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An Internet-of-Things enabled Smart Sensing System for Nitrate Monitoring

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***Abstract*—Monitoring the nitrate concentration in the field is an excellent ability for a water-monitoring study. We report an Interdigital FR4-based capacitive sensor, which is characterized for nitrate concentration. The concentration range of nitrate is 0-40 ppm (mg/L). Different unknown samples were measured and validated with standard UV-Spectrometry. A smart sensing node has been developed which can collect water from a lake, stream, or river, measure the instantaneous nitrate concentration, and transfer the data through the gateway to a user-defined cloud server. The system is completely autonomous and solar powered, robust, and trialed in the field successfully. A simple moving-average algorithm is used to smooth the collected data in the cloud side. The LoRa protocol and WiFi protocol are compared in terms of power consumption. The proposed system is trialed in the field continuously and the result validated with standard UV-Spectrometry. The developed smart system can be easily deployable and friendly to use, and offers new possibilities for both spatial and temporal analysis for nitrate concentration.**

***Index Terms*— Internet of Things, interdigital sensor, sensing node, LoRa protocol, WiFi protocol, WSN, nitrate concentration, water monitoring.**

I. Introduction

Nitrogen is an important nutrient for plants and is contained in the building blocks of life, such as in nucleotides, amino acids, and proteins [1]. The excessive use of fertilizers, urination due to animal farming, and industrial waste are the significant reasons for nitrate leaching in water [2-7]. Excessive nitrate can hamper aquatic life and can lead to algal blooms and eutrophication [8]. According to the US Environmental Protection Agency (EPA), the maximum allowable nitrate concentration in drinking water should be 44.2 ppm. Over this range of concentration it would be considered as contaminated water [9].

The concentration of nitrate fluctuates in water, both spatially and temporally. It also depends on the season, weather conditions and the rainfall of any location. Currently, the regional council or local government collects water samples in a routine manner. This is done by expert staff at regular intervals to track the change of nitrate concentration [10]. However, data taken too seldom may not be adequate to measure the actual nitrate profile.

There are conventional standard methods available for nitrate measurement, such as UV/Vis spectrometry, chromatography, HPLC and capillary electrophoresis. They are unsuitable for creating a large-scale Wireless Sensor Network (WSN) due to their massive instrumentation, bulky features, complex and sensitive measurement procedure; and above all they are costly. They also produce lots of chemical waste which might be harmful to the environment [11].

A wireless sensor network (WSN) consists of a number of dedicated sensor nodes with physical sensing and computing abilities, which can sense and monitor the surrounding physical parameters. A WSN has a lot of essential characteristics and a few constraints, such as limited energy and computational power. During the last decades, WSNs have been widely used in different applications related to water monitoring [12-14], forests [15, 16], industrial [17, 18], and agricultural [19-22] . Some researches were reported [23-25] to monitor the nitrate concentration through the WSN network [26]. Their limitation was that most of them are laboratory based and perform the real-time analysis in the laboratory only. Juan V. Capella et al. [24] reported in-line analysis of nitrate concentration in river water and emphasized the feasibility of development of wireless sensor networks based continuous monitoring.

The Internet of Things (IoT) enables any physical objects to communicate through the internet and transfer data to a specific server for further processing. It requires pervasive computing, smart sensors, embedded devices, communication technologies, internet protocols and applications. IoT-enabled WSNs help to connect more objects for monitoring purposes to build up smart cities, smart industries, smart agriculture, etc.

In this paper, a low-cost interdigital FR4-based capacitive sensor is proposed for nitrate measurement. The developed sensor has been characterized and calibrated against standards to measure nitrate components. The measured results are validated against the standard UV-spectrometry method. A smart sensing node has been developed which is suitable for an IoT-enabled WSN. The sensing node collects water from stream or lake and measures the nitrate concentration. The collected water can be discharged automatically to stream or lake again. A solar panel is used for energy harvesting and provides the system with the necessary energy for monitoring

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continuously. The LoRa protocol is used to transfer the measured data, and saves energy. Finally, the measured data can be transferred to an IoT-based cloud server, which is free for the users. Cloud data is also analyzed further to identify the trend of nitrate fluctuation.

Section II explains the materials and methods, Section III explains the experimental setup and study location, Section IV explains all the collected results and discusses them. The last section has conclusions from the present work and suggestions for future work.

II. Materials and Methods

A. Working principle of interdigital sensor

The operating principle of the planar interdigital sensor [27] is similar to that of two parallel-plate capacitors, and the electrodes open up to one side to provide a one-sided access to the material under test (MUT) [27]. The generated electric-field lines penetrate into the MUT and the impedance of the sensor will change. As a result, the impedance of the sensor becomes a function of the system properties. Therefore, the system properties can be evaluated by measuring the impedance of the sensor.

The term “interdigital” refer to a digit-like or finger-like periodic pattern of parallel electrodes which helps to build up the impedance associated with the provided electric field that penetrates into the material sample [27]. An excitation alternating-current (AC) voltage is applied between the positive terminal, and the negative terminal, and the electric field forms from the positive terminal to the negative terminal. Fig. 1 indicates the evolution of an interdigital sensor towards a one-sided measurement. Interdigital sensors have been used in different applications for domestic and industrial applications [21, 28, 29].

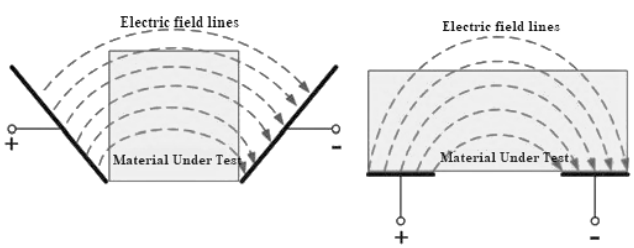

Figure 1: Electric field lines of parallel-plate capacitor and planar interdigital sensor

Fig. 2 shows the FR4 interdigital sensor used in the proposed sensing system and Fig. 3 shows its equivalent circuit. R_p represents the conductive properties of the sample water which is under the effect of an electric field. It also explains the resistive nature of the sample water. C_p represents the capacitance of the sample water to be measured. The fabrication process is similar to the process used to develop a printed circuit board (PCB). Electrodes are made from copper which is a good conductor. The dimensions of the sensing area are 33mm× 17mm, which is easy to dip in to water. Tin oxide is layered as a coating material on the copper electrodes to keep them corrosion free.

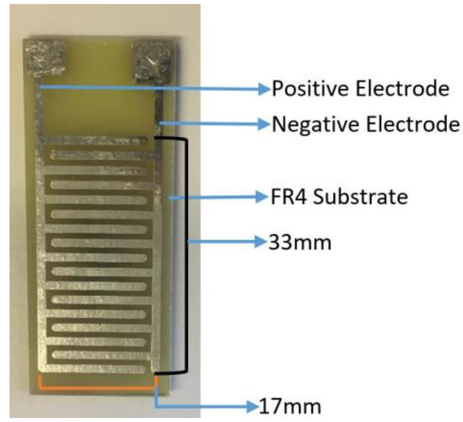

Figure 2: FR4 interdigital sensor and dimensions

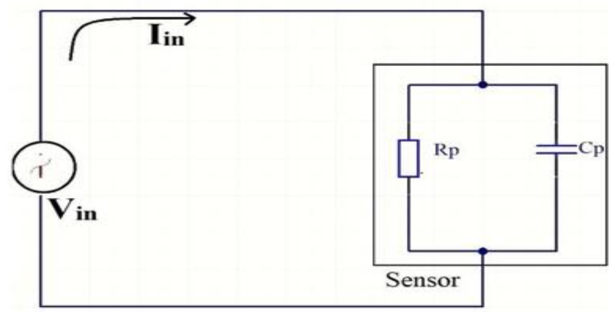

Figure 3: Equivalent circuit of Interdigital sensor

B. Wireless Sensor Networks (WSNs)

A WSN is formed from a number of small sensing systems, named sensing nodes, that collect information from the surroundings through sensors. The sensing systems transmit the collected information to a “gateway” through wireless communication. The collected data can be handled by the gateway and sent to the cloud server where an “Information Management System (IMS)” analyzes the data in real time or for statistical analysis.

C. Structure of WSN

A WSN consists of three different subsystems. They are the nodes, the gateway and the Information Management System.

1) Sensor node

This is also called a sensing system with a low-cost, small low-power sensor, which can get appropriate measurements from the environment, process the measured data, and send them directly to the cloud server through the gateway. It consists of the following elements:

- Microcontroller-based system: This is the core of the sensing node, which will be a low-cost, small, low-power chip. Unfortunately, it is difficult to get all these characteristics due to certain limitations, especially regarding the computer power and memory.
- Power Supply Unit: Sensor nodes require an autonomous functioning system, which can provide

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continuous power to run the system all day round. Sensor nodes always depend heavily on the power supply unit.

- Wireless Communication Network: This network will allow the necessary communication between the sensor nodes and the gateway. They use certain standard protocols which have different coverage regions, power consumptions and suitability for different applications.
- Sensors: The sensor node also contains sensors, which convert the physical parameter into an electrical signal to allow the microcontroller to process the filtered output data and send the data during transmissions.

2) The Gateway

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

3) Cloud Server

This is the last component of a WSN network. It consists of a database and suitable management software. It might be located in the gateway or any other remote computer. Users can get access to the management software through the internet.

D. LoRaWAN Protocol for IoT

LoRaWAN (Long-range, low-power Wireless Area Network) is a data-link layer with long range, low power, and a low bit rate, which is a promising solution for IoT applications. A LoRa-enabled sensor node consumes low energy and transmits only a few bytes, and so is an excellent candidate for use in many different applications (such as smart health care, smart cities, environmental monitoring, industry, etc.). There are two distinct layers: i) a physical layer, based on radio modulation called CSS (Chirp Spread Spectrum); and ii) a MAC-layer protocol which is responsible to get access in LoRa architecture [30]. LoRa modulation has the same characteristics as FSK (Frequency Shift Keying) regarding the communication range in between gateway and sensor node. Thus, LoRaWAN is considered as a communication protocol and network architecture, while LoRa supports the long-range link. The node's battery life, the network capacity, the QoS (Quality of Service), security and reliability are determined by the network architecture and the defined protocol. It also supports virtualized wireless networking technologies, where all base stations work together and are collectively seen by the sensor nodes [30].

E. Energy Harvesting

Sensor nodes are rarely connected to a fixed power supply; rather they are an independent, autonomous system with an energy-harvesting capability. Their energy consumption must be limited, which can be achieved by having low-consumption operating modes. Therefore, chargeable batteries are always used in WSN applications with smart modes (sleep, active). For some applications, it is also required to have a provision to collect the required energy from the environment. These are called energy-harvesting techniques [31]. Energy sources should be clean and environmentally friendly. Different energy sources are available, such as fluid flow, vibration, electromagnetic fields, and so on. However, the most-used energy source for WSN applications is photovoltaic panels or solar panels. The solar panels convert light (sunlight or artificial light) into electricity. Batteries can store the converted electricity and utilize the energy when there is no sunlight, such as on cloudy days or at night. Sensor nodes and systems should run cleverly to extend the battery life, and therefore energy harvesting is an important factor in WSN application.

III. Experimental Setup

A. Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) [32-34] is a highly sensitive method for impedance measurement. There are many methods available to measure impedance, but a Frequency Response Analyzer (FRA) is considered the de facto standard for EIS measurements. FRA requires a small AC voltage with an amplitude of 5-15 mV, and the frequency of the signal sweeps in a certain range based on a direct-current (DC) bias voltage. The signal is connected to the positive electrode, or the working electrode, and a changed voltage is taken from the negative electrode, or sensing electrode. Due to the different characteristics of different materials, their impedance profile is different and the following equation represents the impedance:

$$Z = R + jX \tag{1}$$

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

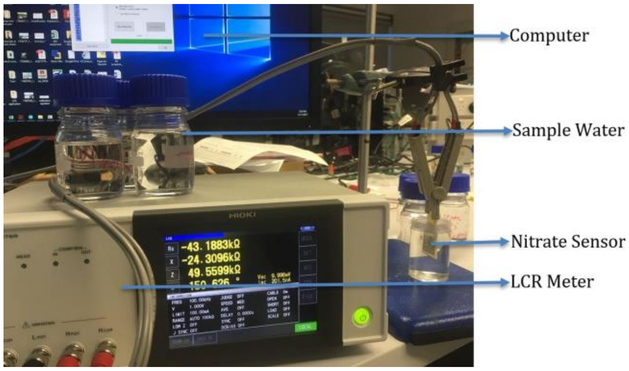

Figure 4 : EIS measurement in laboratory conditions

(Ω). The impedance profile can be represented graphically with what is called a bode plot or Cole-Cole plot. The FR4-

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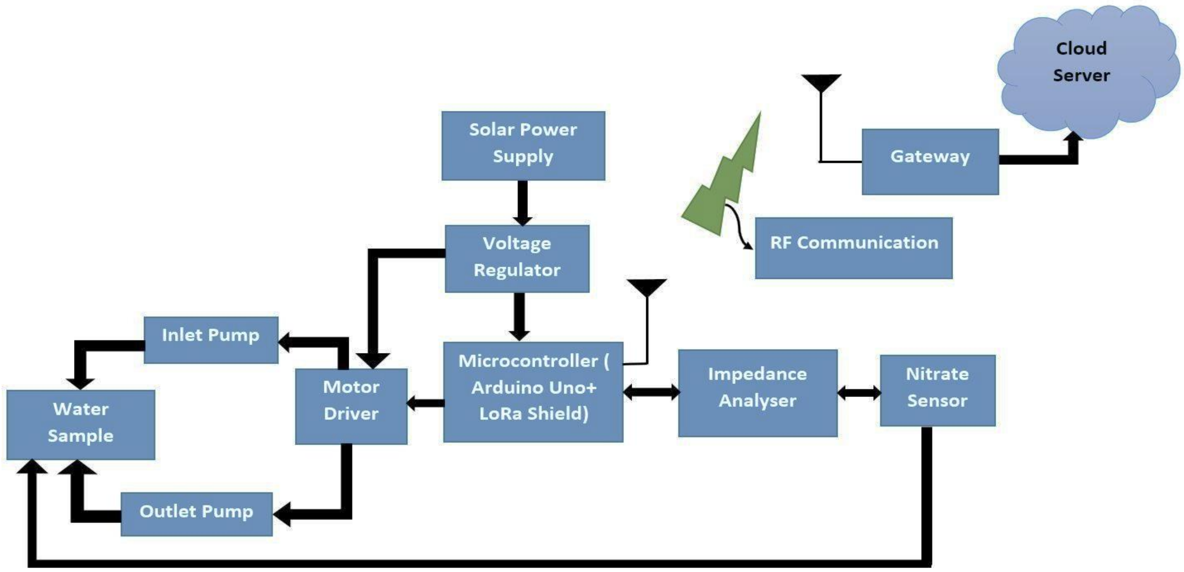

Figure 5: Block diagram of the data transmission

based interdigital sensor was characterized by a Hioki IM 3536 LCR meter where the frequency was swept from 10 Hz to 100 kHz. Standard laboratory temperature and humidity was maintained throughout these experiments. 1, 10, 20, 30, 40 ppm nitrate solutions were taken as standard solutions. Deionized water was taken as a control solution. The average pH of the solution was 6.71, which is also maintained in creek water. Fig. 4 shows the laboratory setup for EIS data acquisition. Initially the sensor was characterized to get the impedance profile to develop the calibration standard for nitrate measurement. All experiments were repeated five times to observe the impedance behavior, and average results were calculated.

B. System Description

A smart sensing system is proposed to carry out the in-line nitrate analysis as per Fig. 5. Fig. 6 shows the circuit diagram of the developed system. Arduino Uno and Arduino Uno Wi-Fi [35] was used as the main microcontroller. An AD5933 [36] is used to get the impedance data from the sensor. The impedance analyzer gets the impedance and the phase shift of the sensor. The impedance analyzer has the ability to sweep the frequency, which is not required in the current application. The operating frequency is fixed and each measurement is done five times. Only the average nitrate concentration is sent to the IoT cloud server.

A Dragino LoRa shield is used as a long-range transceiver to communicate with the gateway. It allows sending data and reaching an extremely long range with low data rates. It is based on the RFM95W/RFM98W [37] and used for 915 MHz transmission/reception. An L298N [38] is used as a motor driver to control the inlet and outlet pumps. The inlet pump brings the water into the reservoir and the outlet pump empties the reservoir after the measurement.

LG01S [39] is used as the LoRa/Wi-Fi gateway to communicate between the sensing node and the cloud server. The gateway is also responsible to send the data to the cloud server. Thingspeak is used as an IoT-based cloud server, which is free to use and can easily store data.

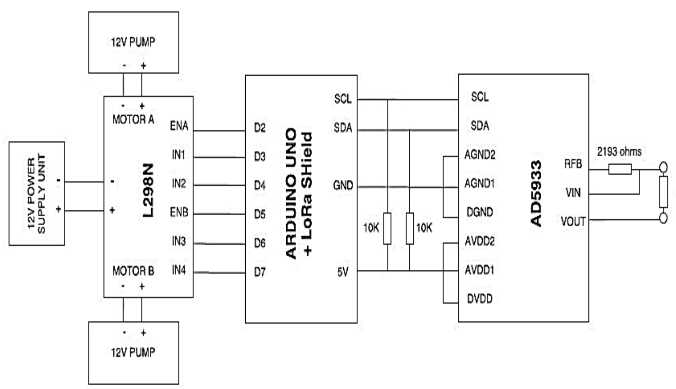

Figure 6: Circuit diagram of the sensing system

WiFi and LoRa, both communication protocols, were used to examine the durability of the sensor nodes. The Arduino Uno WiFi has a WiFi module, which is responsible for transmitting and receiving data through the gateway. An LG01S is also used as a WiFi gateway. All the microcontrollers, sensor, inlet and outlet pumps, rechargeable battery, solar charge controller, and water reservoir are contained in a steel box which is robust and easy to install. Fig. 7 indicates the materials which are used in the sensing node. Fig. 8 shows the inside of the steel box.

C. Energy-harvesting technique

A solar panel (Model: ZM-9051), solar charge controller (MP-3750), and a sealed rechargeable battery (12V, 12AH) were used to provide energy continuously without any human intervention. All through the day the system is controlled from the microcontroller in various operation modes (active, sleep, transmitting/receiving). Due to the steel structure, the microcontroller had some difficulty communicating with the

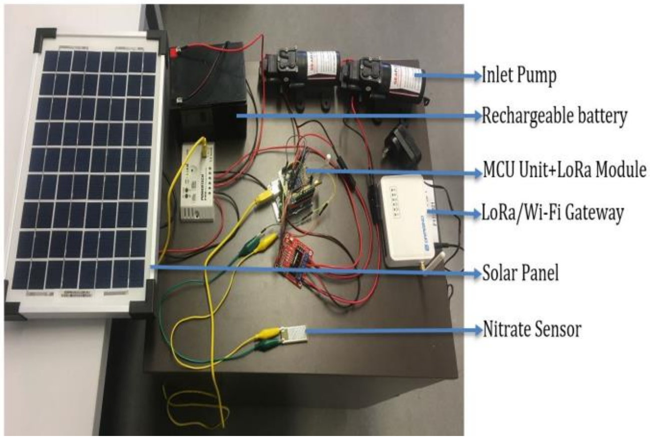

Figure 7: Different parts of the proposed system

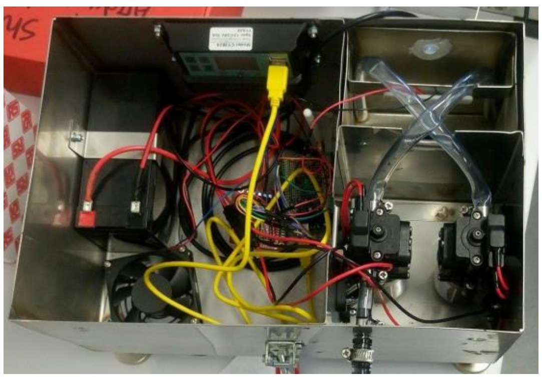

Figure 8: Inside of the sensor node

gateway to send the data from the sensor node with the existing antenna. Therefore, a VERT900 omni-directional antenna was used and extended through the steel box. Finally, it was installed near the study location as per Fig. 9.

Figure 9: Field installation of the smart sensor node

D. Study Location

The study location is in Macquarie University near a small creek. As is seen from Fig. 10, that sensor node is installed 340 m from the gateway. The gateway is installed in such a way that the sensor node has a clear line of sight and there is no obstacle to data transmission. The blue marker in the map indicates the gateway location and the green marker indicates the sensor node's location.

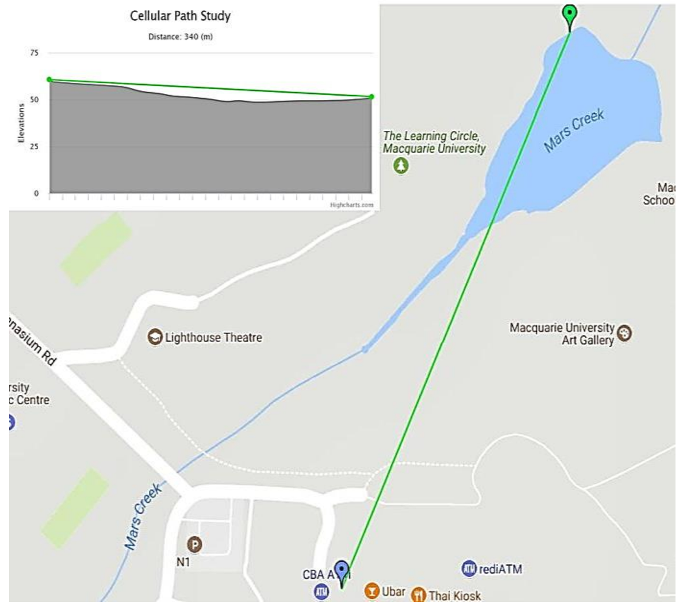

Figure 10: Study location and distance between gateway and the sensor node

IV. Results and Discussion

A. EIS Measurement for Nitrate Concentrations

The impedances of different concentrations of nitrate sample are measured during an EIS measurement and plotted as Fig. 11. It is seen that the bode plots for concentrations of 1, 10, 20, 30, and 40 ppm are different from each other due to the impedance change. The number of ions for different concentrations are different from each other. Therefore, the electric field from the positive electrode bulges through the ions in the aqueous medium towards the negative electrode. The dielectric properties of different concentrations are different,which is reflected in the bode plot [32-34].

The real impedance and imaginary impedance are plotted with respect to frequency, and it is noted that the real impedance has a significant change unlike the imaginary impedance. The change is stable and consistent when the frequency is more than 500 Hz.

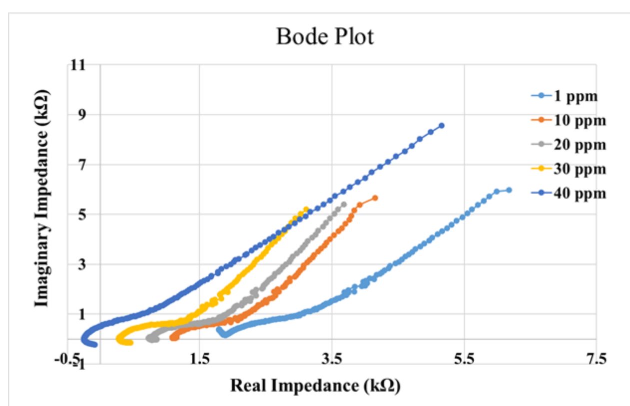

Figure 11: Bode plots for different nitrate concentrations

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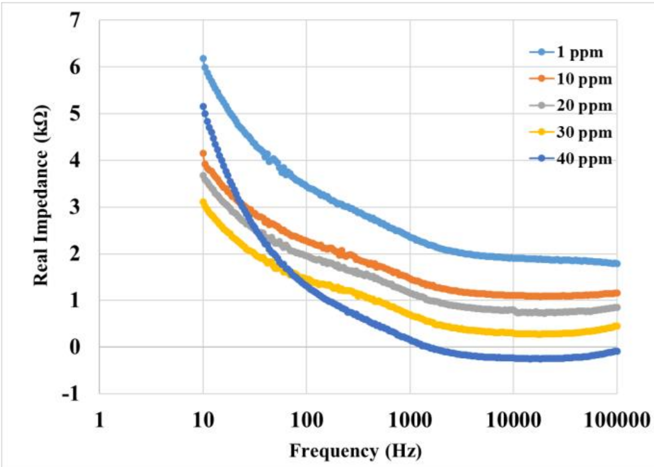

Figure 12: Frequency vs real impedance for different nitrate concentrations

B. Calibration Standard

It is seen from Fig. 12 that the sensitive region for different concentrations is 500 Hz to 100 kHz. There is a significant change in the real impedance in that frequency range for different nitrate concentrations. 1000 Hz is chosen as the operating frequency to develop a calibration standard to measure unknown nitrate concentrations. At 1000 Hz, the real impedances of 1, 10, 20, 30, and 40 ppm of nitrate concentrations were used to develop a calibration standard to measure any unknown concentration. From Fig. 13, it is seen that the nitrate concentrations are plotted on the x-axis and the corresponding real impedances are plotted on the y-axis. They follow a straight line, and the regression co-efficient is R^2>0.98, which is adequate to calculate any unknown impedance. It also means that the actual impedance and predicted impedance are close to each other.

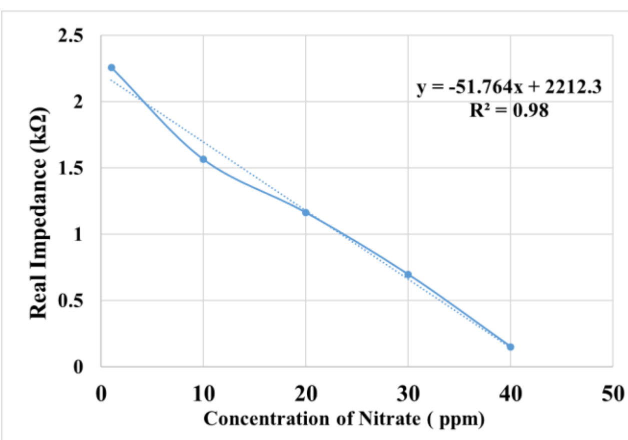

Figure 13: Calibration standard to measure any unknown nitrate concentration

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

$$C = \frac{R-2212.3}{-51.77} \tag{2}$$

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

C. Unknown sample measurement

To measure any unknown sample, different sample waters are collected from different sampling locations, such as river, lake, stream, tap water. Naturally, the concentration of nitrate was not high enough to measure the range to high concentrations. Therefore, a nitrate sample was added to elevate the concentration of nitrate. The FR4-based sensor and sensing system were used to measure the nitrate concentrations and compared with the laboratory standard method. Equation 2 was used to measure the unknown nitrate concentrations. It is observed that the sensor and the developed system can measure the nitrate concentration with an error of less than 5%. When the concentrations are on the higher side, the error is smaller than with lower nitrate concentrations.

Table 1: Unknown sample measurement compared to laboratory standard method

Sample Number	***Smart Sensing node (ppm)***	***UV-Spectrometry method (ppm)***	***Error (%)***
1. River Water*	15.6	15.8	1.27
2. Tap Water*	26.4	26.97	2.11
3. Canal Water*	35.45	36.01	1.56
4. Stream Water*	8.65	8.7	0.57
5. Creek Water	2.01	2.1	4.29

*** The nitrate concentrations are elevated for these samples.**

D. Data transfer to cloud server

It is seen from Fig. 14 that the measured nitrate concentration was transferred from the field location during the field trial. Seven days of sampling data are collected without any interruption and the sampling time was 13 minutes. Though this was a very dense data collection, the sampling time could be easily controlled through the software programming. In 24 hours, 112-113 batches of sampling data could be collected with sampling every 13 minutes. Table 2 shows the average nitrate concentration and compares the data with laboratory measurements. Every morning, afternoon and evening, the sample water was collected from the creek and measured in the laboratory immediately. In a single day, the sampling water was collected and measured in the laboratory to maximize the accuracy. It is obvious that the sampling frequency will be not be similar to the developed smart system. It is also observed that the error (less than 5%) of the sampling data from the

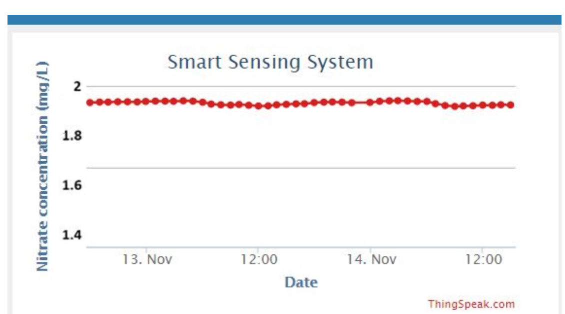

Figure 14 : Nitrate concentration is *Thingspeak* server

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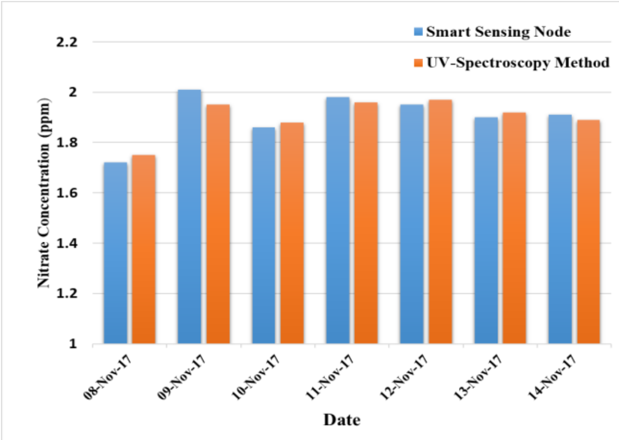

Figure 15: Comparison of daily evolution of nitrate concentration with standard method

developed system is close to the laboratory measurement. A similar thing is also seen from Fig. 15.

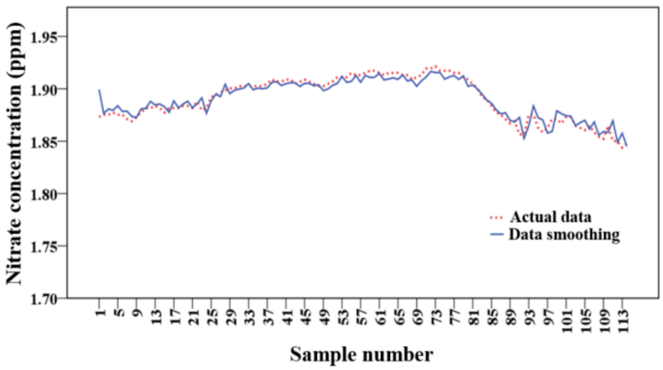

Figure 16: Nitrate concentration of a single day

Fig. 16 illustrates the single-day nitrate concentrations for each sample time. It varied between 1.8 and 1.9 ppm while the average nitrate concentration of that single day was 1.9 ppm. In addition, the collected data have been smoothed with a simple moving-average algorithm. The smoothed data can provide the trend of nitrate concentration, which might be useful over a longer time. The creek does not carry a high level of nitrate concentration as it is located inside the University and the administration of the University control all kind of pollution (air, water, environment) very carefully.

Table 2: Average nitrate concentration of the study location compared with 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

E. LoRa protocol over Wi-Fi protocol

Components for remote IoT applications must draw as little power as possible to maximize battery life. The difference of The LoRa protocol over the WiFi RF protocol was to reduce overall power consumption during sleep mode to less than half. It also allows transmissions to penetrate obstacles and allows the data to travel larger distances whilst consuming less power than the standard WiFi protocol. It optimizes the data exchange with the gateway, allowing for lower power consumption as compared to WiFi. The current drain from each component for each stage, comparing WiFi and LoRa, can be observed in Table 3. It is observed that the LoRa protocol is consuming less current, which helped to harvesting the energy for longer time. The consumption of energy for pumps and motor drivers are similar for both the system. However, WiFi enabled microcontroller consumes 2.22 times more energy than the LoRa enabled microcontroller. Therefore, a LoRa enabled sensing system was used to do the necessary field trial.

Table 3: Comparison of WiFi and LoRa driven sensing system

Mode of Operation	*WiFi (per second)*	*LoRa (per second)*	*Per Sample (13 mins)*
Arduino (5V)			
Sleep	0.119A	0.039A	550s
Motor 1 (Inlet)	0.124A	0.066A	35s
Motor 2 (Outlet)	0.124A	0.066A	66s
Impedance Analyzer	0.124A	0.046A	18s
Data Transmission	0.124A	0.095A	10s
Motor Driver (12V)			
Motor 1 (Inlet)	1.8A	1.8A	35s
Motor 2 (Outlet)	1.8A	1.8A	66s

V. CONCLUSION AND FUTURE WORK

An IoT-enabled smart nitrate sensor and sensing system is proposed to monitor the nitrate concentration in real-time. An FR4-based interdigital sensor is characterized and is extremely useful for robust use during nitrate monitoring. The system is autonomous and was trialed in the field for seven days without any interruption. The LoRa protocol was used to run the system over longer periods than for the WiFi protocol. The LoRa protocol is a low-power energy-saving protocol, which was implemented successfully. The system's collected data were also validated through the UV-spectrometry method. The collected data shows that few data have been lost during transmission, and 98% of data are successfully collected through the gateway to the cloud server. The results show that the proposed smart sensing system can be very useful to develop a WSN to monitor nitrate concentration in real time. It also shows that, without human interaction, changes of both temporal and spatial evolutions of nitrate concentration can be monitored successfully.

The future work would be to use more sensing nodes to create a WSN. The data would be collected for a longer time to predict trends, which will be analyzed in the cloud side. More low-power sensors can be included to monitor the humidity, the temperature, or the conductivity of the water.

VI. ACKNOWLEDGEMENT

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