Chapter 7
IoT Enabled Smart Sensing System

7.1 Introduction

Monitoring the nitrate concentration in the field is an excellent ability for a water-monitoring study. An Interdigital FR4-based capacitive sensor is characterised by nitrate concentration and reported in this chapter. The concentration range of nitrate is 0–40 ppm (mg/L). Different unknown samples were collected from various sources for measurement, and standard UV-Spectrometry was used for validation. An Internet of Things (IoT) enabled smart sensing node has been proposed to measure the rapid nitrate concentration and transferring the data through the gateway to a user-defined cloud server. It can be installed in any locations to collect water, such as a lake, stream, or river. The system is entirely autonomous and solar powered, robust, and trialled in the field successfully. A simple moving-average smoothing algorithm is used to filtering the collected data in the cloud server side. WiFi protocol and the LoRa protocol are compared regarding power consumption. The developed system is tested in the field continuously, and the result validated with standard UV-Spectrometry. The developed smart system has great potential and can be readily deployable in the sampling locations. It also offers new possibilities for both spatial and temporal analysis for nitrate concentration.

7.2 Materials and Methods

The operating principle of planar interdigital sensor [1] is similar like two parallel plate capacitors, where the bare electrodes open up to one side to provide single-sided access to the material under test (MUT) 1. The generated electric field lines penetrate the MUT, and the impedance of the sensor will be changed. The sensor's impedance becomes a function of the material's properties. Therefore, the properties of the system can be estimated by measuring the impedance of the sensor. The term "interdigital" refers to a digit like or finger-like the periodic pattern of parallel elec-

Md E. E. Alahi and S. C. Mukhopadhyay, *Smart Nitrate Sensor*, Smart Sensors, Measurement and Instrumentation 35, https://doi.org/10.1007/978-3-030-20095-4_7

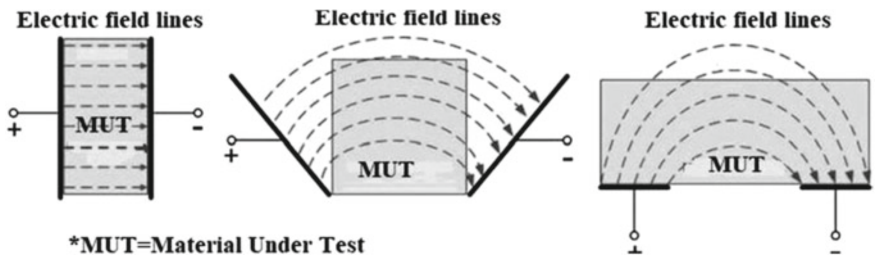

Fig. 7.1 Electric field lines of the parallel plate capacitor and planar interdigital sensor

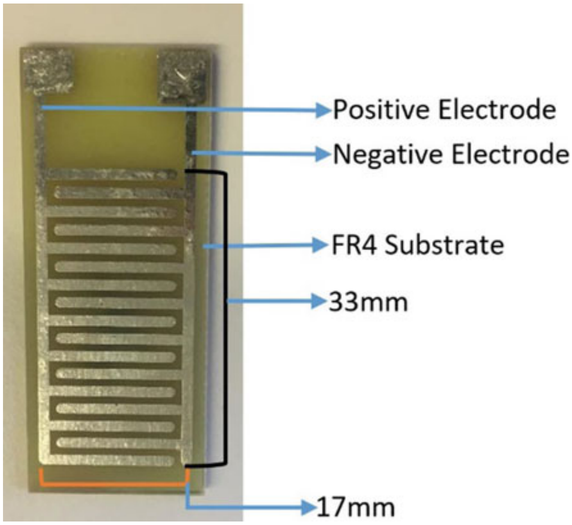

Fig. 7.2 FR-4 interdigital sensor

trodes that helps to build up the impedance associated with the provided electric field that penetrates the sample material 1. An excitation alternating current (AC) voltage is applied to the positive terminal and negative terminal and electric field forms from the positive terminal to the negative terminal as per Fig. 7.1. The interdigital sensor has been used in a different application for domestic and industrial applications [2–4].

Figure 7.2 shows the FR4 interdigital sensor which is used in the proposed sensing system. The fabrication process is analogous to the process, which is used to follow in developing a printed circuit board (PCB). Copper is used to forming the Electrodes which is a good conductor. The dimension of the sensing area is **33 mm x 17 mm**, which is accessible to dip in the water. The Tin Oxide coating material is used as a layer on the copper electrode to keep the electrodes from corrosion.

7.3 Wireless Sensor Networks (WSNs)

The WSN formed with plenty of small sensing systems, which is named as nodes that collect the information from the environments through various sensors. The system consists of various sensors, microcontroller, and necessary electronics to transmit the collected information to a "gateway" through wireless communication. The gateway can process the collected data and send it to the cloud server where the "Information Management System (IMS)" to analyse the data in real time or for statistical analysis.

- Structure of WSN
  A WSN consists of three different subsystems to build a network. They are called the nodes, the gateway and the Information Management System (IMS).

- Sensor Node
  It is also called sensing system with low cost, size, and low power consumption, sensor, which can be able to get an appropriate measurement from the environment, processing the measured data and sending them directly to the cloud server over the gateway. It consists of the following elements:
  Microcontroller Based System: This is the core of the sensing node, which will be low cost, size, low-power consumption, and low-size chip. Unfortunately, it is challenging to get all these features due to certain constraints, especially if computer power and memory are considered.
  Power Supply Unit: Sensor nodes require a self-directed operational system, which can provide continuous power to run the system all day around. Sensor nodes always are contingent heavily on the power supply unit or power management unit.
  Wireless Communication Network: The WSN network will permit the required communication between the gateway and sensor nodes. They are made of specific standard protocols which have different coverage regions, power consumptions and suitable for different applications.
  Sensors: The sensor node also consists of sensors that convert the external physical parameter from surroundings into an electrical signal to allow the microcontroller to process the filter out data and sending the data during transmission [5].

- The Gateway
  The gateway is also called the "base station" of a WSN network. It is the core of the network, collects data from the smart sensor node, processes and helps to forward to store the data to a cloud server. It also has a computing system, which is based on high power microcontroller or high computing ability. It had to be static and plugged into the main power supply, as it requires more energy than the sensor nodes. It also should have the ability of a wireless communication system that is utilised through the sensing nodes. The gateway guides the collected data to the cloud server through Ethernet, WiFi, and 3G/4G, etc.

- Cloud Server
  A cloud server is the last component of a WSN network. It contains a database, suitable management software for implementing cloud computing and visualise

the processed data for end users. It might be located in a remote computer or any other gateway. Convenient users can get access to the management software through the internet.

- LoRaWAN Protocol for IoT
  LoRaWAN (Long range, low power Wireless Area Network) is a data-link layer with extended range, low power, and low bit rate, which is a promising solution for IoT application. LoRa enabled sensor node consumes low energy and transmit few bytes, which is an admirable candidate for being used in many different applications, such as smart cities, smart health care, industry, environmental monitoring, etc. There are two distinct layers: (i) a physical layer, based on radio modulation and also called CSS (Chirp Spread Spectrum); and (ii) a MAC layer protocol which is responsible for getting the access in LoRa architecture [5]. LoRa modulation has the same characteristics of FSK (Frequency Shifting Keying) regarding communication range in between gateway and sensor node. Thus, LoRaWAN is considered as the network architecture, and communication protocol although LoRa supports the long-range link. Battery life, security, the network capacity, the Quality of Service, and reliability of the node are determined by the architecture of the network and the defined protocol [6].

- Energy Harvesting
  Sensor nodes can be rarely connected to a fixed power supply; instead, they are the independent, autonomous system with energy harvesting capability. Their consumption of energy must be limited which can be achieved by low-consumption operating modes. Therefore, rechargeable batteries are always used in WSN application with the smart mechanism. For some applications, it is also essential to have a facility to collect the required energy from the environment. These are called energy harvesting technique [7]. Energy sources should be clean and environment-friendly. There are different energy sources are available, such as fluid flows, vibrations, electromagnetic fields, and so on. However, the most used energy source for WSN application is photovoltaic panels or solar panels. The solar panels convert the light source (sunlight or artificial light) into electricity. The battery can store the converted electricity and utilise the energy when there is no sun, such as cloudy day or night. Sensor nodes and smart systems should run cleverly to prolong the battery life and therefore, energy harvesting is an essential factor in WSN application.

7.4 Experimental Setup

- Electrochemical Impedance Spectroscopy (EIS)
  Electrochemical Impedance Spectroscopy (EIS) is a highly sensitive method for impedance measurement. There are various methods available to measure the impedance, but Frequency Response Analyzer (FRA) is considered the de facto standard for EIS measurement. FRA requires a small AC voltage with the ampli-

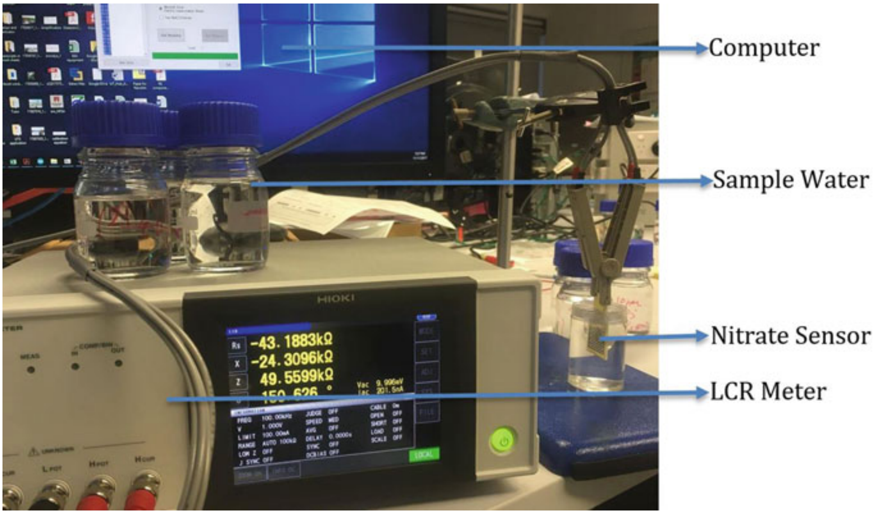

Fig. 7.3 EIS measurement in laboratory conditions

tude of 5–15 mV and frequency of the signal sweeps in a certain range on a direct current (DC) bias voltage. The signal provided on the positive electrode or the working electrode and changed voltage is taken from the negative electrode or sensing electrode. Due to the different characteristics of the different materials, their impedance profile is different, and the following equation presents the impedance:

$$\boldsymbol{Z} = \boldsymbol{R} + j\boldsymbol{X} \tag{7.1}$$

where **Z** is the total impedance (Ω), R is the real part of the impedance (Ω), and X is the imaginary part of the impedance (Ω). The profile of impedance can be characterised graphically which is called a Bode plot or Cole-Cole plot. The FR4 interdigital sensor was characterised by Hioki IM 3536 LCR meter where the frequency swept from 10 Hz to 100 kHz. Standard laboratory temperature and humidity were maintained throughout these experiments. 1, 10, 20, 30, 40 ppm nitrate solution was taken as a standard solution. Deionised water was measured as a control solution. The average pH of the solution was 6.71, which is also preserved in the creek water. Figure 7.3 shows the laboratory setup for the acquisition of data during EIS measurement. Initially, the sensor was characterised to get the impedance profile to develop the calibration standard for nitrate measurement. All the experiments were repetitive for five times to observe the impedance behaviour, and average results were calculated.

- Description of the System
  Figure 7.4 shows the smart sensing system which is proposed to carry out the in-line nitrate analysis. Figure 7.5 illustrates the circuit diagram of the developed system.

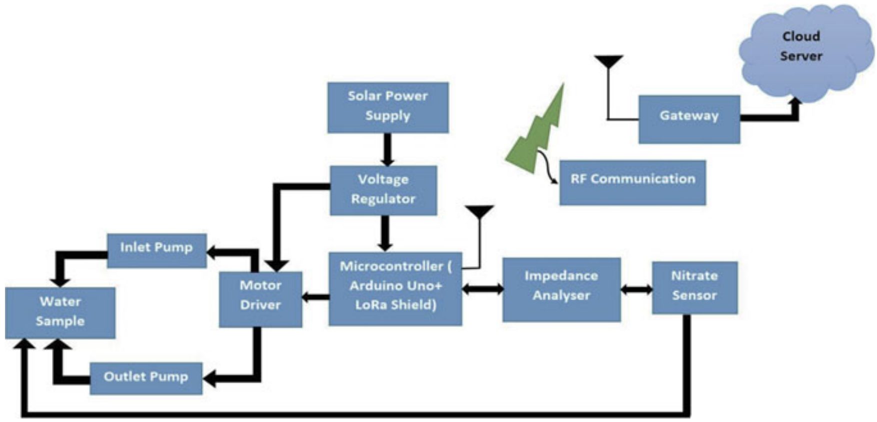

Fig. 7.4 Block diagram of the data transmission

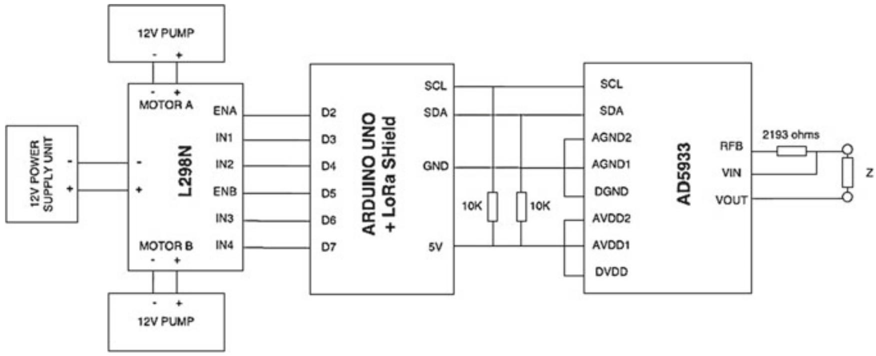

Fig. 7.5 Circuit diagram of the proposed sensing system

Arduino Uno and Arduino Uno Wi-Fi [8] was used as the main microcontroller. An AD5933 [9] is an impedance analyser which has been used to get the impedance data from the sensor. It gets the information in terms of impedance and the phase shift of the sensor. It also can sweep the frequency and gets the corresponding impedance profile, but it is not required in the current application. The operating frequency of the sensor was fixed, and each measurement is taken five times.

A Dragino LoRa shield is required as a remote transceiver to transmit the data to the gateway or receiving the data from the gateway. It allows reaching and sending data to an extremely long-range with low data rates. It is based on the RFM95W/RFM98W [10] and used for 915 MHz transmission/reception. An L298N [11] is a motor drive controller to control the inlet pumps and outlet pumps of the system. The inlet pump is used to bring the water into the reservoir, and the outlet pump is used to empty the reservoir after the measurement.

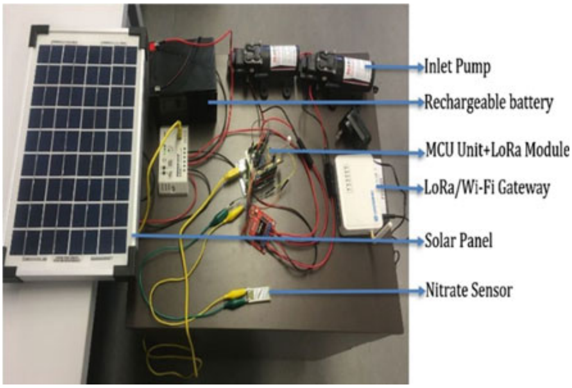

Fig. 7.6 Different parts of the proposed system

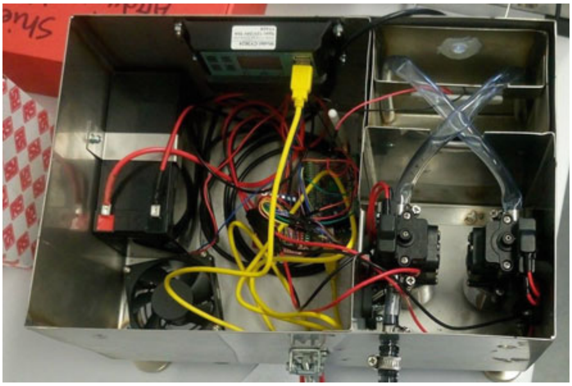

Fig. 7.7 Inside of the sensor node

LG01S [12] is used as the LoRa/Wi-Fi gateway to communicate between the sensing node and the cloud server. The gateway is also responsible for sending the data to the cloud server. Thingspeak is an IoT-based cloud server, which is free to use and can easily store data. It has been used to store all the real-time data which were collected from the sampling field.

Both the WiFi and the LoRa communication protocols were used to observe the resilience of the sensor nodes. The Arduino Uno WiFi contains a WiFi module, which is accountable for transmitting and receiving data through the WiFi gateway. An LG01S is also used which is used as a WiFi gateway. All the microcontrollers, sensors, rechargeable battery, inlet and outlet pumps, solar water reservoir, and charge controller are constrained in a steel enclosure, which is robust and more comfortable to install. Figure 7.6 indicates the materials, which are used in the sensing node. Figure 7.7 shows the inside of the steel box.

- Energy Harvesting Technique

  A solar panel (Model: ZM-9051), a sealed rechargeable battery (12 V, 12AH), and a solar charge controller (MP-3750) were used to deliver continuous energy without any human involvement. The proposed system is controlled from the microcon-

Fig. 7.8 Field installation of the smart sensor node

troller in numerous operational modes (active, sleep, transmitting/receiving) in all through the day. The steel enclosure was designed for housing all the electronics and the reservoirs. The steel structure was robust and more accessible to install in any sampling locations.

A VERT900 omnidirectional antenna was used as an external antenna and extended through the steel enclosure. Finally, it was installed to close to the study location as per Fig. 7.8.

- Study-Location
  A small creek is available inside the Macquarie University campus and located as a study location. As it is seen from Fig. 7.9, the sensor node is situated 340 m away from the gateway. There should be a clear line-of-sight between the sensor node and the gateway to avoid any obstacle during the data transmission. The blue marker in the map designates the gateway location, and the green marker designates the sensor node's location.

7.5 Results and Discussions

- EIS Measurement of the Concentrations of Nitrate
  The real and imaginary impedances for concentrations of nitrate samples are measured during an EIS measurement and plotted as Fig. 7.10. It is seen from Fig. 7.10 that the change of impedance of various concentrations of 1, 10, 20, 30, and 40 ppm are different from each other due to the different dielectric properties of the samples. When the concentrations of nitrate are different, the number of ions for also different and eventually their dielectric properties are also different. Therefore, when the sensing area dipped inside the water samples, the electric field from the positive electrode bulges through the ions in the aqueous medium towards

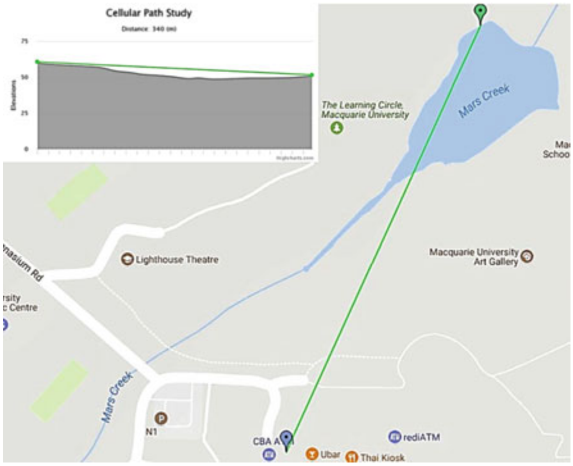

Fig. 7.9 Study location and distance between the gateway and the sensor node

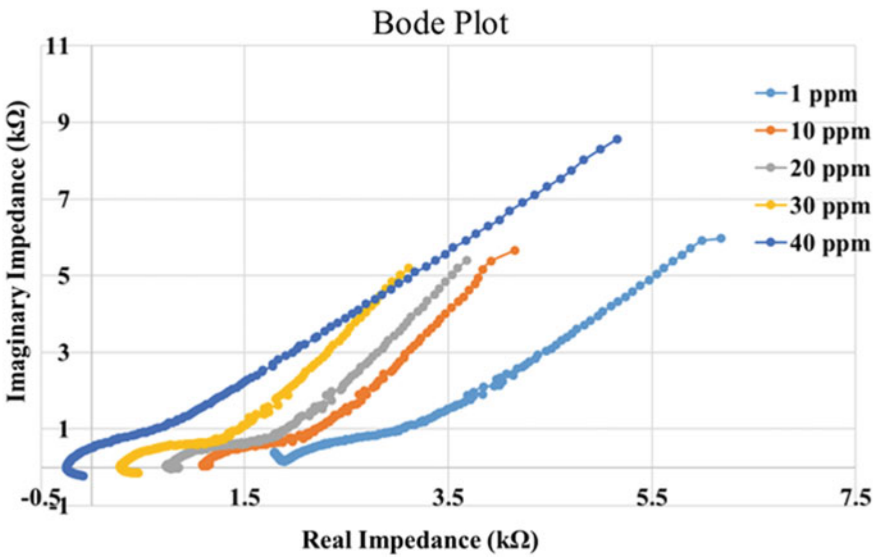

Fig. 7.10 Bode plots for different nitrate concentrations

the negative electrode. The resultant impedance behaviours are different, which is reflected in the bode plot [13–15].

The real impedances and imaginary impedances are plotted concerning frequency, and it is to be noted that the real impedance has a substantial change, contrasting the imaginary impedance. The change is unchanging and steady when the frequency is more than 500 Hz.

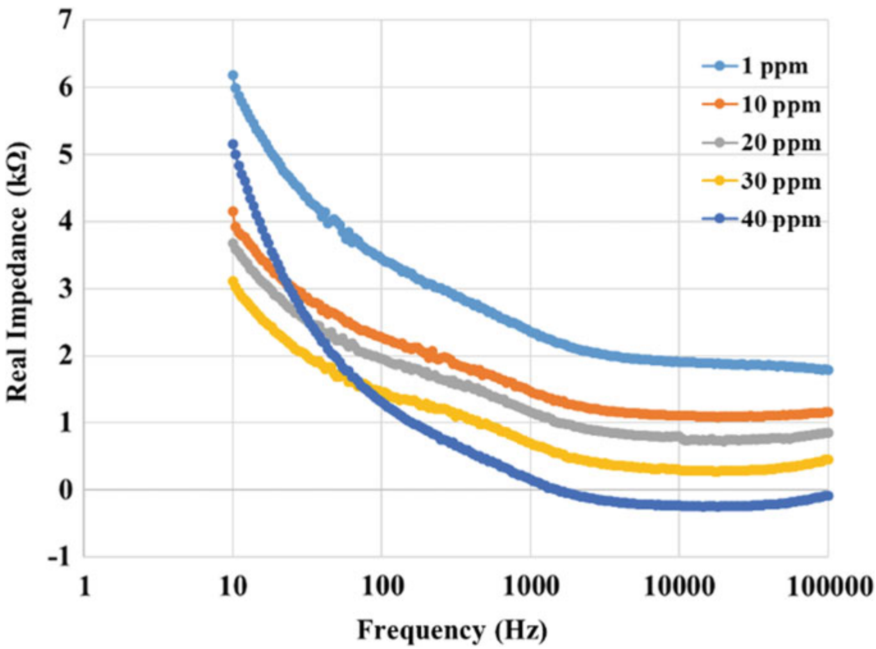

Fig. 7.11 Frequency versus real impedance for different nitrate concentrations

- Calibration Standard

  It is seen from Fig. 7.11 that the sensitive region for various concentrations is from 500 Hz to 100 kHz. There is a noteworthy change in the real impedance in that frequency range for different nitrate concentrations. 1000 Hz is preferred as the operating frequency to progress a calibration standard to measure any unidentified water samples which contain nitrate. At 1000 Hz, the real impedance of 1, 10, 20, 30, and 40 ppm of nitrate concentrations was used to grow a calibration standard to measure an unknown concentration. It is seen from Fig. 7.12 that the various nitrate concentrations are plotted on the x-axis and the analogous real impedances are plotted on the y-axis. They follow a linear straight line, and the regression coefficient is $\mathbf{R^2 > 0.98}$, which is satisfactory to calculate an unknown impedance and unknown nitrate concentrations from any water samples. It also means that the actual impedance and predicted impedance are close to each other.

  Therefore, the calibration standard for an unknown sample concentration is:

$$C = \frac{R - 2212.3}{-51.77} \tag{7.2}$$

  where C is the concentration (ppm) and R (Ω) is the measured real impedance from an unknown sample. It is calculated that the sensitivity of the sensor is **−51.77 Ω/ppm**.

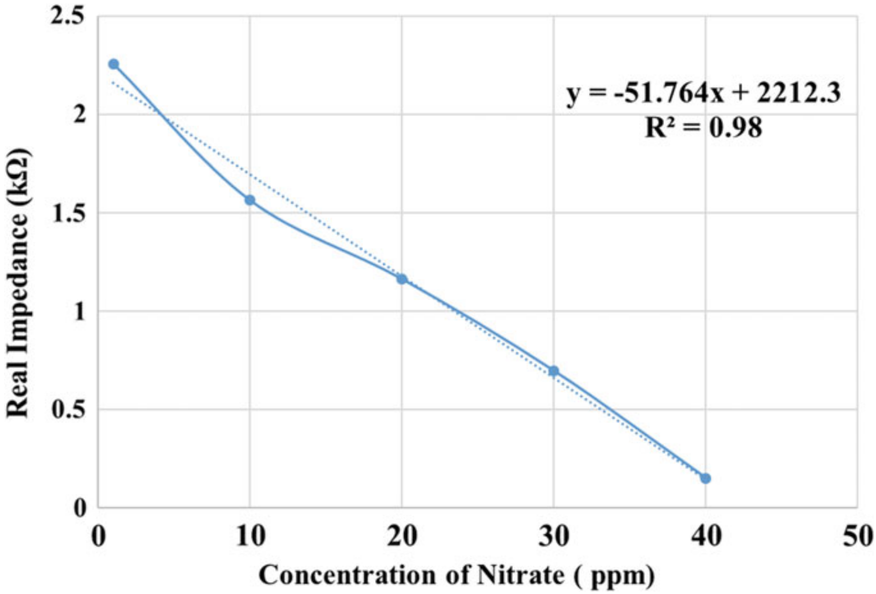

Fig. 7.12 Calibration standard to measure any unknown nitrate concentration

- Unknown Sample Measurement
  Various sample waters are collected from various sampling locations, such as river, lake, stream, tap water to consider measuring unknown samples. Unsurprisingly, the nitrate concentration was not high enough to measure the range to high concentrations. Therefore, a certain amount of nitrate sample was added to uplift the nitrate concentration. The proposed FR4-based sensor and smart sensing system were used to measure the concentration of nitrate and compared with the standard laboratory method. Equation 7.2 was used to measure the real impedance which is used to calculate the unknown nitrate concentrations. It is observed from Table 7.1 that the sensor and the proposed system can measure the concentration of nitrate with an error of less than 5%. When the nitrate concentrations are on the upper limit, the error is smaller than with lesser nitrate concentrations.
- Data Transfer to Cloud Server
  It is seen from Fig. 7.13 that the measured concentration of nitrate was transferred from the sampling field location during the on-field trial. Seven days of sampling data were collected without any disruption and the sampling time was 13 min. The sampling time is easily controllable through software programming, though this was a very dense data collection. 112–113 batches of on field sampling data could be collected with sampling every 13 min in 24 h, Table 7.2 shows the average concentration of nitrate and compares the data with standard laboratory measurements. The sample water was collected from the creek in every morning, afternoon and evening, and measured in the laboratory immediately. In a single

Table 7.1 Unknown sample measurement compared to laboratory standard method

Sample number	Smart sensing node (ppm)	UV-spectrometry method (ppm)	Error (%)
1. River water[a]	15.6	15.8	1.27
2. Tap water[a]	26.4	26.97	2.11
3. Canal water[a]	35.45	36.01	1.56
4. Stream water[a]	8.65	8.7	0.57
5. Creek water	2.01	2.1	4.29

[a]The nitrate concentrations are elevated for these samples

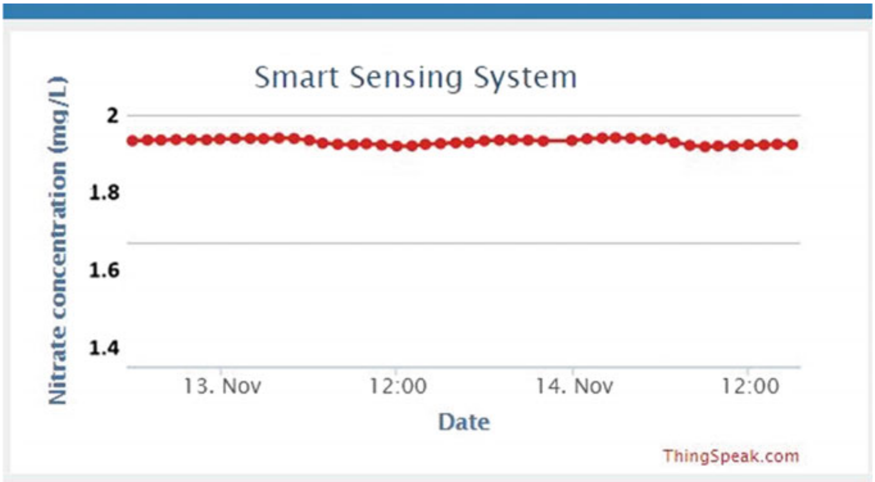

Fig. 7.13 Nitrate concentration is Thingspeak server

day, the sampling water was collected and measured in the laboratory to maximise accuracy. It was evident that the sampling frequency of collecting the sample water manually will not be analogous to the developed smart system. It is also observed that the measurement error (less than 5%) of the sampling data from the developed system is close to the laboratory measurement. A similar graph is also seen in Fig. 7.14.

Figure 7.15 illustrates the single-day nitrate concentrations for each sample time. It is varied between 1.8 and 1.9 ppm while the average concentration of nitrate of that single day was 1.9 ppm. Besides, a simple moving-average algorithm was used in the collected data to smooth the trend. The smoothed data can offer the trend of concentration of nitrate, which might be useful over a long time to monitor the nitrate concentration in real-time. The creek water does not carry an upper level of nitrate concentration as it is situated inside the Macquarie University

Table 7.2 Average concentration of nitrate of the study location compared with the laboratory standard method

Date	Smart sensing node (ppm)	UV-spectroscopy method (ppm)	Error (%)
8th Nov 2017	1.72	1.75	1.71
9th Nov 2017	2.01	1.95	3.07
10th Nov 2017	1.86	1.88	1.06
11th Nov 2017	1.98	1.96	1.02
12th Nov 2017	1.95	1.97	1.01
13th Nov 2017	1.9	1.92	2.60
14th Nov 2017	1.91	1.89	1.05

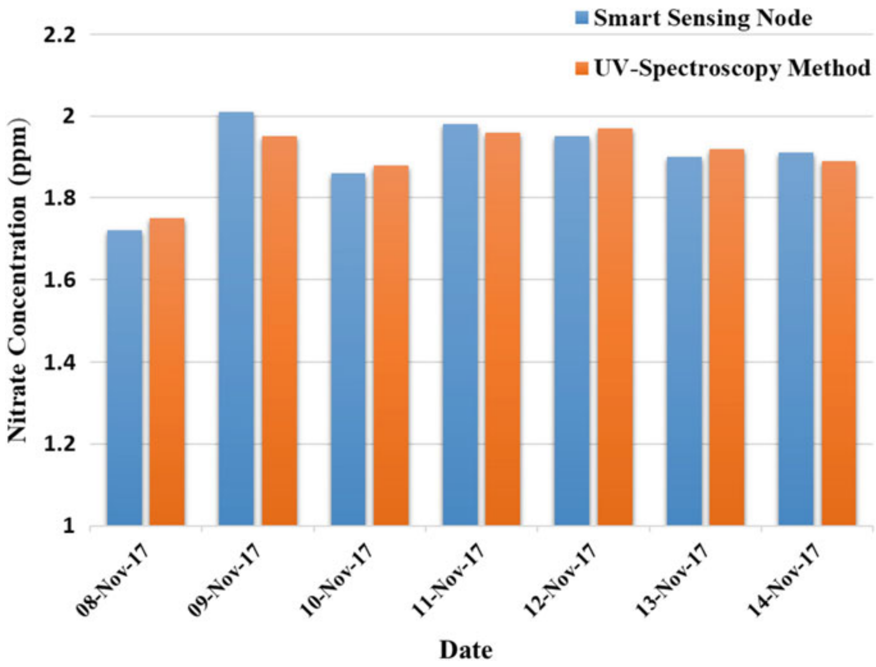

Fig. 7.14 Comparison of daily evolution of nitrate concentration with the standard method

and the management of the University regulates all kind of pollution (air, water, environment) very carefully.

- Comparison of Wi-Fi Protocol over LoRa protocol
  Electronic components for remote IoT applications must consume as little power as possible to maximise battery life. The difference of WiFi RF protocol over the LoRa protocol was to decrease total power consumption throughout sleep mode to less than half. It also permits data transmissions to penetrate various obstacles

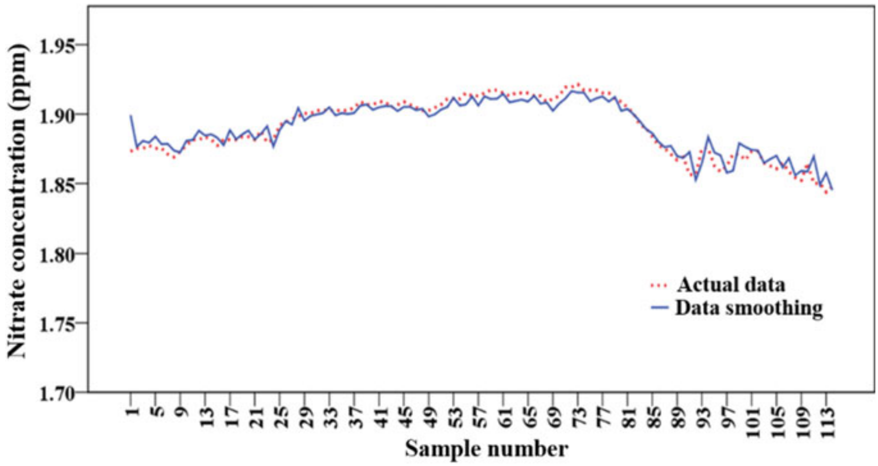

Fig. 7.15 Nitrate concentration of a single day

Table 7.3 Comparison of WiFi and LoRa based sensing system

Mode of operation	WiFi (per second)	LoRa (per second)	Per sample (13 min)
Arduino (5 V)			
Sleep	0.119 A	0.039 A	550 s
Motor 1 (inlet)	0.124 A	0.066 A	35 s
Motor 2 (outlet)	0.124 A	0.066 A	66 s
Impedance analyzer	0.124 A	0.046 A	18 s
Data transmission	0.124 A	0.095 A	10 s
Motor driver (12 V)			
Motor 1 (inlet)	1.8 A	1.8 A	35 s
Motor 2 (outlet)	1.8 A	1.8 A	66 s

and allows the collected data to travel more distances that are substantial whereas consuming a smaller amount of power than the standard WiFi protocol. The LoRa protocol optimises the exchange of data with the gateway, permitting for lower power consumption as compared to WiFi. The current consumption from each electronic component for each stage, linking WiFi and LoRa, can be detected in Table 7.3. It is observed that the current consumption for the LoRa protocol is less compare to WiFi, which helped to harvest the solar energy for an extended time. The energy consumption for inlet and outlet pumps and motor drivers are alike for both the systems. However, WiFi enabled systems to consume 2.22 times more energy than the LoRa enabled the system. Therefore, a LoRa enabled sensing system was proposed and trialled during the necessary field trial.

7.6 Chapter Summary

An IoT-enabled smart nitrate sensor and sensing system are proposed to monitor the concentration of nitrate in real-time. An FR4 interdigital capacitive sensor is characterised, and a calibration curve is developed to measure unknown sample from various sources of water. The system is self-governing and trialled in the field for seven days without any disruption. The LoRa protocol was used to run the system over more extended periods than for the WiFi protocol due to the power consumption variation. The LoRa protocol is a low-power energy-saving protocol, which is executed successfully. The proposed system's collected data were also validated through the standard UV-spectrometry method. The collected data displays that few data have lost throughout the transmission and 98% data are effectively collected through the gateway to the IoT based cloud server. The results show that the proposed smart sensing system can be beneficial to improve a WSN network to monitor the concentration of nitrate in real time. It also demonstrates that, without human help, changes of both time-based and spatial evolutions of the concentration of nitrate can be monitored successfully.

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