the basic model is a 3-layer architecture consisting of perception, network, and application layers [14]. Recently, more models have been proposed to add more functions to the IoT architecture, and a five-layer model has been summarized to deliver the full functionality of the IoT, which are the objects layer, the object abstraction layer, the service management layer, the application layer and the business layer [2]. IoT architecture can be explained in Fig. 1-2.

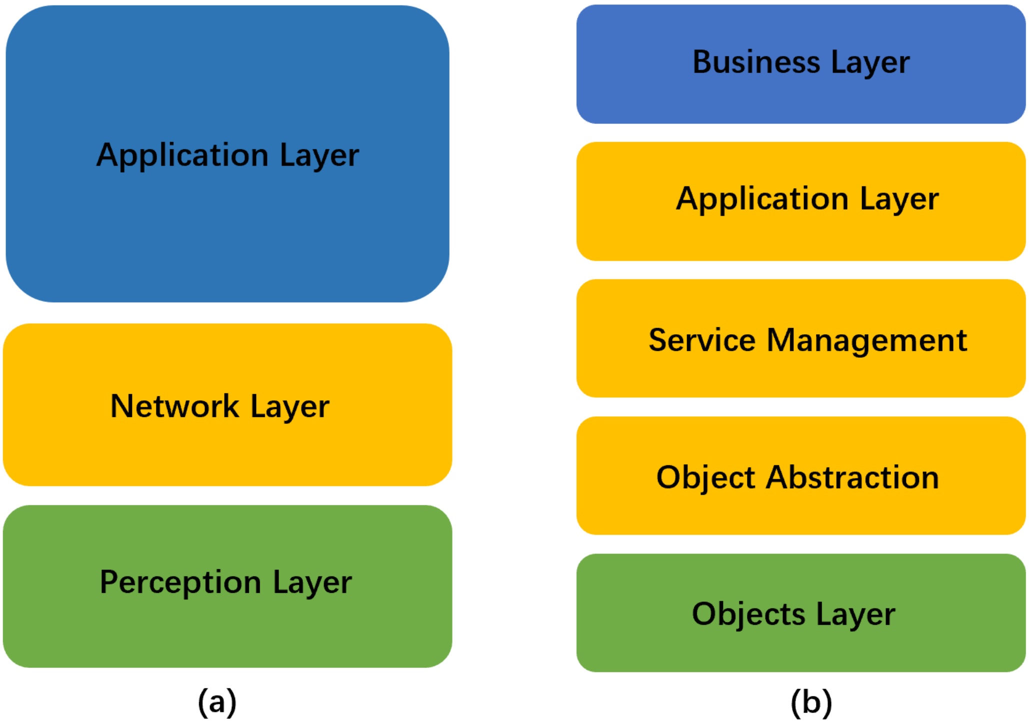

Fig. 1- 2 The IoT architecture [2]. (a) Three-layer. (b) Five-layer.

A. Objects Layer

The first layer can be viewed as the perception layer, where different sensors and actuators are used together to sense data from the ambient environment and perform operations. RFID tags can also be used to track and monitor things. It works as the fundamental layer of the IoT to gather physical information like weight, motions, vibrations, temperature, humidity, brightness, positions, and acceleration to be further processed and analyzed. It provides data to be transferred in the object abstraction layer.

B. Object Abstraction Layer

In this layer, it allows collected data from the objects layer to be transmitted and shared with other devices or central cloud to realize the interconnections of different things. The object abstraction layer provides channels for the data to be transferred by using some advanced communication technologies such as Bluetooth Low Energy (BLE), LTE-M, Wi-Fi, NB-IoT, LoRaWAN, and Zigbee. The communication channel should be designed to be secure, with low energy consumption, and low latency to unleash the performance of the IoT networks.

C. Service Management Layer

The role of the service management layer is to provide functionalities to integrate services and applications in IoT by using middleware technology. It enables IoT application programmers to work with different objects without considering specific hardware or software platforms. A well-designed service layer can identify standard application requirements and provide Application Programming Interface (API) and protocols to support the required services, applications, and user needs [15]. The data obtained in the objects layer will be stored and analyzed in this layer by using some data analysis techniques and data processing algorithms [16].

D. Application Layer

The application layer acts as the interface between the IoT systems and the users. This layer presents the collected information such as temperature, position, and other data to the user to make decisions and realize smart control and management. There are some challenges in this layer that need to be solved to improve the interactions between the IoT systems and the users. Since there will be numerous devices made by different manufacturers to be integrated, the cooperation between different devices, platforms, and clouds is difficult to achieve. The application layer also provides the interface to the business layer, where high-level analysis and reports can be produced [2].

E. Business Layer

The business layer is on the top of the previous four layers, and it manages the overall IoT activities and services. The role of the business layer is to build a business model to provide essential services and to generate profits from the service being provided. It acts as the driving force of the whole IoT activities and services.

1.2 IoT Applications:

The IoT has vast application areas, including smart transportation, smart grid, smart home, logistics, retailing, environmental monitoring, etc. With the help of IoT technologies, the traditional manufacturing processes can be fundamentally changed, and the production efficiency will be dramatically increased. Also, the IoT can be applied in the home, such as the smart lighting system, smart metering, advanced heating, ventilation, and air conditioning system (HVAC), etc. It can improve the comfort level at home and save energy at the same time. The IoT system can generate a large amount of data, and a lot of useful information which could be obtained from the database. For example, a wearable blood pressure meter connected to the Internet can collect and store the blood pressure of the patient over a period, and doctors can then monitor patients in real time and give appropriate medical advices and treatments based on the collected data.

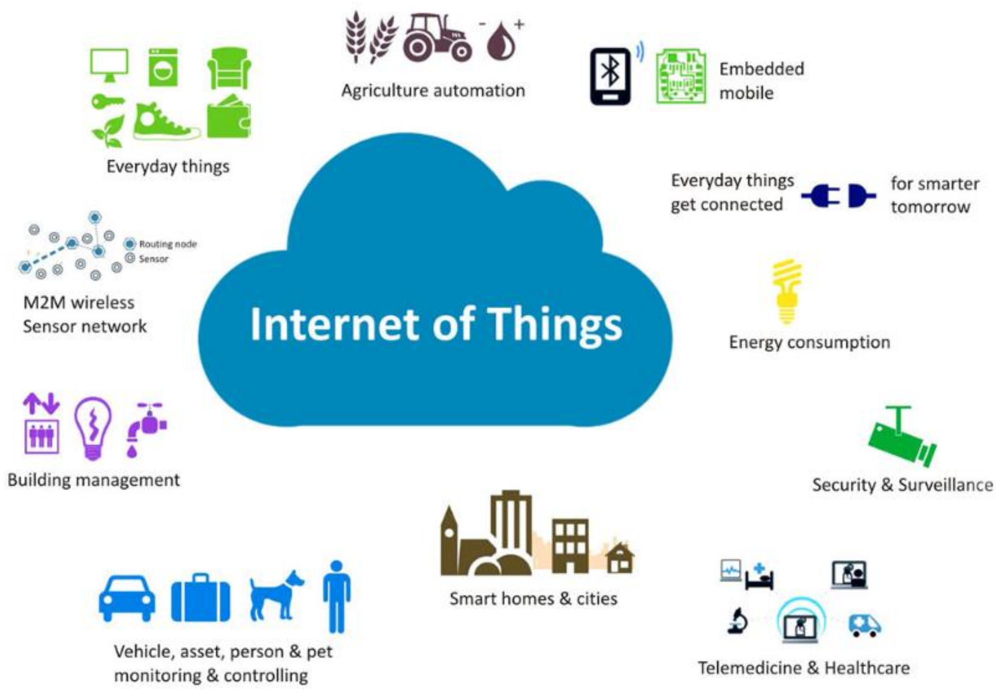

Fig. 1- 3 IoT application areas [17].

1) Smart Home

An increasing number of home appliances like refrigerator, oven, and washing machine are now becoming computing-enabled and can be connected to the internet by using Wi-Fi or Bluetooth. Those Internet-connected devices in the home can provide to the users with more reliable information about their current status, and the user can have more convenient control of those home appliances. There are more advantages an IoT system can bring in a smart home. The smart lighting system and the HVAC system can offer a comfortable living space and save energy at the same time; some security cameras, magnetic door, and window alarms, motion sensors, and smoke sensors can guarantee a safe living space. Some smart speakers are now acting as the interfaces between the users and home appliances, and users can talk with the smart speaker to control some home appliances like light bulbs. However, there are some issues raised by IoT technologies as well, and privacy and data security are vital concerns [18]. With more devices in the home connected to the Internet, more secure, sophisticated, and robust data and access protection systems should be designed to avoid cybersecurity attack.

2) Elderly People Care

The life expectancy of people has continuously increased due to the advanced medical treatments, and the percentage of the elderly people in total population keeps raising as well [3, 19]. Some of the elderly people have to live alone, and they will be difficult to take care of themselves, especially when emergencies happen. A fall-detection system is vital for aged people to send alarming signals to the corresponding people to offer help when a fall is detected [20]. The IoT technologies can be a very promising solution to partially solve the elderly people care problem by deploying some Internet-connected device to realize real-time monitoring and emergency warning. The design and deployment of the IoT based elderly people care system are very challenging. Because elderly people can be relatively difficult to learn new technologies, and the deployed system should be noninvasive so that the new technologies will not change the living style of the elderly people. Also, the collected data should also be kept safe and secure to protect the privacy of the user. The upfront hardware investment of the system and the total cost of the elderly people care service are still too high to achieve a large-scale deployment [21]. A low cost, noninvasive, reliable and user-friendly elderly people care system should be designed, and a replicable business model of the elderly people care service should be developed as well.

3) Health Care

With the help of the wireless sensors and advanced communication technologies, IoT is redesigning modern health with promising technological, economic, and social prospects [22]. IoT based health care can be applied to glucose level sensing, oxygen saturation monitoring, rehabilitation system, medication management, and wheelchair management. RFID tags can be used to monitor and track the production and distribution of medicine to guarantee the quality of each medicine. Different wearable sensors like blood pressure sensors, body temperature sensors, electrocardiograms sensors, and electromyography sensors can be used to collect vital data to support early diagnosis, real-time monitoring, and medical emergencies. With the dramatical expends of the application of wireless sensing technologies in medical treatment, a confined hospital environment can be extended to the patient's home to provide a quiet, familiar and less stressful place for the patent [23]. Some start-up and large companies are actively involved in the building of IoT medical cloud and database to transmit, store, and present collected data. A Chinese firm has developed an all-in-one medical imaging and information management platform supporting cloud-based image storage and computation, 3-D image post-processing, and visualization [22]. More research and development efforts should be put in this area to make health care more convenient, affordable, and effective.

4) Logistics

The development of IoT technologies has provided vital supports to establish a new logistics system to allow the tracking and monitoring of goods on a global scale. The IoT based logistics system dramatically improves the monitoring efficiency in the distribution, delivery, storage, and sales of the products, and it can be a useful tool to build a fast, low-cost, and efficient supply chain. The robots play an essential role in the smart logistic system, and it can pick, transport, and deliver the products to the right conveyor by using the robot arms. The RFID tags have the function to track, monitor and manage the parcels, the RFID sensing doors can be used in congestion with RFID tags to confirm the types and quantities of products to be delivered [24]. The automatic driving car can further reduce the cost and improve the safety level of the transportation of the goods. The adoption of the IoT technologies in logistics can transfer the logistics industry from a traditional labor-oriented industry to a technology-oriented industry.

5) Smart Cities

With the rapid growth of the global economy, people are more concentratedly living and working in big cities. This will bring a negative impact to the cities such as the short of energy sources, polluted air and water, and the traffic congestions, etc. The IoT technologies can be widely applied in different areas in cities such as waste management, noise monitoring, traffic monitoring, air quality monitoring, smart parking, smart grid, and smart railway control system to solve those problems and provide a better living environment for the people in cities. More details are given below:

<u>Smart Grid</u>

IoT accelerates the transformation of the traditional grid to the smart grid with the capabilities of real-time monitoring, situational awareness, and intelligence control to make the electric network more sustainable, reliable, secure, and efficient [25]. The IoT can help to upgrade the grid in two aspects, which are improving the efficiency of the distribution of the energy and the quality of electricity. With the help of advanced photovoltaic and battery technologies, the energy flow in the smart grid becomes bidirectional. Thus, smart power meters need to be connected to measure the energy flow in the grid to meet the users need and improve the efficiency of the energy distribution in the electricity network. The real-time monitoring of the energy flow can also guarantee high-quality energy and uninterrupted energy supply in the smart grid [26].

Smart Parking

The parking spot can be equipped with smart parking meters by using RFID or Near Field Communication (NFC) to realize the detections and identifications of the cars [10, 27]. There is a novel method to track the car in a parking spot, which is to obtain the information of the car and the vehicle license plate by using digital camera imaging sensors. The gathered information of the parking slot can be transmitted to central cloud, and the user can be easier to find the available parking slots through the smart parking system which could save the parking time, decrease the CO2 emission, and reduce the traffic congestion [28].

Environment Monitoring

Environmental issues such as climate changes have received much attention recently, making it an active and hot research area. The acquisition of the environmental data can be achieved by a variety of technologies such as remote sensing, geographical information system, and global positioning system [29]. Wireless Sensor Network can be another promising technology to collect environmental data automatically, it can be used together with the cloud computing to collect and analyze the received environmental data to understand and react to the environment [30]. Internet of things can provide support for the transmission, storage, and management of a large amount of data to accurately record the trend of the climate change over the years [31].

1.3 Motivation of this work:

1.3.1 Motivations

In recent years, people increasingly draw attention to climate change and the greenhouse effect. To statistically study the climate change and the impacts of the human activities on the environment, we need to collect some basic environmental parameters like rainfall, temperature, CO2, wind speed, and air quality [31]. Sensor technologies and wireless network integrated with the IoT technology play essential roles to gather information from the environment. An environmental sensing platform is an essential tool to collect, transmit, and process environmental parameters to analyze and monitor climate change. The environmental sensing platform can also be used in other activities such as structural monitoring, smart agriculture, and asset monitoring.

A structural health monitoring system can be used to make sure the physical configurations such as buildings and bridges are structurally safe [32]. Some sensors such as accelerometers and piezoelectric transducers (PZT) can be densely mounted on the structure to provide health level and spot the damage sites of the architecture [33]. Some signal processing method should be implemented and integrated with the IoT system to remove the noise generated by the sensors to determine the actual condition of the structure [34]. Smart farming is the implementation of different sensors and communication methods to form a wireless sensor network to wirelessly collect environmental data like temperature, soil humidity, and rainfall [35]. The collected data can be sent to a cloud for further processing to realize precision farming. Utilizing the smart farming wireless sensor network, the farmers can improve the production of the crop and reduce the maintenance fee by adopting corresponding measures based on the current condition of the land [36]. There are also some valuable assets such as substations and wind turbines which are directly placed in the outdoor environment. The surrounding conditions of these outdoor devices should be continuously monitored by sensors to guarantee they are in a safe environment and are prevented from malfunctions. IoT is the key enabling technology to achieve the monitoring of the environment and provide useful data for further analyzation and decision making.

1.3.2 Challenges

However, some technical bottlenecks need to be overcome to fully meet the requirements of the wide and dense deployments of the environmental sensing systems. The coverage and the energy consumption of the sensor nodes are two main issues that need to be solved. For some smart city applications such as traffic monitoring and weather forecasting, the user would like to achieve city-scale monitoring, and the design of a communication system to cover a whole city can be challenging. It will be very inconvenient to use wire to form a communication network, and the deployment cost can also be high. Thus, the wireless communication method will be chosen to build a network. However, the coverage of the wireless sensor node is limited, and there are two solutions to overcome this problem. The first is to use the multi-hop communication technology where each sensor node can act as a vendor to both receive and transmit the signal to other nodes, and the information can be transmitted to the gateway in the end. Another option is to use the Low Power Wide Area Network (LPWAN) technology such as LoRaWAN, the coverage of each gateway can be up to 15-30 km, and only a few gateways can provide coverage over a large region.

Since each node is a wireless sensor node, the battery is usually the primary energy source to power the node. The energy consumption of the sensor node should be kept low to prolong the lifespan of the node and guarantee the overall performance of the whole sensor network. Also, the sensor node can be integrated with energy harvesting technology to obtain energy from an ambient environment like solar energy, radio frequency energy, and mechanical energy to become a self-powered device. There are other technologies need to be used in conjunction with the IoT technology to achieve the full functional environmental sensing platform. A central cloud should be used to realize the presentation of the measured results of the sensors in real time and the storage of the measured data. Wireless sensor network technologies should be used to form a large communication network to collect data from different node deployed over a wide region.

1.3.3 Objectives

This thesis is aimed to solve the aforementioned research problems with the following main objectives:

1. To develop an accelerometer-based anemometer with low power consumption which could be part of the weather station. The anemometer should have a compact size and can be powered by using the battery to increase the deployment flexibility.

2. To investigate and compare different communication protocols, and to study the advantages of selected LPWAN protocols in IoT applications. Then, we will build the wireless sensor network for the environmental sensing platform by implementing suitable communication technologies.

3. To develop compact, low cost, and robust environmental wireless sensing nodes with low development and maintenance fee. The sensing node can be easily deployed and integrated into an environmental wireless sensor network which can communicate with other nodes or gateways to collect and transmit useful information.

4. To utilize cloud and IoT based wireless sensor network to develop an environmental

sensing platform which could realize real-time monitoring, data presentation, and data storage.

1.3.4 Original Contributions:

- The first contribution is the development of an ultra-low energy consumption anemometer. A novel method to measure the wind speed and direction is developed which uses a 6-axis accelerometer to measure the change of the acceleration induced by the wind force and then to calculate the corresponding wind speed. The power consumption of the proposed anemometer is only 3.42 mW, which is significantly smaller than other anemometers, thus batteries can be used as the energy source to power the proposed anemometer instead of the power line. The new design can make an anemometer to be a standalone device powered by a battery only, which increases the deployment flexibility of the sensor node. The proposed anemometer has low energy consumption and compact size which also allows it to be easily integrated to be part of an environmental sensing platform.
- The second contribution of this work is the development of an IoT based environmental sensing platform which consists of wireless sensor nodes, a LPWA communication network, data visualization and storage cloud. The environmental sensing platform has the ability of collect, send, present, and store various environmental parameters and it has the advantages of easy deployment, real-time accessibility, low deployment and maintenance cost. The sensing device in the environmental platform is a true standalone device which has wireless connection and can be powered by using a solar panel. The data gathered by the sensor node can be transmitted to a data visualization platform named Cayenne in real time, and the user can easily access the collected data from sensors deployed in different areas.

1.4 Thesis Outline:

This thesis consists of five chapters, and it aims to provide an environmental sensing platform composed of different wireless sensor nodes by adopting the concept of IoT. We aim to reduce the energy consumption of the sensor node to prolong the battery lifetime of the end device and avoid replacing the battery too often to increase the flexibility of the deployment of the sensor nodes. The structure of the thesis is organized as follows.

- Chapter 1 introduces the IoT and discusses the rapid development of IoT technologies over recent years. It also introduces wide applications of IoT in different areas and explore how IoT can help us to improve the living quality and working efficiency. It stresses the importance of the environmental sensing applications and the role that IoT can play in related fields. The main aims and the structure of the thesis are also included in this chapter.

- Chapter 2 introduces different types of communication protocols and how wireless sensors can be connected by using these protocols to form a wireless sensor network. Various communication protocols can be divided into two parts, which are the short-range communication protocols and the LPWAN communication protocols. LPWAN communication methods have merits of wide coverage and consuming less energy, which is more suitable for IoT applications. WSN is a sensor network composed of different sensors deployed in various places to gather useful information for users, and it can be used to construct the environmental sensing platform.

- Chapter 3 proposes a compact anemometer with low energy consumption which could be integrated to an environmental sensing platform. The anemometer can measure both the wind speed and the wind direction by calculating the accelerations obtained from a 6-axis accelerometer. The proposed anemometer has a compact size and is designed to consume extremely low energy so that it can be easily integrated into some power constrained weather stations.

- Chapter 4 presents an environmental sensing platform consisted of self-powered wireless sensor nodes, the wireless sensor network, and data storage cloud. Different sensors can be easily integrated into the existing sensing platform. The sensor node is designed to have a sleep mode, and the device can be put into the sleep mode most of the time to save energy. A 3 W solar panel is used to charge the battery to make the whole device to be self-powered.

- Chapter 5 summaries major contributions of this thesis and provides future work recommendations for this research topic.

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Chapter 2 Literature Review

2.1 Review of Communication Protocols for IoT Applications

2.1.1 Short-Range Communication Protocols

With the rapid development and wide applications of communication technologies in the last two decades, it is estimated that more than 26 billion devices will be wirelessly connected in 2020, and machine-to-machine (M2M) devices will account for nearly half of the total number of the connected device [1]. Some short-range communication protocols like Wi-Fi, Bluetooth Low Energy (BLE), and Zigbee play important roles to realize the IoT vision. This section will give an introduction of the three most widely used short-range communication protocols and analyze advantages and disadvantages of these communication methods for IoT applications.

Wi-Fi

Wi-Fi is one of the radio technologies based on IEEE 802.11 family of standards commonly used for Wireless Local Area Networking (WLAN) of devices promoted by Wi-Fi Alliance. It operates at 2.4 and 5 GHz and is widely used in both business and home environment [2]. Wi-Fi can offer supplementary connections for users to the Internet when the cellular network cannot provide coverage. A typical Wi-Fi router can provide a maximum 55 m coverage range, and the signal may be degraded by walls and other complicated environmental factors [3]. Wi-Fi Alliance proposed a new IEEE 802.11ah wireless networking protocol called Wi-Fi HaLow to provide longer transmission range and obtain better wall penetration performance [4].

Bluetooth Low Energy (BLE)

BLE is also known as Bluetooth smart, which is designed and enhanced for short-range communication with low bandwidth and low latency for IoT applications [5]. It operates in the ISM bands ranging from 2.400 GHz to 2.4835 GHz and adopts 40 channels with each having 2 MHz bandwidth [4]. Compared with classic Bluetooth, it has lower power consumption, shorter setup time, and supporting star network topology with unlimited numbers of nodes [6, 7]. The energy consumption of a BLE device used for communication is 28.5 mW.

ZigBee

ZigBee is another short-range wireless network technology created by ZigBee Alliance based on low-power wireless IEEE 802.15.4 networks standard. The protocol consists of the physical layer, the Medium Access Control (MAC) layer, the network layer, and the application layer [8]. There are three types of devices in the ZigBee network layer, which are the router, the coordinator, and the end device. In a ZigBee network, the end devices are used to generate the message, the routers have the routing capability, and the coordinator manages the whole network.

Table 2- 1 Comparison of three short-range communication protocols

Characteristic	Wi-Fi	ZigBee	BLE
Launching year	1997	2003	2010
PHY/MAC	IEEE 802.11.1	IEEE 802.15.4	IEEE 805.15.1
Frequency band	2.4 GHz	2.4 GHz	2.4 GHz
Coverage	100 m	10 - 100 m	30 m
Data rate	54 Mbit/s	250 Kbit/s	1 Mbit/s
Topology	Star	Mesh	Star/Mesh
Power level	90-350 mW	72-84 mW	26.5-28.5 mW
Alliance	Wi-Fi Alliance	ZigBee Alliance	Bluetooth SIG

2.1.2 Low Power Wide Area Network (LPWAN) Protocols

LPWAN technologies combine both robust modulation and low data rate to achieve long coverage and low energy consumption. A Low Power Wide Area (LPWA) base station can cover up to 15 km in rural areas, and the maximum battery life of the LPWA device can be up to 10 years [9, 10]. There are several LPWAN technologies, such as SigFox, NB-IoT, and LoRaWAN. SigFox is a single operator network which plans to offer coverage all over the world incorporation with member companies [11]. However, it can only obtain a data rate up to 100 b/s in the uplink, and the maximum packet payload is limited to 12 bytes, which also restricts the wide application of SigFox. Narrow Band IoT (NB-IoT) is a cellular-based licensed technology introduced by the 3rd Generation Partnership Project (3GPP). NB-IoT can coexist with existed GSM and LTE networks, and it is operated by telecommunication companies to provide reliable wireless access for low-power devices. LoRaWAN is different from SigFox and NB-IoT. LoRaWAN operates in the unlicensed band, which makes it can be used free of charge. It also allows to set up the private network which can be integrated into different global network platforms (e.g., The Things Network) [11] which could increase the flexibility of deployments. The merits of the LoRaWAN put it in an advantage position compared with other LPWAN technologies.

Table 2- 2 Comparison of three LPWAN communication protocols

Characteristics	LoRaWAN	SigFox	NB-IoT
Frequency (MHz)	433/868/780/915	868	832-862 (Upload) 791-821 (download)
Bandwidth (kHz)	125/250	0.1	180
Data rate upload	0.25 kbps – 50 kbps	100 bps	200 kbps

Data rate download	0.25 kbps – 50 kbps	600 bps	200 kbps
Network operator	Private operators	Sigfox	Telecommunication Companies
Transmission power consumption	88.4 - 493.2 mW [12-15]	181.3 – 1036.0 mW [16-18]	479.89 – 1032.3 mW [19]
Receiving power consumption	40.7 – 170.2 mW [13-15, 20, 21]	31.1 – 199.8 mW [16-18]	75.1 – 240.1 mW [19]
Battery life	5-10 years	5-10 years	5-10 years
Developer	LoRa Alliance	Sigfox	3GPP
Developed Year	2015	2009	2016
Coverage	2-5 km (urban), 15 km (rural)	3-10 km (urban), 17 km (rural)	1 km (urban), 10 km (rural) [22]
Modulation	Chirp Spread Spectrum	DBPSK/GFSK	GMSK/SC-FDMA
Sensitivity (dBm)	-142	-142	-142.8 [23]
Topology	star	Star	star
Payload Upload Length (bytes)	51 [24]	12	128
Payload Download Length (bytes)	51	8	85

LoRa Physical Layer:

LoRaWAN is a LPWAN protocol for wide area networks based on the long-range LoRa radios patented by Semtech Corporation [11, 25]. It is designed to achieve long range and low energy communication between the end devices and gateways. The LoRa physical layer utilizes Chirp Spread Spectrum (CSS) modulation, which can improve the resilience and robustness against interference, Doppler effect, and multipath [9]. It operates at 868 MHz in Europe and 915 MHz in the USA with a typical bandwidth of 125 and 250 kHz depending on different spreading factors (SF). An Adaptive Data Rate (ADR) mechanism is adopted by LoRa to meet the needs of varying transmission scenarios, and some parameters such as bandwidth, spreading factor and Code Rate (CR) can be adapted to realize the customization of the LoRa modulation. Spreading factor is used to adjust the bandwidth and data rate to achieve better coverage. The spreading factors of the LoRa can also be changed from 7 to 12. Spreading Factor 7 has the shortest coverage with the highest data rate, and the widest coverage can be achieved by using spreading factor 12 with the lowest data rate. A detailed comparison between different spreading factors can be found in Table 2-3.

Table 2- 3 The comparison between different LoRaWAN spreading factors based on EU 868MHz band

Spreading factor	Bandwidth(kHz)	Air bit rate (kbps)	Sensitivity (dBm)
7	250	10.936	-122
7	125	5.468	-124
8	125	3.125	-126
9	125	1.757	-129
10	125	0.976	-132
11	125	0.537	-134.5
12	125	0.293	-137

The data rate of the LoRaWAN transmission can be calculated based on Equation (2.1).

$$R_b = SF * \frac{B}{2^{SF}} * CR \tag{2.1}$$

where R_b is the data rate, SF is the spreading factor, B is the bandwidth, and CR is the code rate.

LoRaWAN MAC Layer and Network Architecture:

LoRaWAN MAC layer provides the medium access control mechanism on top of the LoRa physical layer to enable communication between multiple devices and gateways [11]. It has a star topology where each end nodes are connected to the gateway directly. LoRaWAN defines three types of devices with different transmission mechanisms namely Class A, Class B, and Class C. Class A is mandatory for all LoRaWAN devices, it allows the bidirectional communication between the gateway and the end devices. Two downlink receiving windows will only be scheduled after a successful uplink signal interpreted by the gateway. The two downlink receiving windows start 1 and 2s after the end of the uplink transmission. Class A devices have the lowest energy consumption among all LoRaWAN devices. Class B devices are synchronized by using periodic beacon sent by the gateway to arrange an additional receiving window for downlink transmission. PNG stands for the ping-slot and BCN means the beacon. The gateway can then be able to send a downlink signal to the end device without prior successful transmissions. Class C devices will always listen to the gateway unless they are in the uplink transmission periods. Since Class C devices are always on, they are the most power-hungry devices compared with other LoRaWAN devices.

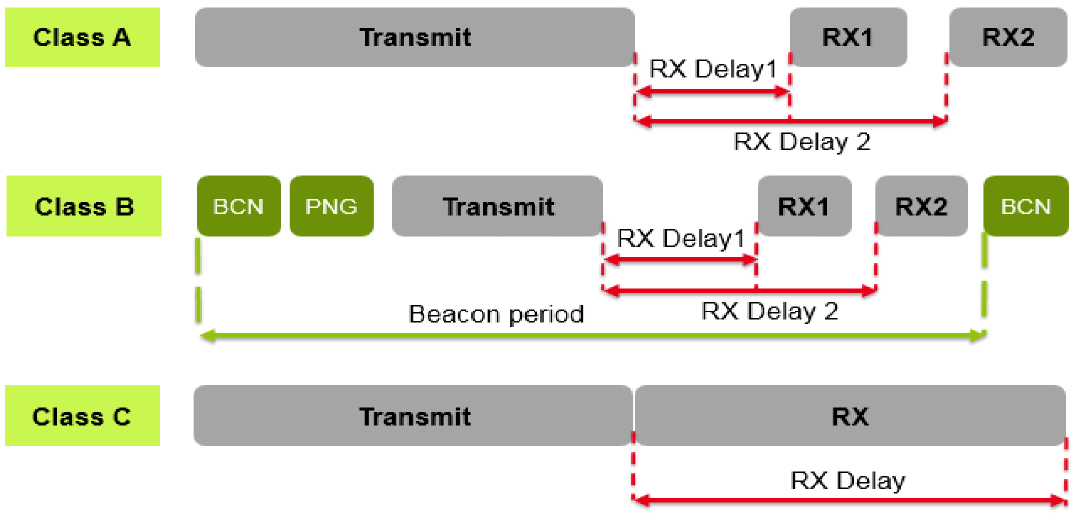

Fig. 2- 1 Three classes of LoRaWAN end devices [26].

There are two ways to activate end devices in a LoRaWAN network, which are the Activation By Personalization (ABP) and the Over The Air Activation (OTAA). Three sets of security keys, namely Network Session Key (NwkSKey), Application Session Key (AppSKey), and Application Key (AppKey) are used for activating devices during transmission. All three keys have a length of 128 bits. Network Session Key and Application Session Key are fixed for a device activated by ABP. OTAA utilizes Application Key to dynamically derive Network Session Key and Application Session Key to join the network on every activation. Thus, OTAA is a more secure activation method compared with ABP. The LoRaWAN architecture (Fig. 2-2) is that the end device transmits data to a gateway by using LoRaWAN protocol and the gateway is responsible for furthering forwarding the received message to the network server by using an IP-based protocol (e.g., Ethernet, Wi-Fi or cellular).

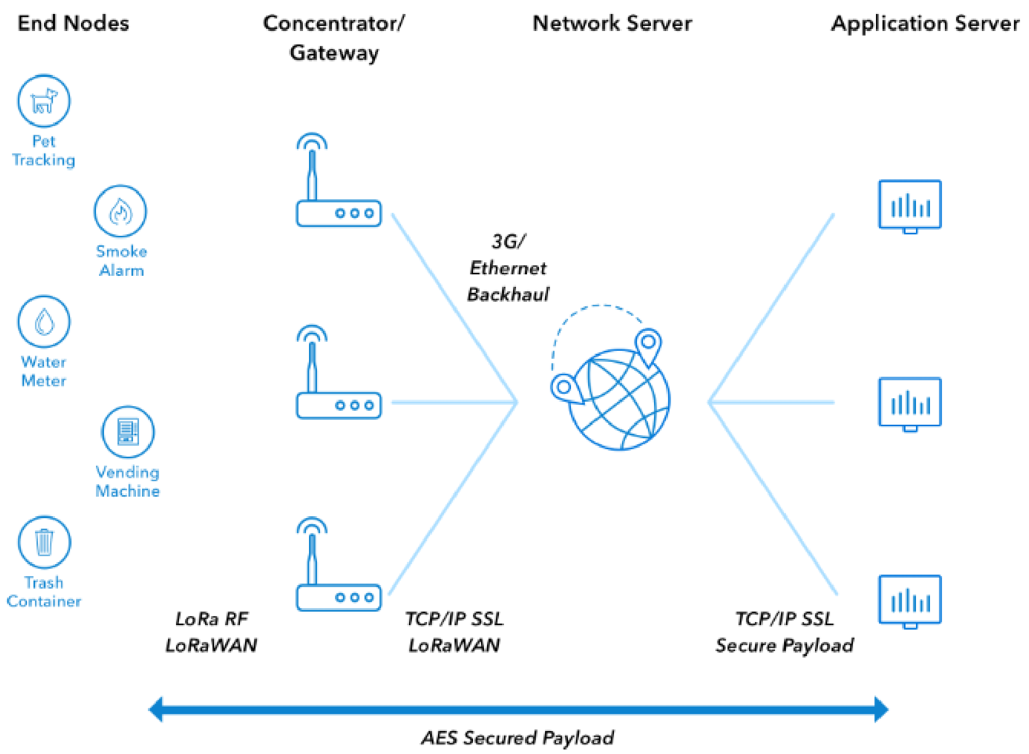

Fig. 2- 2 The LoRaWAN architecture [27].

2.2 Review of Wireless Sensor Network

The drastic improvements in micro-electro-mechanical-system (MEMS) technology, advanced wireless communication methods, and innovative networking protocols enable forming a network of small, low-price, and powerful wireless sensor nodes. The Wireless Sensor Network (WSN) can be defined as a network consists of a large number of sensor nodes composed of the sensing unit, the data processing unit, and the communication unit. The protocol stack used by the sinks and all sensor nodes is composed of three planes and five layers, as shown in Fig. 2- 3. The WSN is an essential IoT technology which can be applied in various areas like military applications, environmental applications, health applications, smart home applications, and other commercial applications [28].

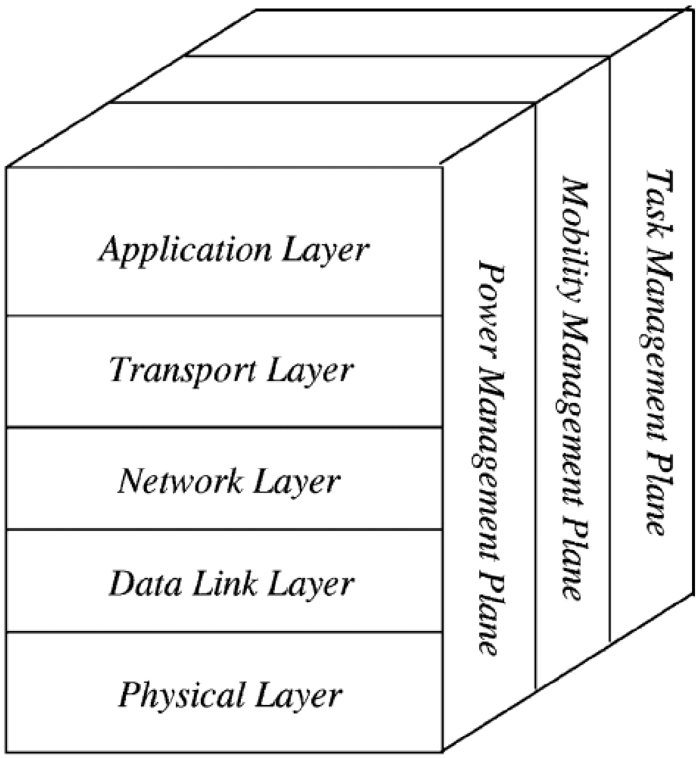

Fig. 2- 3 Five layers protocol stacks for wireless sensor network [29].

Some sensor nodes may be placed at places hard to reach, and therefore, it will be difficult to change the battery of the sensor. The energy consumption and power efficiency are the most important design criteria of a sensor node. Since the power consumption of the sensor itself is very low, most of the energy is consumed during the transmission of the signal. It is essential to design a power efficiency transmitting protocol, which can also maintain the Quality of Service (QoS) and security at the same time [30]. The deployment of sensor nodes can be formulated as a constrained multi-objective optimization problem where the aim is to maximize the coverage and the lifetime and minimize the power consumption and the number of the deployed nodes [31]. Liu Jingxian proposed that the sensor node can harvest the RF energy from the sink node by investing the optimal energy beamforming [32]. Samith Abeywickrama improved this idea by using a novel scheme that facilitates energy beamforming by utilizing the Received Signal Strength Indicator (RSSI) value to estimate the channel [33]. Solar energy harvesting technology is a very mature energy harvesting method to obtain energy in the outdoor environment. The solar energy can be a very promising method to provide electricity to the sensor nodes due to its relatively high power density [34]. Instead of gathering energy from other energy sources, some energy saving techniques can be applied in the communication and networking of the wireless sensor network. Networking Coding and Power Control based Routing is designed by X, Liu which can reduce the number of packets transmitted by encoding multiple packages which have the same destination into one packet and then less energy will be used in the communication [35].

To provide a reliable and low energy consumption connection for the wireless sensor node, which may be placed in lots of different places, a low power and long-range machine-to-machine communication method should be used. The current low-power and long-range M2M solutions can be basically divided into three parts, which are LPWA network, IEEE 802.11ah, and cellular-based network infrastructure [36]. LoRaWAN is one of the most widely used LPWA networks especially in Europe. LTE-

M and NB-IOT are two typical cellular-based M2M solutions. They can all cover a wide area and consume less energy, but the data rate is relatively low in compensation. For IEEE 802.11ah, although it has a higher data rate, it consumes more power and has less communication coverage. LoRaWAN has a star connected network topology which combines low data rate and robust modulation to achieve multi-kilometer communication range, and it is a suitable communication method used to form a private wireless sensor network [9].

The WSN has very wide applications, and it can be a very promising technology to collect ambient environmental data, and further transmit, store and analyze the collected data. It can be used in congestion with other communication technologies, networking methods, and data processing techniques to improve the overall performance of the sensing network. Murad Khan developed a smart home control system which not only saves energy but also is aware of the interference of different wireless technologies coexisting in the same ISM band [37]. A coordinator is used to receive the signal from an isolated WSN and transfer those parameters to the management station via power line communication (PLC) and the control signal for home appliances are also sent through PLC as well to reduce the impact of wireless interferences [21]. An intelligent controller by integrating internet of things with cloud computing and web services is designed to control the heating ventilation and air conditioning (HVAC), the random neural network is also implanted on the sensor node and base station in this case [38]. The occupancy status can be predicted by using the CO_2 sensor measuring the concentration of CO_2 in the air and using some algorithms like machine learning to predict the existence of people [39, 40].

There are some design criteria to be met to unleash the full functionality of the sensor nodes in a wireless sensor network. The node should have a compact size, and the battery will be the primary energy source so that it can be easily deployed without wired connections [41]. The energy consumption of the end device should be kept low to increase the lifetime of both the node and the wireless sensor network. An energy harvesting system can be added to the sensor node, and the end device can continuously work without changing batteries to prolong the lifetime of the wireless sensor network [42]. There are some restrictions on the size and the cost of the sensor node so that it can be densely deployed. Also, each device should be easily connected to the cloud, and the users can have access to the data in real time. The interoperability of the wireless sensor network is another critical design criterion so that more functions and other devices can be easily integrated into the existed sensing platforms.

2.3 Review of Environmental Monitoring Activities

Some essential environmental parameters such as temperature, humidity, brightness, wind speeds, and wind directions are needed in different applications such as environmental monitoring, asset monitoring, smart agriculture, weather forecasting, aviation, and load prediction. 40 percent of the aviation accidents are due to the adverse weather conditions, and therefore, some weather stations should be deployed near the airport to know the real-time weather conditions [43]. To reduce the greenhouse effect by using renewable energy to decrease the emission of CO_2, the wind turbine can be a sustainable replacement of the thermal power plant. The site selection of the wind farm is very crucial to guarantee more energy can be obtained from the environment, and wind sensors can be deployed in different sites to record the wind speeds and directions over a long time. The wind turbines can then be installed in suitable places with optimized facing directions which could maximize the energy extracted from the wind [44]. Weather prediction is essential for our day by day life, especially in agribusiness, and national weather data may not contain the precise information of some particular areas [45]. It is essential to deploy weather stations to monitor and predict the weather conditions near the farm to realize precision agriculture.

The environmental monitoring system also plays an important role in the electricity distribution system to improve the safety and stability of the power systems. The main contribution of the environmental sensing platform to the power grid can be categorized into two parts which are the condition monitoring of the outdoor devices in the grid and the load predictions based on the weather conditions. Since some important assets in the power grid such as transformers, substations, and power lines are directly placed in the outdoor environment. The conditions of these devices should be continuously monitored so that it will be easy to do the maintenance work and prevent them from malfunctions to cause interruptions in the power supply [46-48]. Weather conditions have an important influence on the generation, transmission, and the distribution of electric power [48, 49]. The clean and environmentally friendly renewable energy such as photovoltaic and wind power generation are now penetrating the power grid at an accelerating speed [48, 50]. However, the randomness and volatility of renewable energy also affect the safety and stability of the power system, and weather stations should provide abundant, accurate and real-time metrological data to predict the load and achieve the smart control in the modern power grid [46].

Currently, with the help of advanced communication methods and sensing technologies, a weather station can be integrated with more functions which can collect, process, and transmit various environmental parameters. By adopting the concept of the wireless sensor network, the traditional weather station can be transformed from a standalone device to be part of an environmental sensing platform. The weather stations can be deployed in different places, including in harsh environments such as high mounts, deserts, and Antarctica [51]. The data can be automatically uploaded to the central cloud of the environmental sensing platform without the presence of the human. By using the cloud computing technology, the environmental sensing platform can then present and process the data, and the user can have real-time access to the measured data and make decisions based on the collected information [52]. A large number of research projects such as Smart Santander and URBAN GreenUP aims to continuously monitor environment by using advanced IoT technologies to provide environmental, social and economic value.

Fig. 2- 4 presents a typical weather station, including the wind speed sensor, the wind direction sensor, the rain bucket, solar panels, and wires to connect different devices [47]. The weather station has a bulky size which may make it to be easily spotted and difficult to be deployed. It can also be found that some connection wires are directly exposed to the environment, and the wires may be damaged by the birds or strong winds, which could increase the chance of malfunctions.

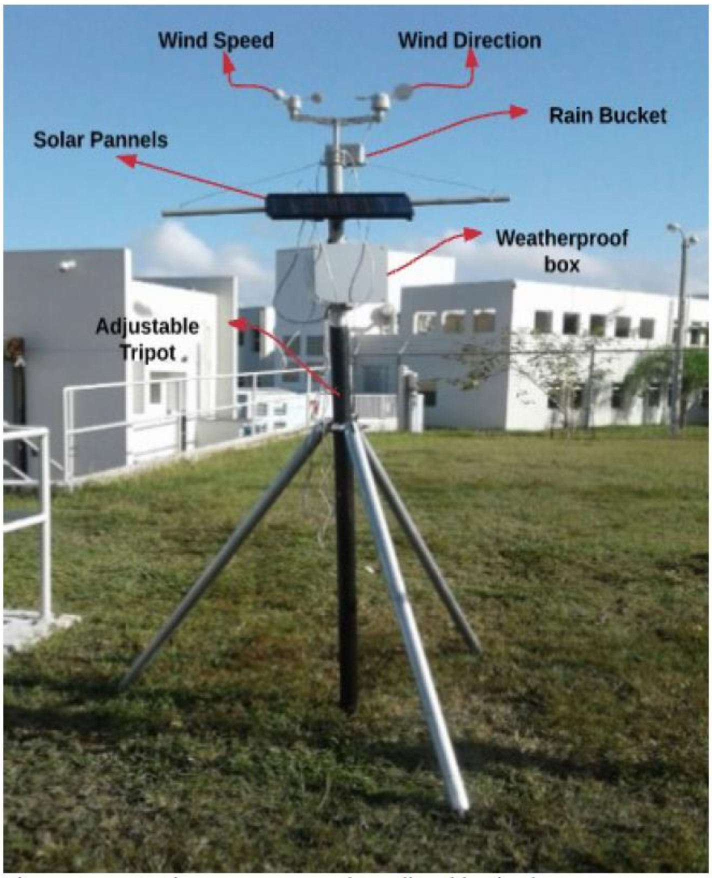

Fig.2- 4 A weather station mounted on the adjustable tripod [44].

There are some design criteria need to be met to unleash the full functionality of the WSN based environmental platform. The sensor node should be small in size and is powered by the battery so that it can be easily deployed without wired connections [53].

The energy consumption of the nodes should be kept low to increase the lifetime of both the node and the wireless sensor network. An energy harvesting system can be added to the sensor node, and the end device can continuously work without changing batteries to prolong the lifetime of the whole environmental monitoring system [54]. There are some restrictions on the size and the cost of the weather station so that it can be densely deployed. Also, the weather station should be easily connected to the cloud, and the users can have access to the data in real time. The interoperability of the weather station is another critical design criterion so that more functions and other devices can be easily integrated into the existed sensing platforms.

2.4 Summary

A detailed introduction of the popular communication protocols, including both the short-range communication protocols and the LPWAN protocols was given. The studies and applications of the Wireless Sensor Network have been discussed as well. It can be concluded that LPWAN protocols have the merits of wide coverage and low energy consumption, which is more suitable to transmit data in an energy-constrained wireless sensor network. Three popular LPWAN protocols, which are the LoRaWAN, SigFox, and NB-IoT are studied, and the LoRaWAN has the advantages of flexible private deployment and low energy consumption feature. The information in this chapter provides basic knowledge of the communication protocols and the wireless sensor networks which may be needed in the following sections of the thesis. This chapter also spots the research gaps and challenges of the current weather stations for us to overcome in this work.

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Chapter 3 A Compact Anemometer with Ultra-low Energy Consumption

Wind speeds and directions are essential environmental parameters, and it is required in different environmental monitoring applications such as the aviation, the site selection of the wind farm, structural health monitoring, etc. However, the energy consumption of the traditional wind sensors such as the ultrasonic wind sensors and the hot-film wind sensors typically consumes a large amount of power. These wind sensors are normally powered by using power lines, and it will be very challenging to use batteries to power them. Since energy consumption is one of the constrained design factors needs to be concerned in the development of wireless weather stations. In this chapter, we would like to propose a novel wind sensor which can measure both the wind speeds and the wind directions by using a 6-axis accelerometer. The proposed wind sensor has a compact size and extremely low energy consumption so that it can be easily deployed and powered by using batteries.

3.1 Introduction

Wind measurement has been widely used in different applications, such as weather forecasting and outdoor asset monitoring [1]. With the development of advanced communication technologies, an anemometer can act as a sensor node to be connected to the internet so that all the measured data can be uploaded and visualized in real time. To realize the concept of IoT, we need to pay more attention to the requirements of the wind sensors such as miniaturized size, low cost, and low energy consumption [2, 3]. There are various types of traditional anemometers, such as cup-type anemometers, ultrasonic anemometers, and thermistors-based anemometers as displayed in Fig. 3-1,

Fig. 3-2, and Fig. 3-3. However, none of these existing measuring methods can meet all three requirements. In this chapter, we will propose a novel and compact anemometer which can measure both the wind speeds and directions by using a 6-axis accelerometer with low cost and ultra-low energy consumption.

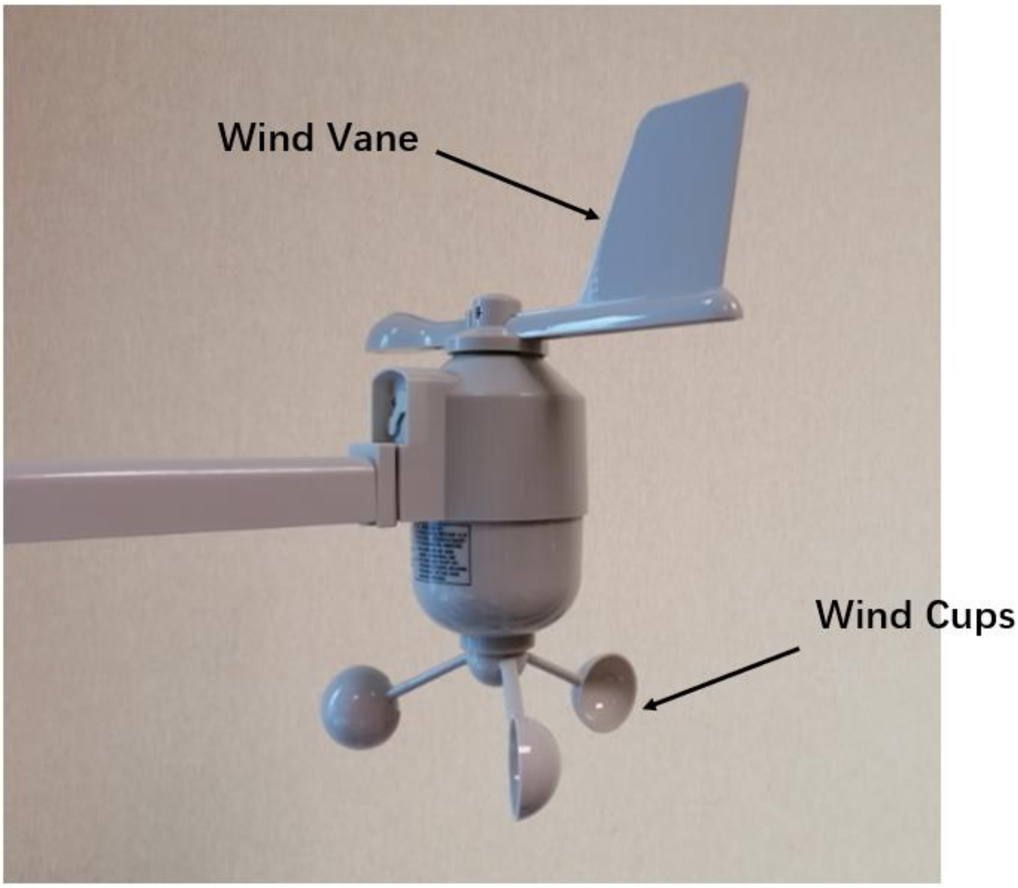


Fig. 3- 1 A cup-type anemometer.

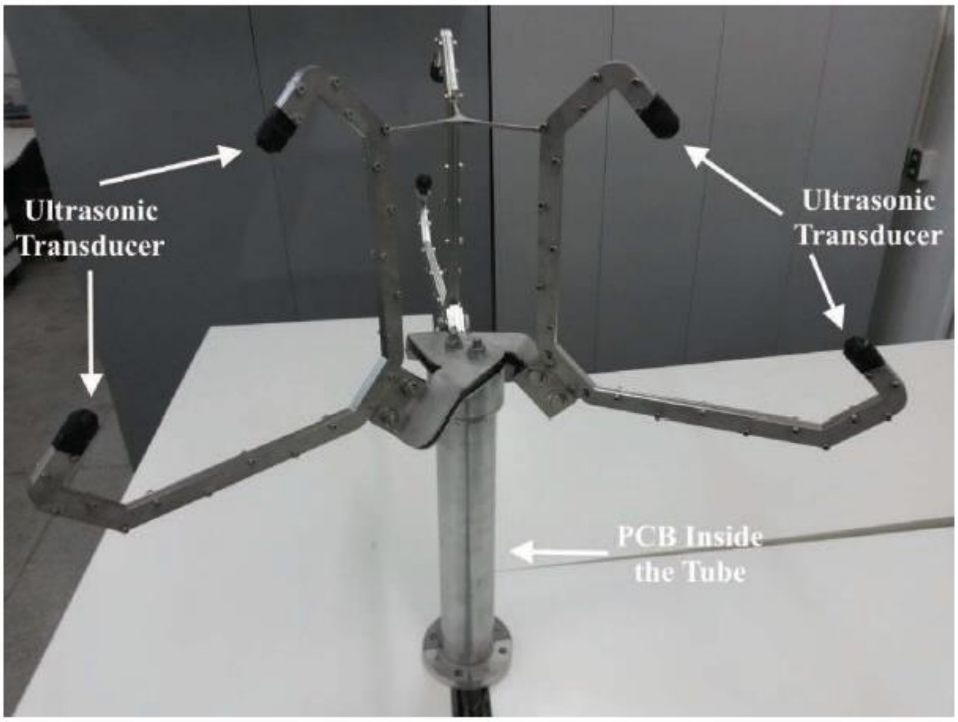


Fig. 3- 2 An ultrasonic anemometer [11].

The cup-type anemometer is the most widely used anemometer because it has low production costs and can sustain a variety of harsh environments [4]. However, the implementation and the application of the cup-type anemometer are limited by its bulky size and mechanical performance degradation over a long time [5-7]. The traditional cup-type anemometer can only measure the wind speed in one direction, and an extra part named wind vane is needed to obtain the wind direction. The inertia of the rotating part will cause measurement errors because the cup will keep rotating when the wind ceases [4]. To overcome these limitations of the cup type anemometer, some advanced anemometers like the ultrasonic anemometer and the hot-wire anemometer are developed. For an ultrasonic anemometer, although the size is shrunken to the dimension of a few tens of centimetres and there is no moving part. Further miniaturization will be impractical due to the increasing measurement errors [8, 9]. The physical structures to mount the ultrasonic transmitters and receivers can severely interfere with the wind flow when the wind comes from the direction which is parallel to the mounting structures [10, 11]. Also, the application of ultrasonic anemometer will be restricted due to its high cost and high energy consumption [12, 13]. The temperature of the air can also affect the travel speed of the ultrasonic wave and therefore affect the wind speed measurement.

Fig. 3- 3 A hot-wire anemometer [16].

Hot-wire anemometers are developed to measure the drift of heat induced by the wind and calculating the corresponding wind speed [14, 15]. Fig. 3-3 presents a typical hot-wire anemometer including the sensing unit and the data processing unit. Although the size of the sensor has been significantly miniaturized, there are still some limitations such as the temperature of the ambient environment can affect the measuring results [16]. Since the film should be heated, and a large amount of energy needs to be dissipated to conduct the measurement [17, 18]. The energy consumption of a hot-wire anemometer can be 2 W to elevate the temperature of the sensing head to a desirable level [19]. There are other wind measuring methods such as remote sensing techniques [20, 21]. Coherent Doppler LiDAR can be used to measure the wind speed remotely over a large range without contact with the moving air [22, 23]. Lidar can emit laser light and detect the doppler shift in the backscattered light, and the wind speed can be measured according to the doppler shift. However, this method cannot obtain accurate wind speed in specific sites.

The energy consumption of conventional anemometer could be 2 W and some well-designed low energy consumption anemometer could still consume more than 20 mW power. The battery level of a wireless weather station could be drained quickly if the high energy consumption anemometer is integrated into the weather station. In this chapter, we will introduce a novel, compact, low cost, and low energy consumption anemometer which can also be integrated as a part of a weather station by using Bluetooth Low Energy (BLE). The energy consumption of the proposed anemometer has been reduced to 3.42 mW. In this design, we will calculate the wind speed by measuring the change of the position of an accelerometer induced by the wind force. The measured data can be easily processed by using a Gaussian-weighted moving average filtering algorithm to reduce the error and uncertainty of the measurement.

3.2 Model Establishment and Theory

3.2.1 Sensor Design and Measuring Method

In this design, we propose an accelerometer-based anemometer which can measure the 2-dimensional wind speed by calculating corresponding accelerations of the sensor case along two axes in a horizontal plane. The new anemometer mainly consists of four parts which are an accelerometer, a 3D printed sensor case, a universal joint, and a mounting structure. The accelerometer as shown in Fig. 3-4a is placed in the sphere sensor case as shown in Fig. 3-4b and 3-4c, and the sphere sensor case is placed under a clamp stand by using a universal joint connected with a 3D printed pole as presented in Fig. 3-4d. When a wind occurs and hits the sensor case, the sensor case moves corresponding to the wind. The wind can generate a force exerted on the sensor case, and the sensor case will move towards a new equilibrium position. The new equilibrium position will result in the changes of accelerations measured by the accelerometer, and the wind speed can be obtained by calculating the changes of accelerations.

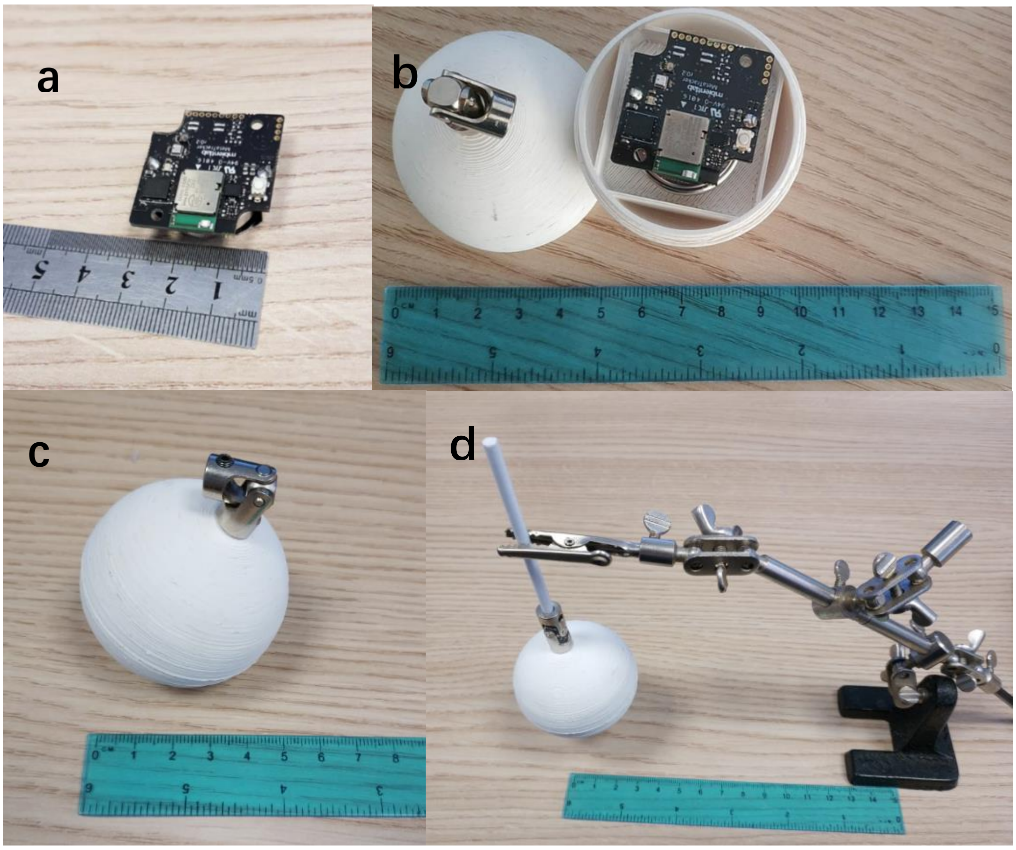


Fig. 3-4 The accelerometer, sensor case, and mounting structure. (a) The accelerometer; (b) The accelerometer placed in the sensor case; (c) The sphere sensor case and the universal joint; (d) The sensor case hung over the clamp stand.

<u>Accelerometer</u>

A 6-axis Inertial Measurement Unit (IMU) BMI160 which is designed and developed by Bosch is used to measure the acceleration. BMI160 has a minimum division of the 0.000598 m/s^2 which is sensitive enough to determine the small change of position induced by the wind. The power consumption of the BMI 160 is only 3.42 mW when it is in full operation and 10.8 μW when it is in the low-power mode. Thus, to use the IMU BMI160 to measure the wind speed can significantly reduce the energy consumption compared with other conventional anemometers. The BMI160 is integrated into a small Printed Circuit Board (PCB) with a size of 30mm * 30mm, as shown in Fig. 3-4a and it will be placed flat into the sensor case as shown in Fig. 3-4b. The board also has a central processing unit to process the data and Bluetooth module to transmit the measured data wirelessly. It can measure three sets of accelerations along three perpendicular axes. In this design, we only focus on the accelerations along two perpendicular axes in the horizontal plane, namely A_x and A_y.

3D Printed Spherical Sensor Case

The sensor case is designed to be a sphere with a diameter of 5 cm so that it is perfectly symmetrical in all directions. And the same amount of force can be exerted on the sensor case when winds with same speeds from different directions hit the sensor case. The sensor case is 3D printed by using Acrylonitrile Styrene Acrylate (ASA) which is thermoplastic material. This material is suitable for outdoor weather applications due to its high UV stability and chemical resistance. The sensor case consists of two parts which are the base and the lid. There is a square container embedded in the base half sphere, and it is used to hold the accelerometer. There is a hole with 3mm in diameter in the lid which is used to connect with the universal joint. The picture of the base and the lid can be found in Fig. 3-4b. The structure is designed to have no gaps between the lid and the base so that the sensor case can prevent the rain and the dust.

Universal Joint and Mounting Structure

A stainless universal joint with low friction is chosen to connect the sensor case to the mounting structure. It allows the sensor case to move freely along two perpendicular axes in the horizontal plane. One side of the universal joint is connected to the lid of the sensor case, and the other side of the joint is connected to a 3D printed pole. Then, the 3D printed pole is clamped by the clamp stand to fix the anemometer. The main body of the clamp stand is 15cm away from the anemometer to minimize the wind interferences it may induce. The whole structure of the sensor case clamped by the clamp stand is shown in Fig. 3-4d. The anemometer can also be easily placed under other places depends on the application and deployment.

3.2.2 Model Establishment

Wind Force Model:

The wind is the motion of the air, and it can generate a drag force on the object, namely the wind force. Since the area of the contact surface is small, it can be assumed that there is no turbulence, and the air pressure is evenly distributed across the contact surface. Also, the average wind force acting on the sensor case within a short time can be viewed as a stationary force [1, 2]. The wind speed can be calculated by measuring the wind force exerted on the sensor case. The wind force $F(t)$ can be expressed as a function of wind speed varies with time which is proportional to the area of the contact surface A as well as the density of the air ρ, and it is 1.226 kg/m^3 at the standard atmosphere. The geometry shape of the contact surface can also affect the wind force generated on the object, and the shape factor is defined as μ. The wind force can be expressed in the following equation.

$$F(t) = \frac{1}{2}\mu\rho A V(t)^2 \tag{3.1}$$

where $V(t)$ is the speed of the wind varying with time.

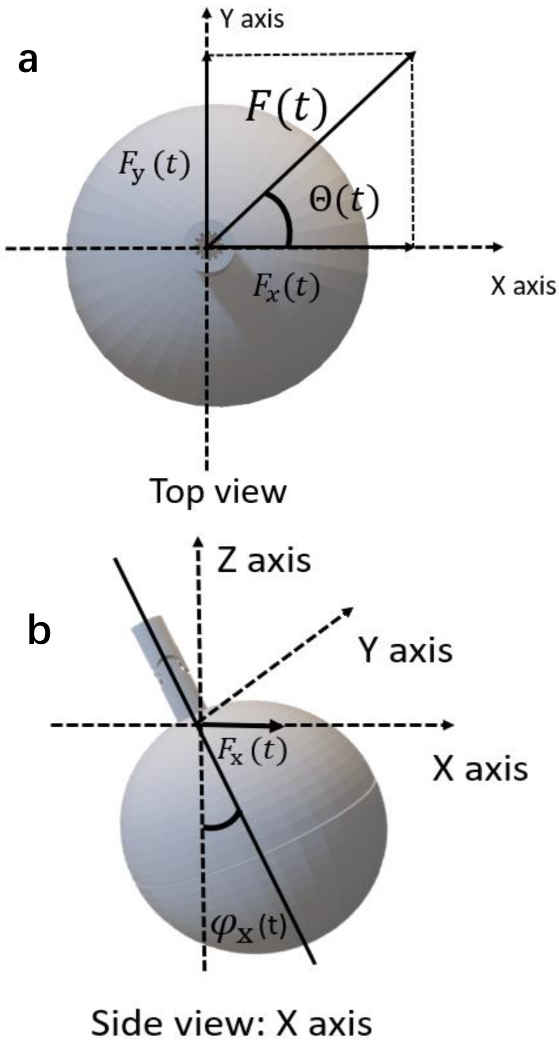
3D Dynamic Model of the Anemometer

1. Top View: Force Analysis

A wind force $F(t)$ as a function of t is generated on the sphere sensor case as shown in Figure. 3-5. $\theta(t)$ is defined as the direction of the wind, and the wind direction is also a function that varies with time. The diagram of the force analysis from the top view can be found in Figure. 3-5a. The wind force can then be divided into two parts along the X-axis and Y-axis. The equations are shown below.

$$F_x(t) = F(t)\cos(\theta(t)) \tag{3.2}$$

$$F_y(t) = F(t)\sin(\theta(t)) \tag{3.3}$$



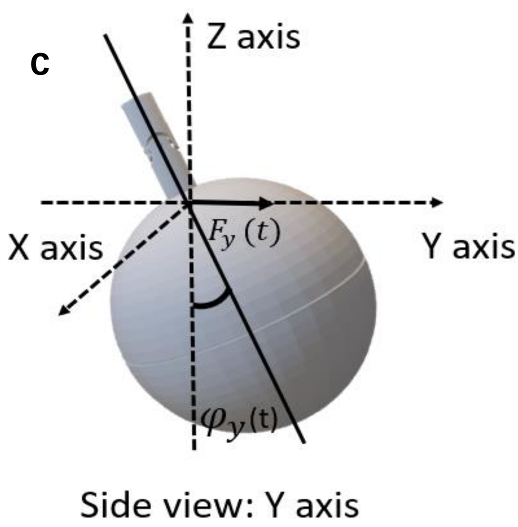


Fig. 3- 5 The 3D force analysis of the anemometer. (a) The wind force divided into X-axis and Y-axis from the top view of the anemometer; (b) The force analysis along X-axis and Z-axis; (c) The force analysis along Y-axis and Z-axis.

2. Side View: Equation of Rotation Movement

The anemometer has two Degrees of Freedom (DoFs), and it can do pendulum movements in the X axis and Y axis. The mass distribution of the sensor case and the accelerometer is measured, and the mass of the whole structure can be equivalently replaced by a single point, which is called the centre of mass. The model can be further simplified as the centre of mass rotating around the universal joint. The wind can exert a force on the whole contact surface of the sensor case, and an equivalent wind force exerted point is introduced to simplify the wind force exertion. Then, the wind force can be viewed as being generated on a single point rather than the whole contact surface. The sensor case will rotate around the joint when a wind comes, $\varphi_x(t)$ and $\varphi_y(t)$ are the rotation angle in X-axis and Y-axis, respectively. There are two torques applied to the system which are the gravity torque and the torque generated by the wind. The equations of dynamics of the anemometer moving along two axes can be described in the following equations.

$$I\frac{d^2\varphi_x(t)}{dt^2} = F_x(t)l_1\cos\varphi_x(t) - mgl_2\sin\varphi_x(t) \tag{3.4}$$

$$I\frac{d^2\varphi_y(t)}{dt^2} = F_y(t)l_1\cos\varphi_y(t) - mgl_2\sin\varphi_y(t) \tag{3.5}$$

where I is the moment of inertia of the anemometer, l_1 is the distance between the joint and the wind force exerted point, and l_2 is the distance between the centre of mass and the joint.

3. Acceleration Interpretation

$\varphi_x(t)$ and $\varphi_y(t)$ are measured by calculating the changes of accelerations along X-axis and Y-axis. If there is no wind, the accelerometer will remain in the horizontal plane and the accelerations of the two axes A_x and A_y are 0 m/s^2. When a wind occurred, the anemometer can be rotated to a new equilibrium position, and the changes of accelerations can be used to determine the rotation angles. When a rotation occurred, the gravity will have two components of forces along the two axes of the accelerometer. Accordingly, the measured accelerations A_x and A_y can be used to determine the rotation angle $\varphi_x(t)$ and $\varphi_y(t)$. The following equations give the relation between the A_x, A_y, $\varphi_x(t)$ and $\varphi_y(t)$.

$$A_x(t) = g\sin(\varphi_x(t)) \tag{3.6}$$

$$A_y(t) = g\sin(\varphi_y(t)) \tag{3.7}$$

Based on equation (3.1) - (3.7) it can be derived that:

$$V(t)^2\cos(\theta(t)) = \frac{2}{\mu\rho A l_1\cos\left(\sin^{-1}\left(\frac{A_x(t)}{g}\right)\right)}\left[I\frac{d^2\left(\sin^{-1}\left(\frac{A_x(t)}{g}\right)\right)}{dt^2} + ml_2A_x(t)\right] \tag{3.8}$$

$$V(t)^2\sin(\theta(t)) = \frac{2}{\mu\rho A l_2\cos\left(\sin^{-1}\left(\frac{A_y(t)}{g}\right)\right)}\left[I\frac{d^2\left(\sin^{-1}\left(\frac{A_y(t)}{g}\right)\right)}{dt^2} + ml_2A_y(t)\right] \tag{3.9}$$

We can represent the wind speed $V(t)$ and the direction $\theta(t)$ of the wind by the measured accelerations along two axes of the accelerometer.

Maximum and Minimum Wind Speed Analysis

The minimum wind speed measured by the anemometer depends on the sensitivity of the accelerometer. The sensitivity of the accelerometer is $6.10*10^{-5}$ g, and according to the equation 3.1, the corresponding minimum wind speed to be measured is calculated to be 0.22 m/s. The measurement of the maximum wind speed depends on the maximum rotating angle away from the initial point. According to the physical structure of the sensor box and the universal joint. The maximum rotating angle is considered to be 45° , and the corresponding force induced by the wind acted on the sensor box is equal to the gravity acted on the sensor box. The maximum wind speed could be measured is 28.26 m/s based on equation 3.1.

3.3 Experimental Results and Discussions

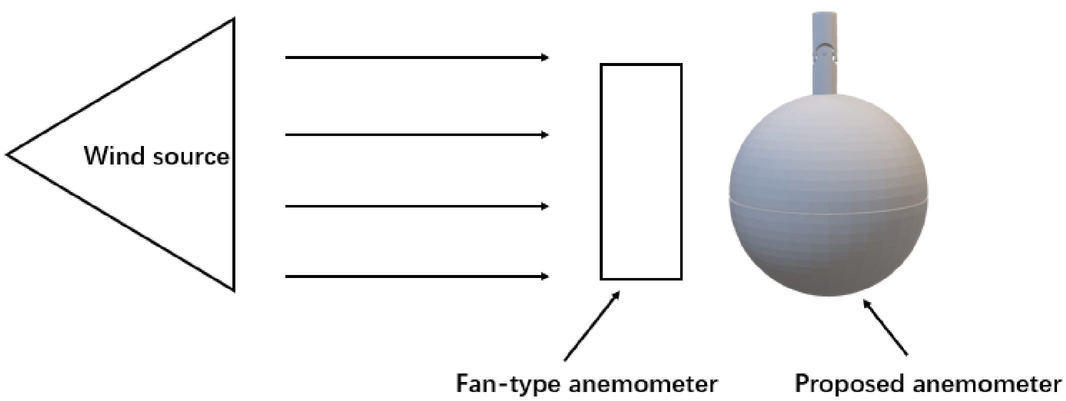


Fig. 3- 6 The setup of the wind speed measurement.

To verify the performance of the proposed accelerometer-based anemometer, we place the anemometer near to a wind source. The wind source can generate steady winds with different speeds varying from 1 m/s to 10 m/s. A fan-type anemometer is placed between the wind source and the proposed anemometer to measure the ground truth value of the wind speed generated by the wind source, as shown in Fig. 3-6. A total number of 50 sets of accelerations can be measured by the proposed anemometer in 1 second. Based on the collected accelerations in two axes, both the wind speeds and the wind directions can be derived. The experiment is carried out based on the procedure, as shown in Table 3-1, and the raw data obtained from the accelerometer is shown in Fig. 3-7. The measured accelerations will be transmitted to a smartphone by using Bluetooth, and the measured acceleration will be further processed to obtain the wind speeds and wind directions.

Table 3- 1 The measurement procedure of the proposed anemometer.

Time period (s)	Wind speed (m/s)
0-5	0
5-15	5.5
15-25	5.0
25-35	4.5
35-45	5.5
45-50	0

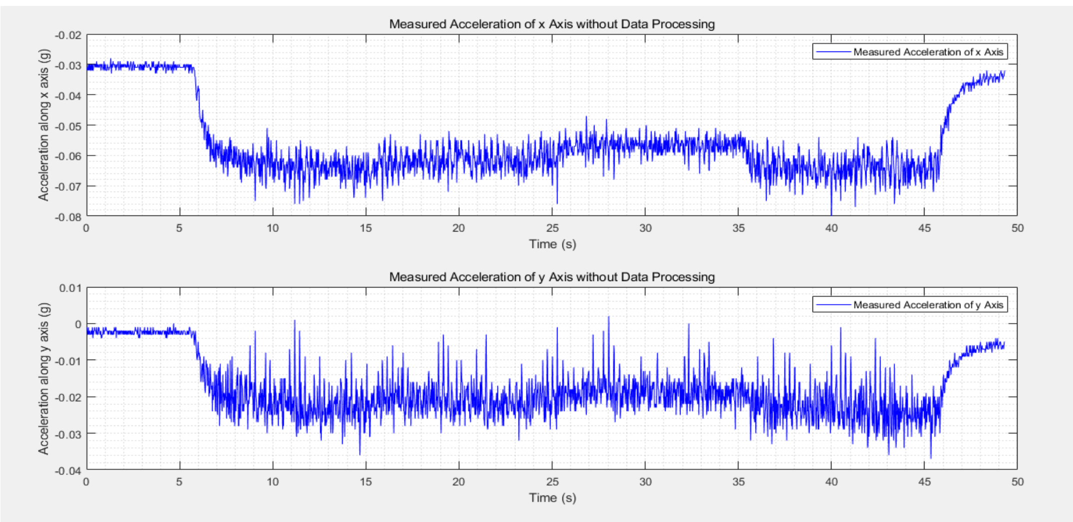


Fig. 3- 7 The measured accelerations of two axes without data processing.

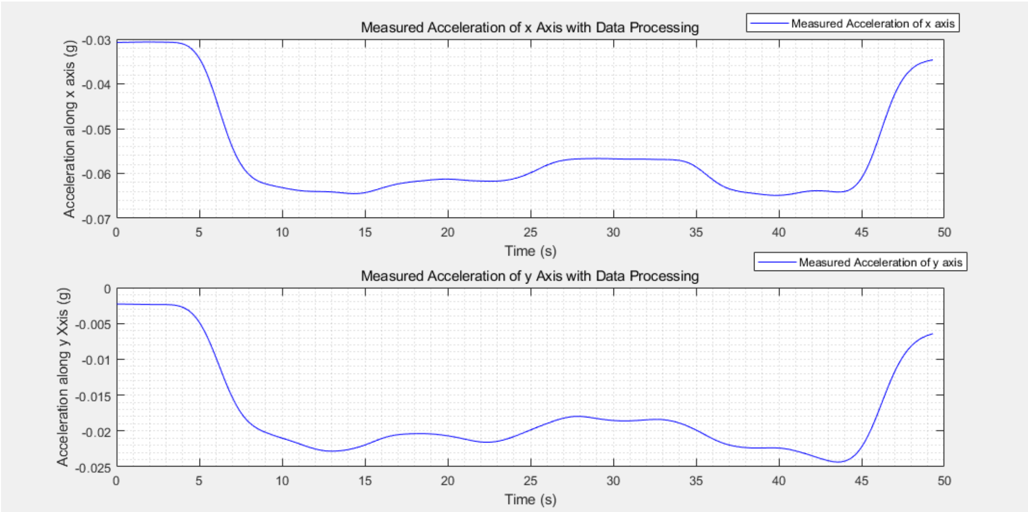


Fig. 3- 8 The measured accelerations of two axes with data processing.

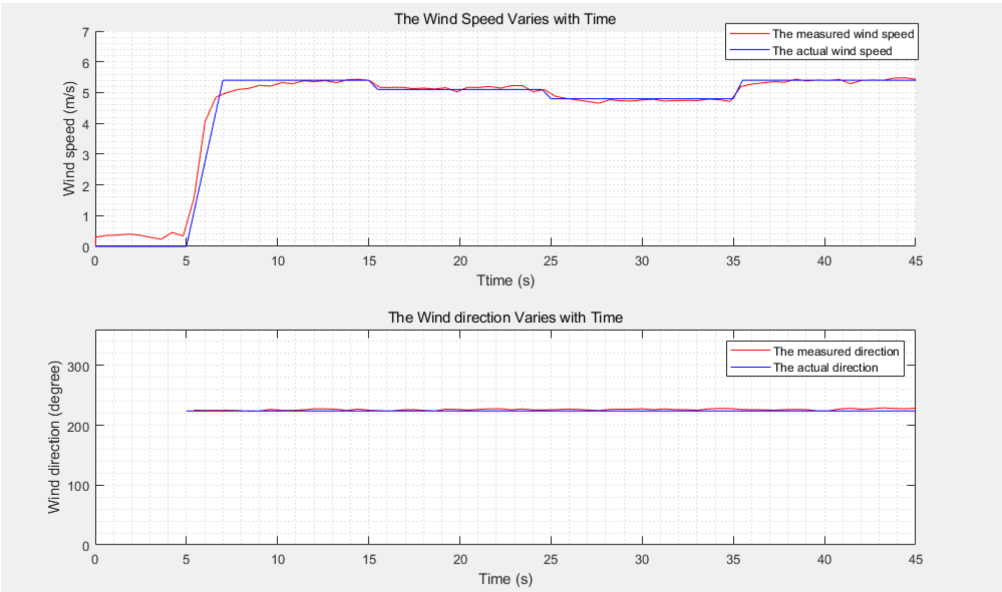


Fig. 3- 9 The comparison between the measured wind velocity and the actual wind velocity.

From the measured accelerations in the two axes, it can be found that the noise level is very high, and a filtering algorithm should be applied to remove the noise. A Gaussian-weighted moving average filtering method is applied to remove the noise. The measuring frequency of the accelerometer is 50 Hz, and the algorithm can sum up every 30 discrete points and calculate the average value of the wind speed. The averaged values can then be acted as the modified results, which are more closed to the real values of the accelerations in those conditions. The results of the processed accelerations after the filtering algorithm are shown in Fig. 3-8 It can be found that the noise has been removed and the result is more accurate. Then, the wind speeds and the directions can be calculated based on Equations (3.8) and (3.9), which are shown in Fig. 3-9. Both the measured results of the wind speed and the wind directions matched well with the actual values.

To further verify the performance of the proposed anemometer, we have compared the proposed anemometer with a commercial cup-type anemometer in an open parking lot as displayed in Fig. 3-10. The proposed anemometer is mounted on the pole near to the cup-type anemometer to ensure both devices are exposed to the same wind speed and direction. The upper part of the cup-type anemometer is a wind vane which is used to measure the wind direction and the lower part of the anemometer has three rotating wind cups to measure the wind speed.

Fig. 3- 10 The comparison between the proposed anemometer and the commercial cup-type anemometer.

The wind speed and direction were sampled every minute in the time frame. The weather condition was partly cloudy as shown in Fig. 3-10. The measured wind speed and direction of two anemometers in 15 minutes are displayed in Figs. 3-11 and 3-12. Based on the measured results, it can be found that both the wind speed and direction measured by the two devices are consistent with each other, and errors are constrained in a reasonable region.

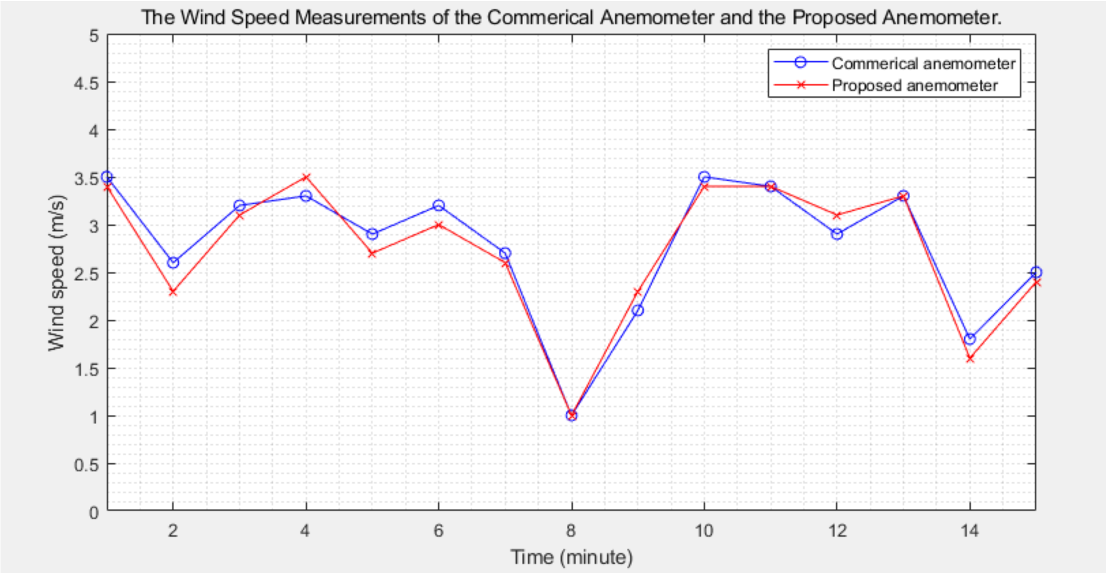


Fig. 3- 11 The wind speed measurements of the commercial anemometer and the proposed anemometer.

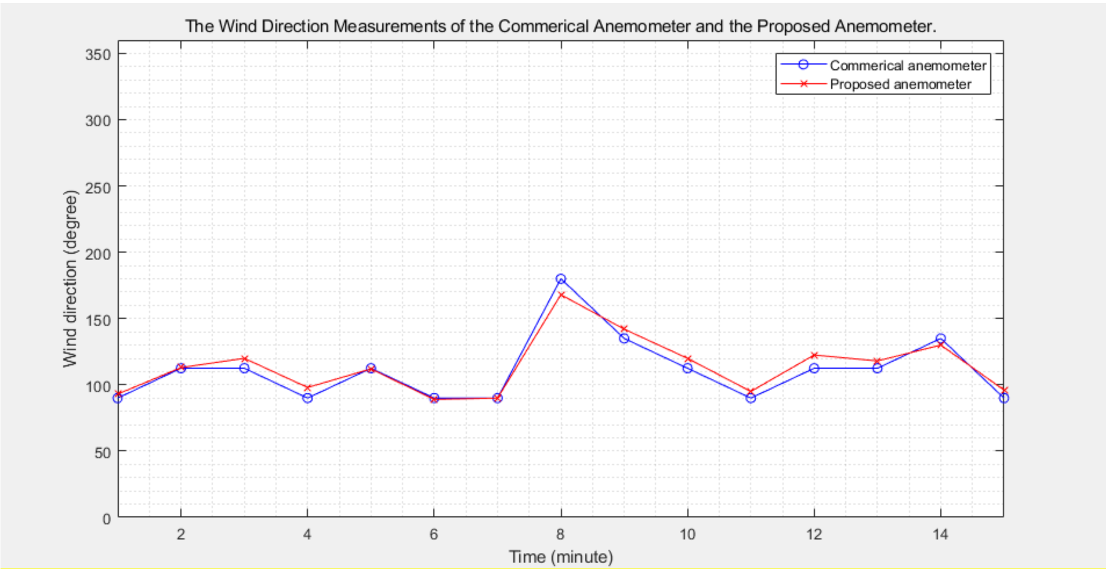


Fig. 3- 12 The wind direction measurements of the commercial anemometer and the proposed anemometer.

The accelerometer is held in the sphere 3D printed sensor case, and the diameter of the sensor case is only 5 cm. Compared with other anemometers, the proposed anemometer has a very compact size, which allows it to be more easily deployed. Since the accelerometer is the only device used to measure the wind speeds and wind directions, and the power consumption of the anemometer will be the energy consumed by the anemometer. The energy consumption of the accelerometer is only 3.42 mW, which is significantly smaller than other wind sensors listed in Table 3-2. The following table summarizes the comparison of key characteristics between different anemometers and the proposed anemometer, and it can be concluded that the proposed anemometer has a compact size with lowest power consumption which is more suitable for IoT environmental sensing applications.

Table 3- 2 Comparison of proposed anemometer with other designs

Ref (year)	Figure	Anemometer type	Power consumption	Size
[24] 2018		12-pressure-sensors-based anemometer	400 mW	100 mm in diameter
[16] 2017		Hot-film anemometer	20 mW	Not given
[25] 2018		Hot-film anemometer	20 – 45 mW	Not given

[11] 2017		Ultrasonic anemometer	Not given	Larger than 200 mm
[26] 2018	Not given	Ultrasonic anemometer	840 mW	Not given
This work		**Accelerometer-based anemometer**	**3.42 mW**	**50 mm in diameter**

3.4 Summary

In this chapter, we have proposed a new compact anemometer with ultra-low energy consumption feature which could be suitable for energy constrained IoT environmental sensing applications. The diameter of the sphere anemometer is 50 mm, and the anemometer only consumes 3.42 mW when it is in operation. The proposed wind sensor can be easily deployed in different places due to its compact size. The main contribution of this work is that the proposed anemometer has low energy consumption feature which allows it to be powered by using battery only. The wind force model and the 3D dynamic model have been established to derive the equation of dynamics of the anemometer, and the expressions between the wind velocity and the acceleration have been given. A Gaussian-weighted moving average filtering algorithm is used to remove the measuring noise, and we have demonstrated that the anemometer can measure both wind speeds and wind directions accurately.

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Chapter 4 An Environmental Sensing Platform with Self-powered Standalone Weather Stations

Chapter 3 has proposed a novel and compact wind sensor with ultra-low energy consumption feature which can be integrated into a weather station. In this chapter, we will develop a weather station which can act as a wireless sensor node. The weather station should be small in size and consume low energy to meet the requirements of IoT applications. A solar energy harvesting system will be integrated into the sensor node to make it to be self-powered. The weather station should have a stable wireless connection, and different weather stations can be deployed in different places and connected to build an environmental sensing platform.

4.1 Introduction

Real-time environmental data (e.g., temperature, humidity, lightness, wind speeds, and wind directions) is needed in different applications such as weather monitoring/ forecasting, smart city, smart agriculture, air quality monitoring, and load prediction [1, 2]. Climate changes have received much attention recently, which makes it an active and hot research area. To statistically study the climate change and the impacts of the human activities on nature environment, we need to collect data like rainfall, temperature, CO2, wind speed, and air quality from various places over the time [3]. Environmental monitoring can also be used in other applications. For example, environmental sensors should provide accurate and real-time metrological data to predict the load and the amount of energy generated from solar farm and wind turbine to meet the requirements in the smart grid [4-6]. Additionally, to realize smart agriculture, different sensors should be deployed over a wide region to monitor the crop and environmental conditions in the farm [7-9].

Different sensors are widely deployed to realize environmental monitoring applications, and how to connect those sensors to allow real-time data transmission is a challenging problem. With the rapid growth of IoT technologies, some machine type communication (MTC) protocols like NB-IoT, LoRaWAN and Sigfox have emerged and gained wide attention from many researchers [10]. They have low energy consumption and wide coverage, which is suitable for IoT applications. Among them, LoRaWAN allows to set up a private network, which can be integrated into different global network platforms (e.g., The Things Network) [11]. Thus, LoRaWAN has been selected for this project.

The power consumption of the sensor node is another main design challenge, which is important to determine the lifespan of the node and maintain the overall performance of the whole sensor network [12]. However, few research has been focused on the energy consumption of the sensor node [13, 14]. It will increase the cost and difficulty of the deployment of the sensing system if power lines are used to power the end devices. The sensor node could be designed to be powered by the battery to increase deployment flexibility. Energy-saving techniques and energy harvesting methods should also be implemented to reduce battery replacement frequency and save the maintenance cost. Solar energy has a relatively high power density, and solar panel is used to provide energy to the sensing device.

This chapter proposes a new design of smart environmental sensing system with self-powered sensor nodes, LoRaWAN communication network, and real-time data accessible cloud. The wireless sensor node is embedded with a sleep mode control to save operating power. Moreover, a solar energy harvesting powering method is developed for the sensor. By integrating the solar energy harvesting method, the sensor node can become self-powered without the need of changing the battery. LoRaWAN is used to provide a real-time, robust, and wide range connectivity for the sensor nodes. The real-time data gathered from the sensor nodes can be easily monitored and obtained from a Could App (Cayenne). The total cost of one sensor node is around 100 pounds.

4.2 Hardware and Software

4.2.1 Hardware

Wireless Weather Stations

The weather station can be viewed as a sensor node composed of four parts which are the Power Management Unit (PMU), the sensing unit, the microcontroller unit (MCU), and the communication unit as shown in Fig. 4-1. The sensors can measure different environmental parameters, and the measured data can be read by the MCU. The MCU will process the raw data and transfer the data obtained from the sensors into a single payload which is ready to be sent to the cloud. Then, the LoRaWAN communication unit can transmit the payloads containing the value obtained from the environmental sensors to the LoRaWAN gateways.

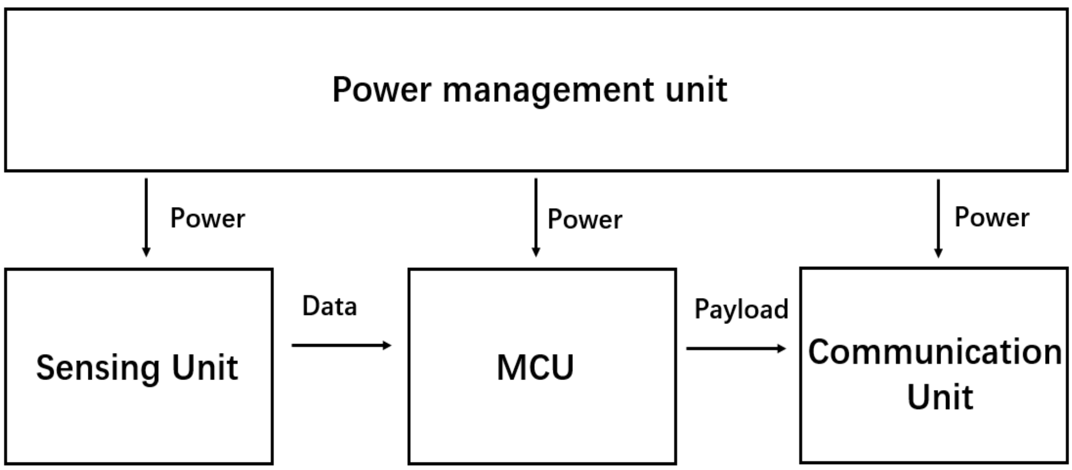


Fig.4- 1 The architecture of the weather station.

Table 4- 1 The characteristics of sensors

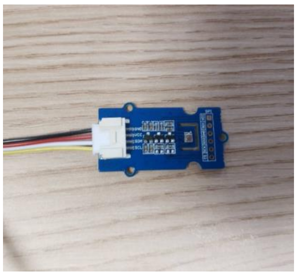
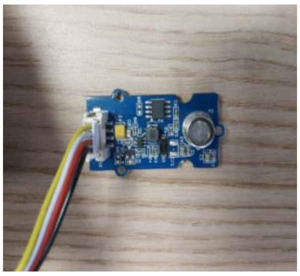
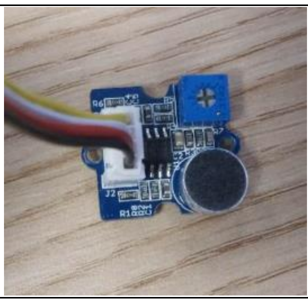
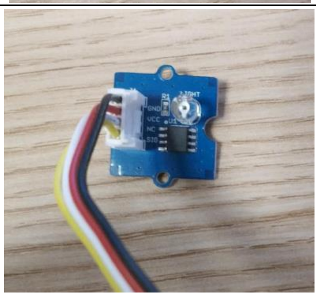
Model	Figure	Functions	Size	Power consumption
BME280		Temperature, humidity, air pressure	40 mm * 20 mm	< 13.32μW
MP503		Carbon monoxide, alcohol, acetone	40 mm * 20 mm	< 300 mW
LM386		Loudness	20 mm * 20 mm	< 25 mW
GL5528		brightness	20 mm * 20 mm	< 15 mW

Table 4- 2 The Specifications of Parts of the Sensor Node

Name	Model	Function
Microcontroller Unit (MCU)	Sodaq Mbili	Data processing and power management
LoRaWAN communication module	RN2483	Data communication
6000 mAh LiPo battery	KC 906090P	Providing power to the device
3 W solar panel	SKU 313070001	Providing power to the battery

The main feature of the sensor node is that the whole device can be self-powered so that the battery does not need to be replaced manually. To realize this function, a 3W solar panel and a 6000 mAh Lithium Polymer (LiPo) battery are used to provide energy to the whole sensor node. The PMU of the sensor node has two Japanese Solderless Terminal (JST) ports to connect to the solar panel and the LiPo battery. Since the harvested energy from the solar is not stable and consistent, and the battery is used to provide a steady 3.7 V output voltage to ensure that each module of the sensor node can work properly. The solar panel with a maximum output voltage of 6 V is used to charge the LiPo battery under the control of the PMU. Four different sensors which are the brightness sensor, loudness sensor, the air quality sensor, and the TPH sensor which can measure the temperature, air pressure, and humidity are used in each sensor node. More information about the four sensors can be found in Table 4-1. All the sensors are connected to the Sodaq Mbili board by using grove connections, which can supply energy to the sensors and allow the communication between the sensors and the MCU. The Sodaq Mbili board has ten grove connectors, and more sensors can be connected to the board depends on the applications.

The Sodaq Mbili uses a Microchip ATmega 1284p as its microcontroller which has 128kB ISP flash memory with read-while-write capabilities, 16kB SRAM and a real-time counter. The MCU is designed to support low energy applications, and the current consumption is 0.4 mA in the active mode and 0.6 µA in the power saving mode when it operates at 1MHz, 1.8 v, 25 °C. The real-time counter embedded in the MCU can be used to put the device into the sleep mode or wake up the board from the sleep mode at specific times which could further reduce the energy consumption of the sensor node. Another main function of the MCU is that it can read the data gathered by the sensors, and the measured results are encoded to the payloads. The payloads are transmitted to the LoRaWAN gateway by using the RN2483 LoRaWAN transceiver, as shown in Fig. 4-2. The instant transmission current consumption of the RN2483 is 44.5 mA, and the idle current consumption is 3.1 mA when the transceiver is connected to a 3.6V power supply. One of the operating frequency bands of the transceiver is 863 MHz to 870 MHz, which supports the LoRaWAN operating frequency in Europe.

Fig.4- 2 RN2483 LoRaWAN communication module.

The wireless sensor node is held in an IP66 dustproof and waterproof box in congestion with a 3D printed base, as shown below. The box has a transparent cover which is made of polycarbonates (PC) and an opaque base which is made of acrylonitrile butadiene styrene (ABS). The 3D printed black base is placed at the bottom of the sensor box, which is used to mount sensors, the battery, and the Sodaq Mbili board. The sensor box is sealed to an IP66 standard to prevent the rain. The inside look and the outside look of the sensor node are presented in Fig. 4-3 and Fig. 4-4.

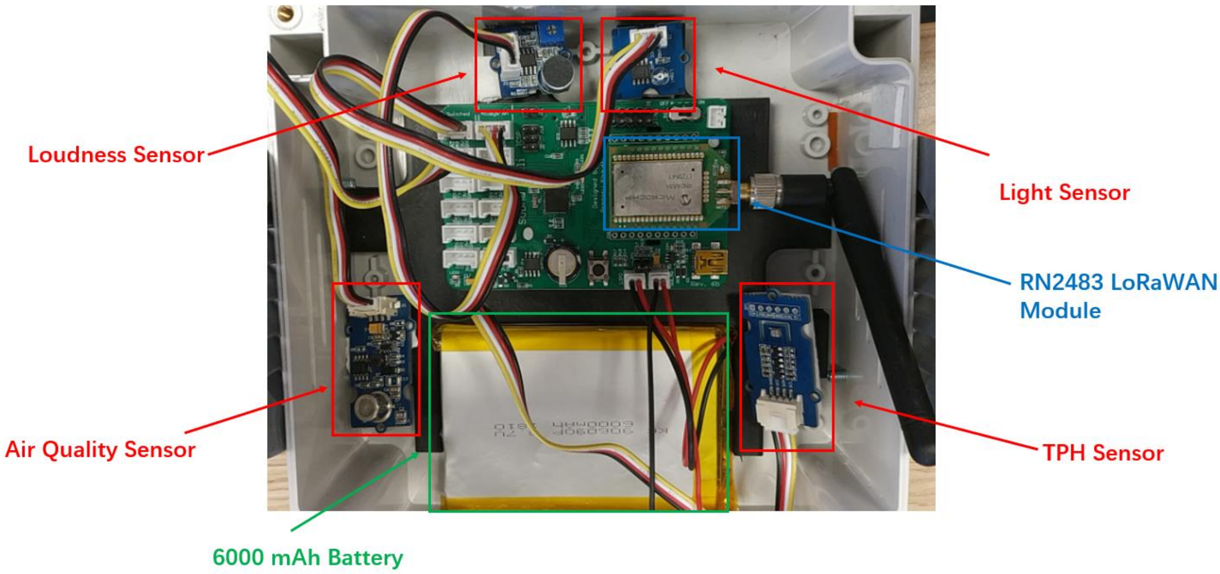


Fig.4- 3 The inside look of the sensor node.

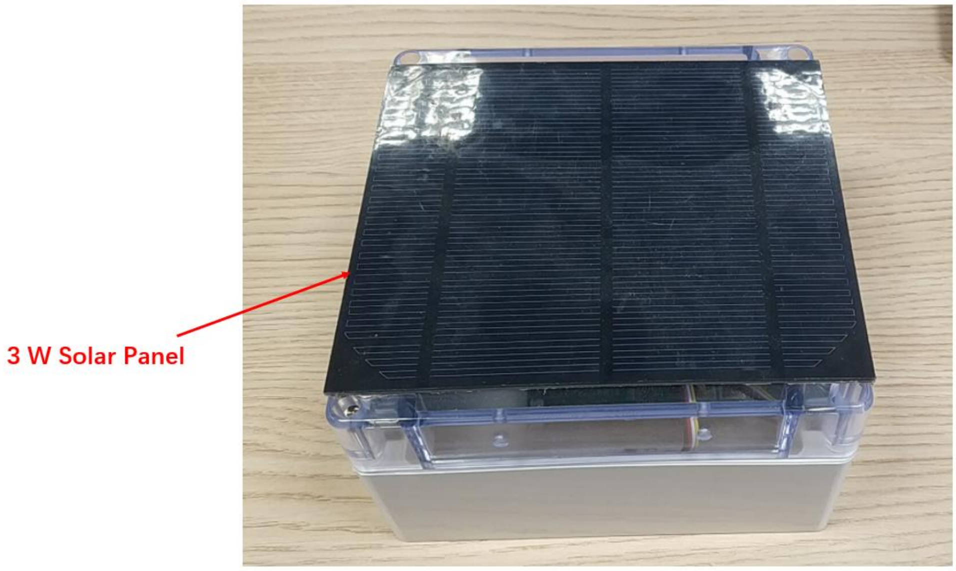


Fig.4- 4 The outside look of the sensor node.

Fig.4- 5 The LoRaWAN gateway.

LoRaWAN Gateway

The wireless environmental sensing nodes will be connected to the gateway by using LoRaWAN protocol to form a wireless sensor network. To set up the LoRaWAN based environmental sensing network, an 8 channels LoRaWAN gateway is used to provide the LoRaWAN coverage to the sensor nodes. The indoor LoRaWAN gateway is built based on the Raspberry Pi 3 and the RAK831 concentrator module (see Fig. 4-5). The RAK831 is a multi-channel high-performance transmitter/receiver module designed to receive up to 8 LoRa packets with different spreading factors at the same time on multiple channels. It operates in the 863 MHz to 870 MHz frequency band and supports both the LoRa and Frequency Shift Key (FSK) modulation techniques. A Raspberry Pi 3 acts as a host board to control the RAK831 frontend. A 5V and 2A power supply needs to connect to the Raspberry Pi 3 to activate both the Raspberry Pi 3 and the RAK831.

4.2.2 Software

The wireless sensor node is developed based on the Sodaq Mbili which is based on the Arduino development board. To program the sensor node and LoRaWAN transceiver, we write all the programs by using the open-source Arduino Software (IDE). The Arduino IDE is written in the programming language Java, and it supports C and C++. The code for the node plays an essential role to guarantee the environmental sensing platform can work properly. It needs to put the MCU and the sensors into sleep mode to save energy and wake up them by using the interference generated by the real-time clock to collect environmental data. The working diagram of the software is displayed in Fig. 4-6. The activation method of the LoRaWAN connection, as well as activation keys such as Network Session Key (NwkSKey), Application Session Key (AppSKey), and Application Key (AppKey), should also be initialized in the code. Various sensed environmental parameters such as temperature, humidity, loudness, and air pressure need to be encoded to payloads, which can be interpreted by the Cayenne cloud.

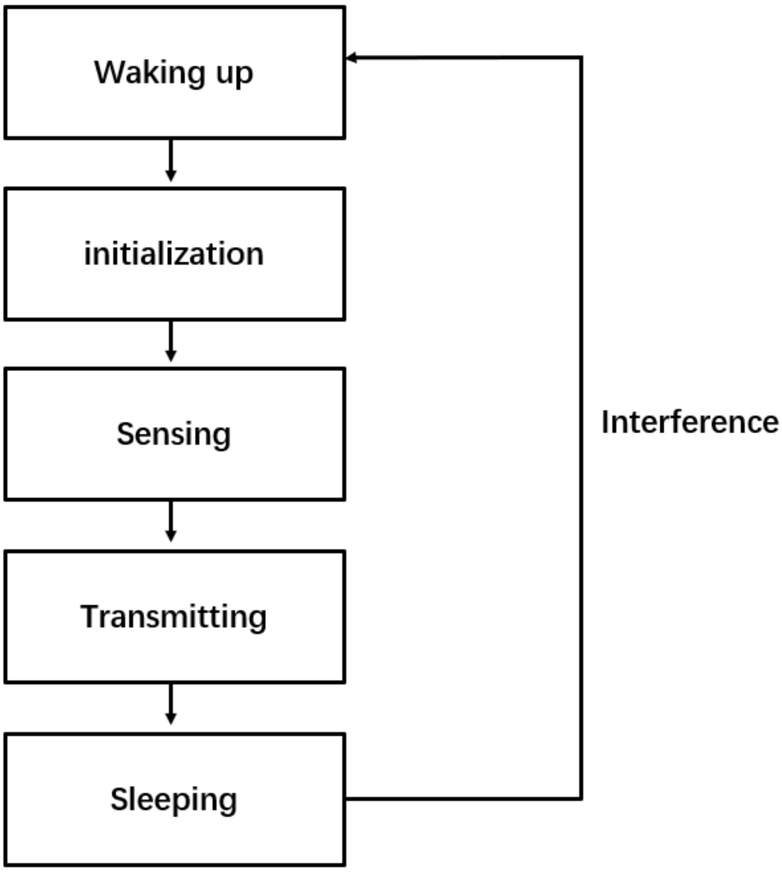


Fig.4- 6 Software working diagram

The gateway will upload the received message from sensor nodes to a cloud platform, namely The Things Network (TTN). To allow the received data to be sent to The Things Network server, the Raspberry Pi 3 should be connected to the Internet by using 3G/4G, Wi-Fi, or Ethernet. The working diagram of the connections between the sensor nodes, gateway and, the cloud is displayed in Fig. 4-7. The gateway should be registered to TTN to transmit the received data from the sensor nodes to the TTN console. Firstly, the gateway needs to be registered in the TTN platform, and the TTN will automatically generate the gateway ID and the gateway keys. The gateway ID and the gateway key should be manually entered to the host board. Then, the status of the gateway in TTN will be changed to connected, and the gateway is registered successfully in TTN console.

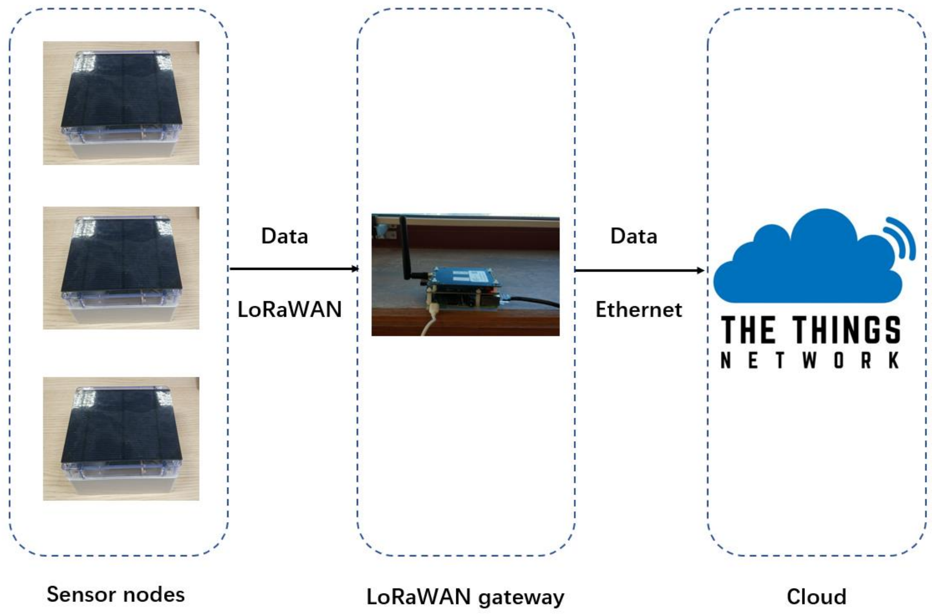


Fig.4- 7 The architecture of the environmental sensing platform.

<u>The Things Network and MyDevice Cayenne</u>

TTN is a free global open LoRaWAN network provider established in the Netherlands, and there are more than 6000 LoRaWAN gateways registered in TTN all over the world. To connect LoRaWAN end device to the TTN platform, a registered gateway in the TTN is necessary. Once a LoRaWAN gateway is registered in the TTN, it provides LoRa coverage to nearby sensor nodes. For a LoRaWAN end device, it also needs to be registered to the TTN first before sending and receiving payloads. After that, a nearby TTN LoRaWAN gateway can extract the payload sent by the node and, the payload can be received and presented in the user's TTN account. However, the data presentation and storage function of the TTN is limited, and therefore in this proposed environmental sensing platform, a data storage and visualization cloud named myDevice Cayenne is integrated to the TTN to present and store the measured data. The payload sent by the end device should be encoded by using Cayenne Low Power Payload (Cayenne LPP) and, the Cayenne cloud can then decode the payloads correctly. The received payload in TTN can be synchronously transmitted to myDevice Cayenne by using Application Programming Interface (API) to realize real-time data communication. Finally, all environmental data measured by sensors can then be visualized and stored in the Cayenne. The users can access the data from the Cayenne IoT website or mobile APP in real time.

4.3 Measurement and Discussion

4.3.1 Deployment

Three wireless sensor nodes have been deployed across the University of Liverpool as a pilot trial for more than three months sensing up to 5 environmental parameters including temperature, air pressure, humidity, loudness, and air quality. They are placed in both indoor and outdoor conditions, as displayed in Fig. 4-8. Since we aim to make each sensor node be a standalone device which can be powered by using solar energy, the device is placed near the window in indoor circumstances to obtain enough sunlight. The LoRaWAN gateway is an indoor gateway, and it is placed in a typical office, as shown in Fig. 4-8. The gateway is placed near the window facing the city center to cover more end users.

Fig.4- 8 The deployment of sensor nodes and the LoRaWAN gateway. (a) The sensor node in indoor condition; (b) The sensor node in indoor condition; (c) The sensor nodes in outdoor condition; (d) The LoRaWAN gateway in indoor condition.

4.3.2 Measurement Results

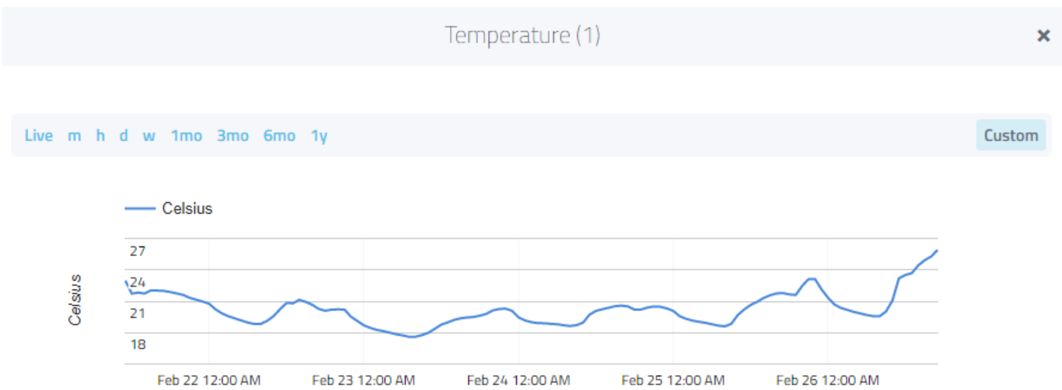


Fig.4- 9 The measured temperature over 5 days.

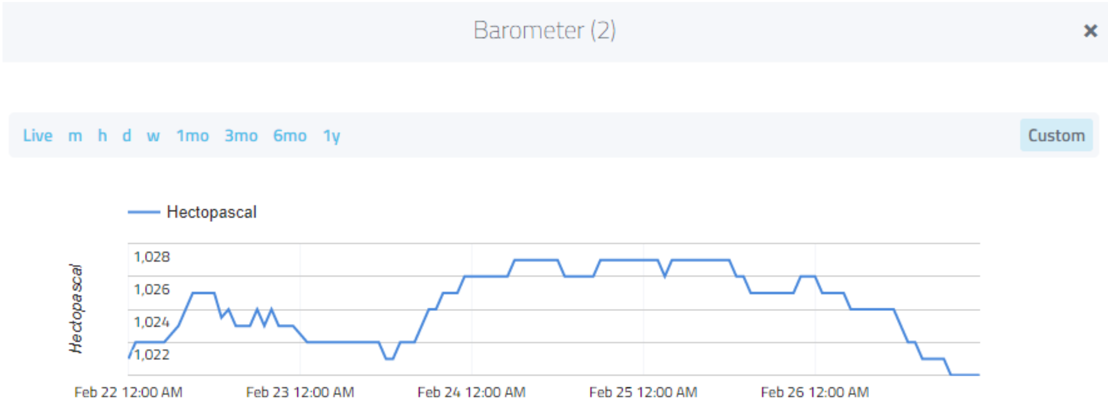


Fig.4- 10 The measured air pressure over 5 days.

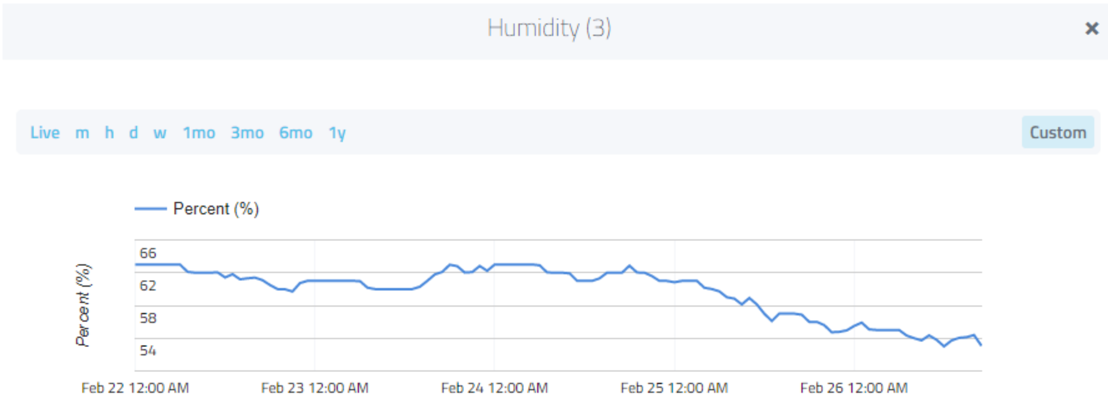


Fig.4- 11 The measured humidity over 5 days.

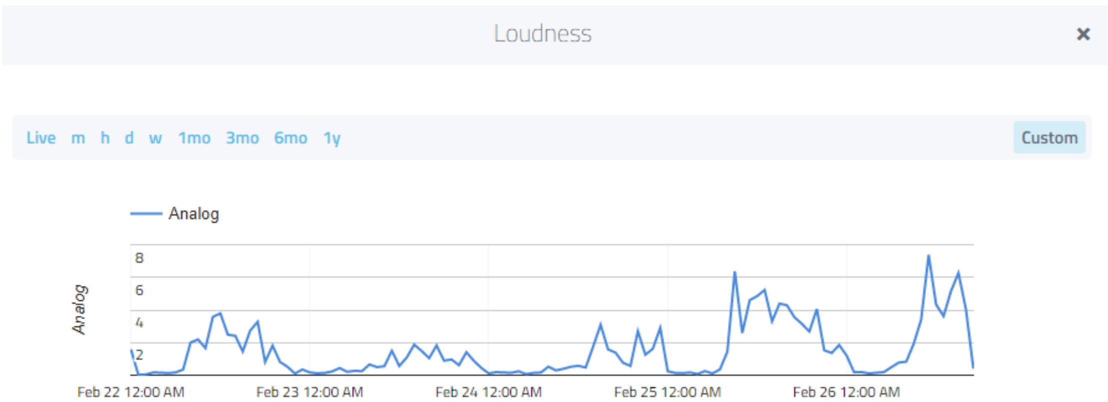


Fig.4- 12 The measured loudness over 5 days.

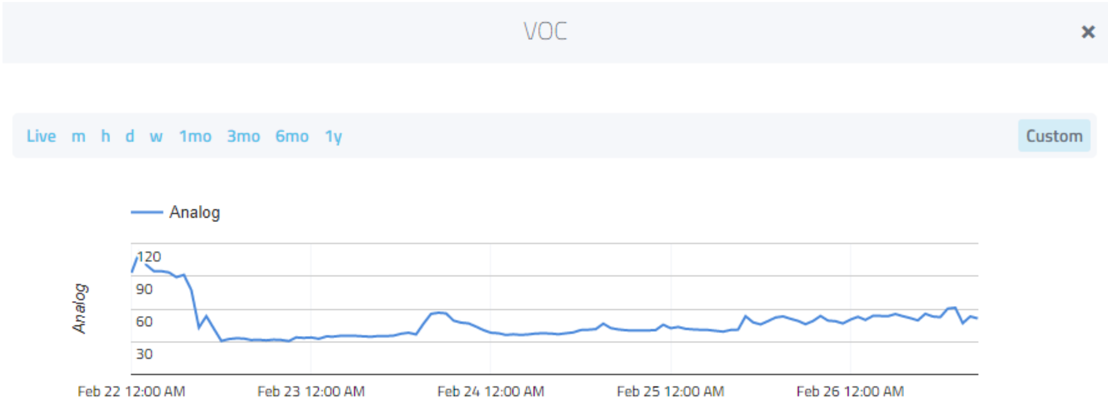


Fig.4- 13 The measured air quality over 5 days.

All the measured environmental data will be stored and presented in the myDevice Cayenne cloud. Fig. 4-9 to Fig. 4-13 present 5-days continuous environmental monitoring results of 5 measuring parameters from one device. Fig. 4-9 presents the variation of temperature over 5 days, and it can be easily found that there is a peak during the daytime and a trough at night every day. It agrees with the common knowledge of the temperature change during a day. The air pressure and humidity are displayed in Fig. 4-10 and Fig. 4-11, the variation of these two parameters is relatively small according to the measured results. The loudness level shown in Fig. 4-12 has a similar trend as the temperature variation. It is because more activities will be carried out during daytime which could make noise. Also, the noise level has sudden changes, which also agrees with the nature of the noise generated by different activities. VOC measures the concentration of volatile organic compounds in the air and can be used to describe the air quality. VOC varies in a small region, and it does not have significant differences between day and night.

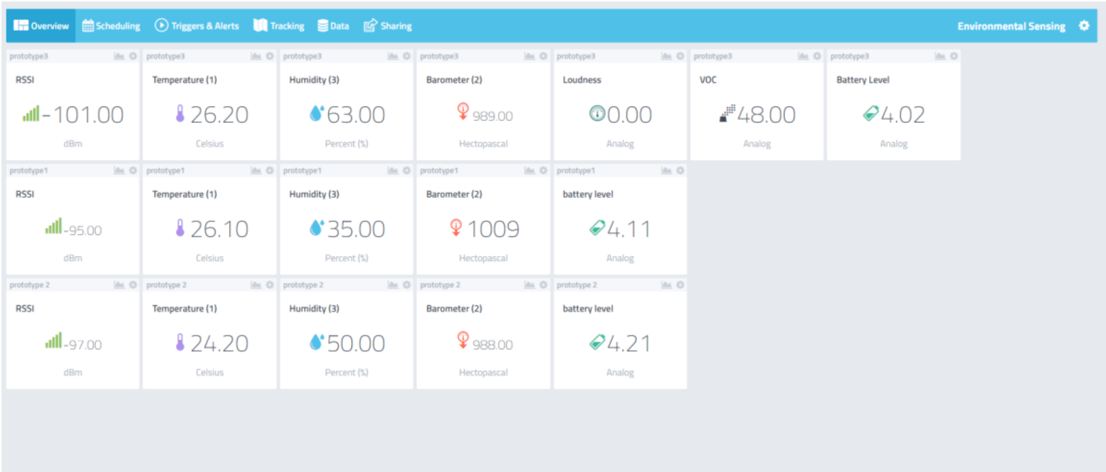


Fig.4- 14 The measured results of three sensor nodes.

A small wireless sensor network consisting of three sensor nodes which is used to monitor the ambient environment has been successfully built. Fig. 4-14 is an overview of all the environmental data obtained from three wireless sensor nodes. All these parameters are received and displayed in real time. The RSSI value can be used to tell the received signal strength of each sensor node to guarantee the connection is stable. The battery level indicates the voltage of the supply battery, and it can be used to monitor the remaining energy in the battery. It is also a critical parameter to investigate if the sensor node does not work properly. The sensor nodes can be deployed over a wide region which is covered by the LoRaWAN gateway. The users can have access to all the measured results from all three sensors deployed in different places to monitor and manage corresponding activities.

4.3.3 Coverage Analysis

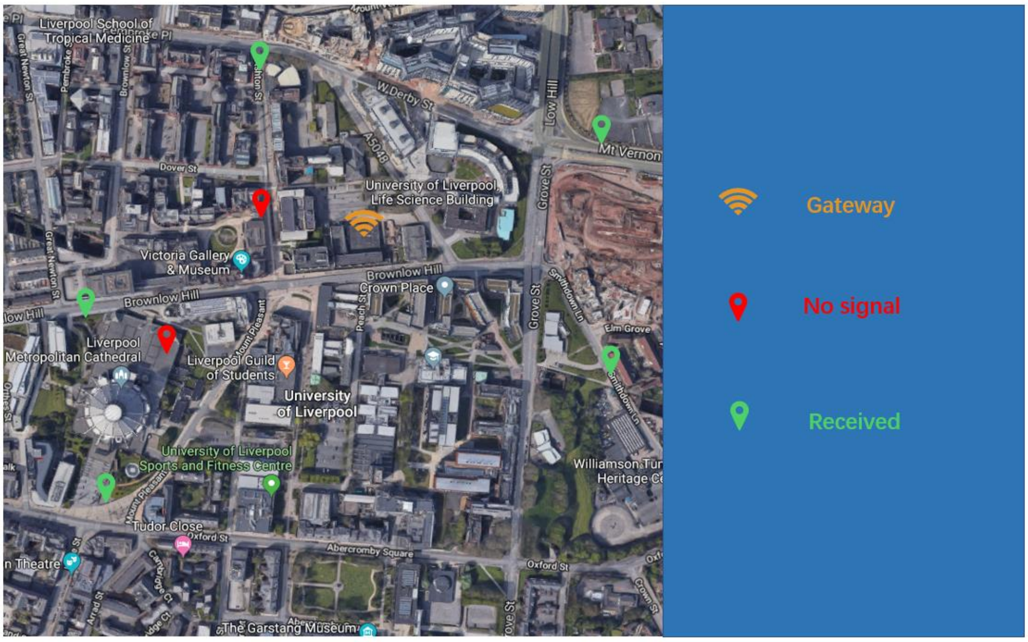


Fig.4- 15 The coverage test of LoRaWAN.

To do the coverage test, the team placed the gateway on the first floor of the Electrical Engineering building, which is indicated by the orange icon. The position labelled by using the green icon can receive the LoRaWAN signal, and there is no signal at the place marked by the red icon. The two places with no signal are due to the obstruction of the tall buildings. Based on the test, it can be found that the LoRaWAN can achieve better coverage with line-of-sight, and the obstruction can block the signal. Therefore, the deployed position of the gateway should be carefully chosen to maximise the coverage, and it will be better to put the gateway in a high place with less obstruction.

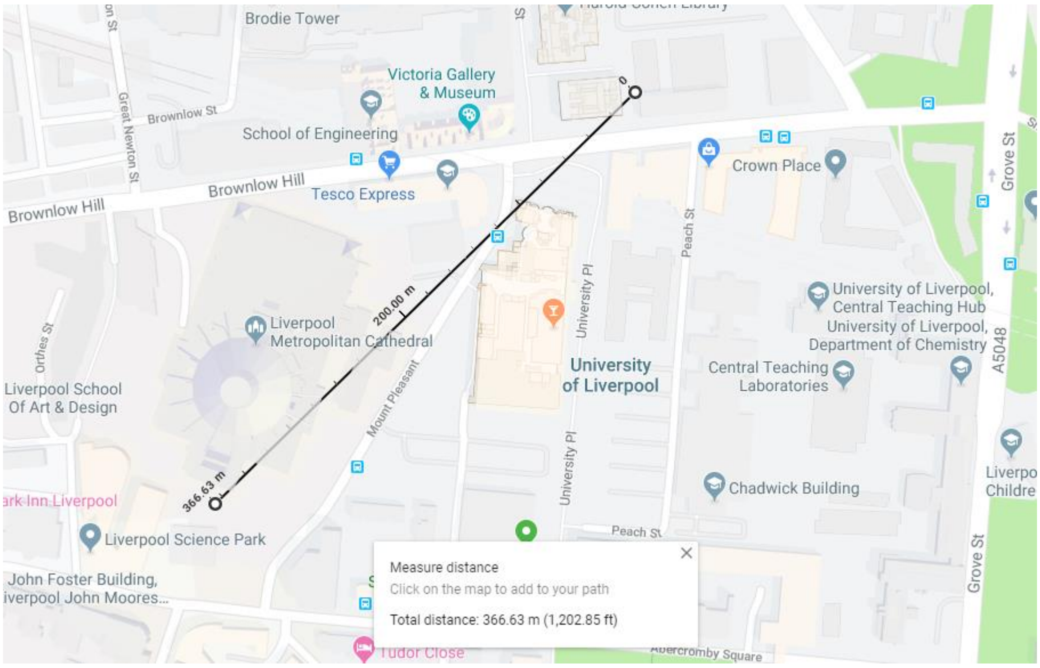


Fig.4- 16 The coverage distance of the LoRaWAN gateway.

The longest coverage distance obtained from the previous test is 366.63 m, as shown in Fig. 4-16, which is smaller than the distance stated in the datasheet of the LoRaWAN. The measurements agreed with some of the experiments did by other researchers. Junqing measured a coverage of 500 m, and Erbati obtained a coverage of 300 m from an outdoor gateway [15, 16]. There are few factors to cause the limited coverage of the LoRaWAN gateway. The first is that it is an indoor gateway, and the transmission power of the indoor gateway is relatively low. Since it is placed in the indoor environment, and the building will obstruct the signal, which can reduce the coverage as well. The penetration loss is 20 dBm for indoor devices [17]. Also, the gateway is placed on the first floor, and wider coverage can be achieved if the gateway is placed in a high place [18]. Another cause of the short coverage is because the gateway is placed in the urban area. Different obstacles, such as high rise building and tall street furniture will cause none line-of-sight (LoS) propagation and the multipath effect, which will reduce coverage area as well[19].

To statistically analyse the coverage distance of the proposed LoRaWAN environmental sensing system, Okumura Hata model is used to theoretically study the fade margin and to determine whether the theoretical value is consistent with the measured value. The calculated path loss by using the Okumura Hata model is 108 dBm. According to the specification of the RN2483 LoRaWAN transmitting module, the output power could be 10.4 dBm. Since, the gateway is placed in the indoor condition, another 20 dBm path loss should be added to the total path loss. The received signal strength could then be calculated to be -118.6 dBm, which is very closed to the LoRaWAN lowest sensitivity at the SF 7. It could be proved that the measured results agree well with the theorical values.

4.3.4 Energy Performance Analysis

The energy consumptions of some sensors are very low, and a TPH sensor only consumes 13.32 μW. However, the air quality sensor has an energy consumption of 300 mW when it is in operation, and it will drain the battery very quickly if it is continuously switched on. To reduce the energy consumption of the whole device, we add a sleeping function to the MCU. The whole device will be put into the sleep mode with extremely low energy consumption. The device will only be activated in a short period, and it will be sleep again after the sensing and transmission of environmental parameters. Since the MCU and sensors will be in the sleep mode most of the time, and sensors with high energy consumption will not have huge impacts on the overall energy performance of the device.

To numerically study the energy consumption of the sensor node, we measured the current consumption of the sensor node over a period, and the results are shown in Fig. 4-17. The total wake-up time of the sensor node is 4.5 s, and there are five current peaks which represent the board initialization, sensor initialization, transmission, and two receiving windows. The maximum current consumption is during the LoRaWAN transmission, which is about 52 mA. However, it only lasts for 0.067 s, and only 12.395 mJ will be consumed during each transmission. The sensor node will go to the sleeping mode by the end of the second receiving window, and the current consumption during the sleep mode is only 3.7 mA which makes the overall power consumption of the sensor node to be 13.69 mW.

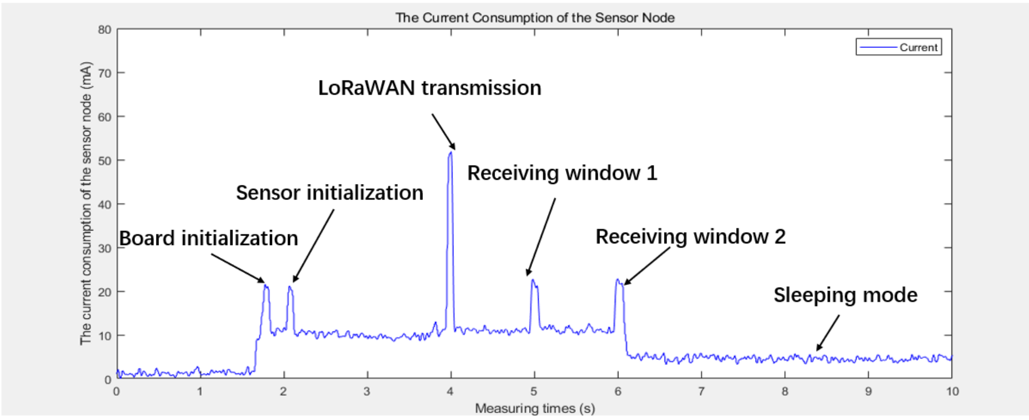


Fig.4- 17 The current consumption of the sensor node.

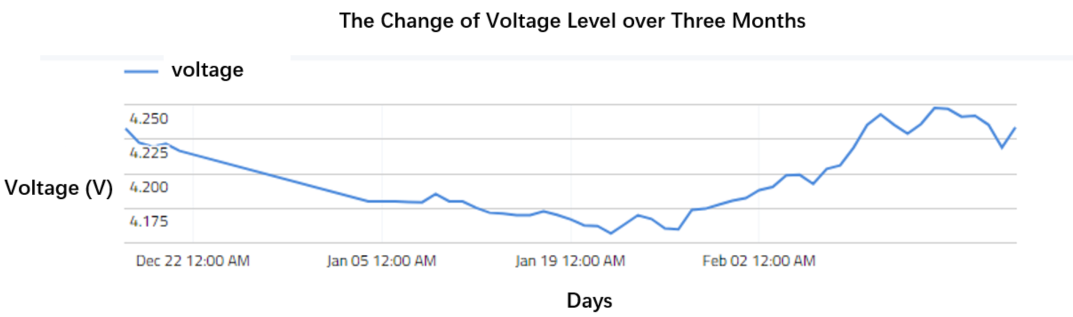


Fig.4- 18 The change of the voltage level in 3 months.

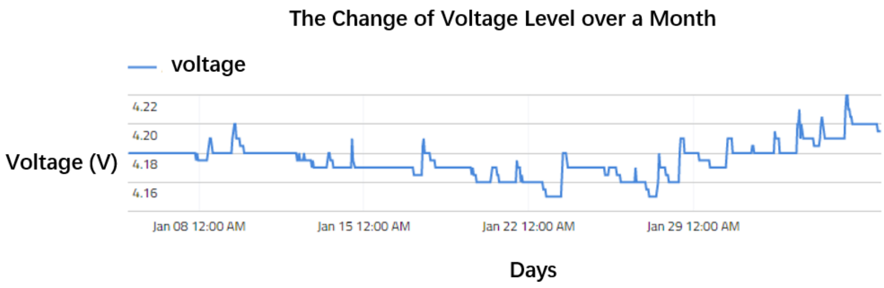


Fig.4- 19 The change of the voltage level in 1 month.

We continuously monitored the energy remained in the battery of the weather station over three months starting from December 17th, 2018. In this test, we use the output voltage level of the battery to determine the remaining energy in the battery. The battery voltage level over three months can be found in Fig.4-18. Fig.4-19 presents a detailed voltage level change over 30 days starting from January 5th, 2019. Form Fig. 4-18, we can find that the voltage level drops and goes up on different days. It means that the sensor node consumes the remaining energy in the battery when the solar panels cannot extract enough energy. The main factor which could affect the amount of harvested energy from solar panel is the weather condition. The voltage level continuously drops due to the consistent rainy weather from December 17th, 2018 to January 22th, 2019. However, the solar panel will charge the battery if the weather conditions are good, and after 10 days, the voltage level goes from 4.18 V to 4.20 V (see Fig. 4-19) which means that more energy is received and charged to the battery than the amount of the energy that the sensor node consumes. It demonstrates that more energy is harvested by using the solar panels than the energy consumed by the sensor node, and the device can then be a self-powered sensor node without changing the battery.

The deep charging cycle of the KC 906090P battery used in the sensor node is more than 1000 times. Solar panel is used to provide power to the battery, and the battery can be quickly recharged in a relatively short time. This charging method could be defined as the shallow discharge. Shallow discharge is better to battery compared with deep discharge, which means the battery can be used longer when using the solar panel to power it. The battery can be used to power the sensor node for 2 months in one full charge - recharge cycle, and the battery life could therefore be more than 166 years theoretically.

4.3.5 Discussions

Table 4- 3 Comparison of the proposed weather station with other designs

Ref (year)	Platform	Environmental parameters	Energy consumption	Cloud	Energy harvesting	Cost
[20] 2015	Robin Z530L	Temperature, humidity, air pressure, wind speed	Not given	Yes	No	Not given
[21] 2017	STM32F103VETb	Temperature, humidity, light intensity, wind speed, wind direction	68.75 mW	No	Solar panels and wind	Not given
[22] 2017	Not given	Temperature, humidity, wind speed, rain, solar radiation	Not given	Yes	No	Not given
[23] 2017	Raspberry PI and Arduino	Temperature, humidity, air pressure, wind speed, wind direction	Not given	Yes	No	GBP 127.5
[24] 2018	Raspberry PI	Temperature, humidity, air pressure, wind speed, wind direction,	2.775 W	Yes	Solar panels	GBP 231.81
[25] 2019	Arduino	Temperature, humidity, air pressure	Not given	No	Solar panel	Not given

[26] 2018	Arduino	Temperature, humidity, air pressure, rain detection	Not given	Yes	No	Not given
This work	**Arduino**	**Temperature, humidity, air pressure, brightness, loudness, air quality**	**13.69 mW**	**Yes**	**Solar panel**	**GBP 112.59**

A comprehensive comparison between different weather stations has been listed in the above table. It can be concluded that all the weather stations can sense some basic environmental parameters such as temperature, humidity, and air pressure. However, there are some advanced functions such as the connection to the cloud and the energy harvesting which are not included in all the weather stations. Only one of the seven weather stations include both the cloud connection and the energy harvesting features. Also, most of the researches did not investigate the energy consumption of the devices, and the weather station including both cloud connection and energy harvesting function consumes 2.775 W which is extremely high for an electronic device, and it may not be able to be powered by only using the battery [2]. In this work, we proposed a low cost and low energy consumption weather station which only consumes 13.69 mW, and it can be integrated to the TTN cloud and the Cayenne cloud so that the users can have access to the measured data in real time. We have demonstrated that the weather station can be self-powered by using the energy received from solar panels.

An environmental sensing platform has been successfully built by integrating three weather stations and two clouds. The environmental parameters collected from different weather stations can be transmitted to the cloud by using LoRaWAN, and the measured data can be presented and stored in the cloud to be easily accessed by the users. In this sensing platform, each sensor node has a compact size and can be self-powered so that the sensor nodes can be flexibly deployed. The sensing platform can be used to collect various environmental parameters in different applications to achieve monitoring and management purposes.

4.4 Summary

The environmental sensing platform consists of three wireless weather stations has been proposed. We have demonstrated the excellent performance of the sensing platform from three aspects, which are the real-time data presentation and storage in the Cayenne cloud, the wide coverage, and the integration of self-powered weather stations. Since we aim to densely deploy weather stations which could cover a wide area, the wireless connection and the energy consumption of the sensor nodes are key design challenges need to be overcome. In this design, we use the LoRaWAN communication method to provide a wide wireless connection for the sensor nodes. The coverage of the LoRaWAN gateway can be 366.63 m in the urban area. We reduce the energy consumption of the weather station to 13.69 mW and use a 3 W solar panel to power the device. Based on the tests, it can be proved that the solar panel can provide enough energy to make the device to be self-powered.

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Chapter 5 Conclusions and Future Work

5.1 Summary

In this thesis, an accelerometer is used to detect wind speeds and wind directions. The power consumption of the anemometer is only 3.42 mW. We have also applied some latest IoT technologies to build an energy-saving anemometer and a modern environmental sensing platform. LoRaWAN, as one of the state-of-art Low Power Wide Area Network (LPWAN) communication methods has been used to transmit messages between the sensor node and the gateway to achieve low energy consumption in the sensor node and wide coverage. To increase the flexibility of the deployment of the sensor nodes, we make the device to be self-powered by adopting energy saving techniques and using a solar panel to charge the device. The energy consumption of the proposed sensor node is only 13.69 mW, which is significantly smaller than other weather stations. The environmental sensing platform integrates with two clouds which are the The Things Network (TTN) and the Cayenne to achieve real-time data presentation and data storage.

In chapter 2, we have surveyed two types of communication protocols, namely short-range communication protocols and LPWAN protocols. It could be concluded that LPWAN protocols have the merits of wide coverage and low energy consumption, which is more suitable to transmit data in an energy-constrained wireless sensor network. Three LPWAN communication methods which are LoRaWAN, SigFox, and NB-IoT are discussed, and the LoRaWAN has the advantages of flexible private deployment and low energy consumption feature which is more suitable to form a private network. A brief introduction of the wireless sensor network is also discussed in this chapter to provide basic knowledge about the architecture of the wireless sensor network.

A compact anemometer with ultra-low energy consumption has been proposed in chapter 3. The anemometer is composed of a sphere 3D printed sensor case and a 6-axis accelerometer. The 3D dynamic model of the anemometer has been built, and the equations of the dynamics of the wind sensor have been derived as well. The diameter of the sphere anemometer is 50 mm, and the anemometer only consumes 3.42 mW when it is in operation. The wind sensor can be easily deployed in different places and can be powered by using batteries only, which could increase the flexibility of deployment. A Gaussian-weighted moving average filtering algorithm is used to remove the measuring noise, and we have demonstrated that the anemometer can measure both the wind speeds and wind directions accurately.

In chapter 4, we have presented an environmental sensing platform, including both the hardware and the software. The environmental sensing platform is consisted of three wireless weather stations, and each of them is connected to the gateway to receive and transmit data. In this design, we use the LoRaWAN communication method to provide a wide wireless connection for the sensor nodes. The coverage of the LoRaWAN gateway can be 366.63 m in the urban area. The information obtained from the weather stations can be transmitted to the TTN and the Cayenne cloud where received data can be presented and stored in real time. We have investigated the energy consumption of the weather station, which is only 13.69 mW. It can be proved that the weather station can be self-powered by harvesting solar energy based on the measurements over a month.

5.2 Key Contributions and Limitations

This work has provided a thorough study on the environmental monitoring applications from an individual wind sensor to the whole environmental monitoring system. The key contributions and limitations are discussed as follows.

- **A Low Energy Consumption Anemometer**

The most important contribution in this chapter is the development of an ultra-low energy consumption anemometer. There are various ways to measure wind speeds and directions. Some latest measuring methods like ultrasonic sensors and hot-film sensors typically dissipate a large amount of power. A novel method to measure the wind speeds and directions has been developed which are using a 6-axis accelerometer to measure the changes of the accelerations induced by the wind force and then to calculate the corresponding wind speed. The energy consumption of the proposed anemometer is only 3.42 mW, which is significantly smaller than other anemometers. However, the measurement accuracy of the anemometer should be further improved. To increase the measurement accuracy of the accelerometer-based anemometer, a Gaussian-weighted moving average filtering algorithm is applied to remove the measuring noise.

- **The development of an environmental sensing platform**

In this chapter, we have developed an environmental sensing platform including, wireless sensor nodes, communication network, and the data visualization and storage cloud. Most reported weather stations do not include cloud, and in this work, we utilize two cloud servers to transmit, visualize, and store the measured data. Also, many researchers do not investigate the energy performance of the weather stations, which makes the energy consumptions of the designed weather stations to be very high. We have implemented some energy saving techniques such as putting the device into the sleep mode and using low energy consumption communication module to reduce the overall energy consumption of the proposed device to be only 13.69 mW. We also integrate a 3 W solar panel to the weather station to make the whole device to be self-powered. The performance of the real-field deployment of the environment sensing platform including coverage and maximum data flow needs to be further studied. More functions could be added to the sensing system based on the needs of different applications. Also, the package design of the sensor node needs to be improved to protect the sensing device in extreme weather conditions.

5.3 Future Work

Based on the conclusions above and considering the limitations of the work existed, future research could be carried out in the following areas.

- The package design of sensors is a challenging topic. The size of the sensor node should be designed to be compact to reduce the manufacturing cost and increase deployment flexibility. Different modules, such as sensing modules, communication modules, power management modules should be placed together in a limited space. There are various deployment requirements on different modules. For example, some environmental sensors like gas sensor and rain detection sensor should be placed in contact with the outside environment. However, the batteries should be placed in an enclosed environment to prevent damage from rain and short circuits. The sensor box of the anemometer can be designed like a "golf ball" to reduce the turbulence induced by the wind and improve the measuring accuracy and sensitivity.

- The proposed weather station can now measure 6 environmental parameters which are the brightness, loudness, temperature, air pressure, humidity, and air quality. In the future, more sensors with more functions should be added to the existed device to meet more requirements from other applications. For example, to monitor the structural health level, an accelerometer is used to measure the vibrations of buildings and bridges. Also, the proposed anemometer can only transmit data to the smartphone by using Bluetooth. The next step of the work can be integrating the anemometer with the proposed weather station to measure the wind speeds and wind direction。

- Currently, we only collected basic environmental parameters for three months around the campus. More data can be collected in different places such as city centers, factories, and rural areas for a long-time span. The coverage of the environmental system should be further tested to meet the requirement of IoT applications. The collected data can provide sources to analyze the measured environmental changes over the years across different places and study how human activities can affect the environments. Currently, we only measure and present the environmental parameters, and further studies can be carried out to analyze and predict the condition of the ambient environment based on the collected results. For example, some researchers found that the concentration of the CO_2 level in a room is related to the number of people inside the room, and then they use measured CO_2 level to predict the number of people in the room.