Reconfigurable Smart Water Quality Monitoring System in IoT Environment

Cho Zin Myint*, Lenin Gopal*, and Yan Lin Aung†

*Department of Electrical and Computer Engineering
Curtin University
Sarawak Campus, CDT 250,
98009 Miri, Sarawak, Malaysia
Email: cho.zin.myint@postgrad.curtin.edu.my, lenin@curtin.edu.my

†School of Computer Science and Engineering
Nanyang Technological University
Singapore 637553
Email: layan@ntu.edu.sg

***Abstract*— Since the effective and efficient system of water quality monitoring (WQM) are critical implementation for the issue of polluted water globally, with increasing in the development of Wireless Sensor Network (WSN) technology in the Internet of Things (IoT) environment, real time water quality monitoring is remotely monitored by means of real-time data acquisition, transmission and processing. This paper presents a reconfigurable smart sensor interface device for water quality monitoring system in an IoT environment. The smart WQM system consists of Field Programmable Gate Array (FPGA) design board, sensors, Zigbee based wireless communication module and personal computer (PC). The FPGA board is the core component of the proposed system and it is programmed in very high speed integrated circuit hardware description language (VHDL) and C programming language using Quartus II software and Qsys tool. The proposed WQM system collects the five parameters of water data such as water pH, water level, turbidity, carbon dioxide (CO_2) on the surface of water and water temperature in parallel and in real time basis with high speed from multiple different sensor nodes.**

Keywords*— *Internet of Things (IoT); smart; Wireless Sensor Network (WSN); water parameters; Zigbee

I. INTRODUCTION

The Wireless Sensor Network (WSN) [1] and wireless communication technologies have been increasingly developed for assisting human's personal and professional daily tasks. The applications of wireless technologies have been developed for the data acquisition, building control, environmental monitoring systems and automation of manufacturing processes in recent years. Today's state-of-the-art WSNs have more advantages such as low costs for both installation and maintenance, and longer operating time. The remote sensor network can be used for stationary or mobile sensor networks. The remote sensor network is commonly used for different purposes such as surveying the development of city infrastructure, environmental monitoring, telemedicine or remote health care, research in agriculture, fishing surveillance, farming, border security, traffic management, forestry management, and disaster prevention [2]. A WSN consists of compactly dispersed sensor nodes for sensing, signal processing, embedded computing, and connectivity [3]. This system enables the interaction between persons or computers and the surrounding environment through wireless link [4]. Although the WSNs were used in military and heavy industrial applications originally, today's WSN applications are used for different purposes from the light industrial to heavy industrial systems. The WSN system allows users to monitor and control the connected devices from the base station through different wireless communication standards such as WiFi, General Packet Radio Service (GPRS), Bluetooth, Zigbee, Radio Frequency Identification (RFID), and cellular technologies [5]. The users can monitor the data through a wireless network which can be designed based on one of those wireless communication standards. The advantages of WSN are low power consumption, redundant data acquisition, remote monitoring, fast network establishment, wide coverage area, and high monitoring precision and low duty cycle. Thus, the WSN to the real world is practically unlimited from physical security, environmental monitoring and climate changes, positioning and tracking and health care to logistic, localization, and so on [6]. The Internet of Things (IoT) was developed in parallel to WSNs and is a physical network which connects all things in order to exchange the data and information through the data sensing devices such as sensors, actuators and computers in line with relevant protocols. In other word, many things are connected into networks in one form or another. The aims of intelligent, identifying, monitoring, locating, tracking and controlling things are achieved by IoTs [7]. There is a variety of IoT applications such as RFID tags, sensor technology, mobile technology and other smart technologies [8]. The integration of inexpensive and low powered sensors into IoT is a major evolution of

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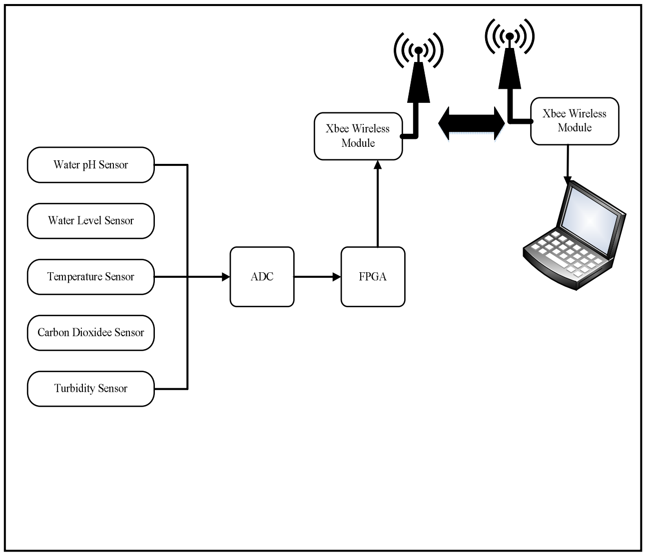

Figure 1: The block diagram of smart water quality monitoring system

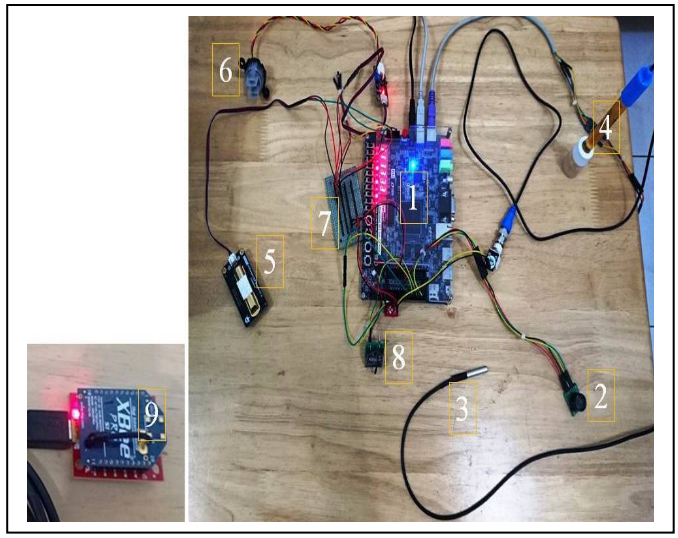

Figure 2: The hardware experimental set-up of smart water quality monitoring system

WSNs [9]. The WSN in IoT applications enables the information and communication systems invisibly embedded in the environment since the sensor network enables people to interact with the real world remotely [10]. Recently, an environmental monitoring system based on WSN system using different wireless communication standards has attracted intensive interest. Jing [11] designed a wireless remote monitoring system for water supply based on GPRS using PIC microcontroller. The PC management software is developed using VC++6.0 software platform. Purohit and Gokhale [12] designed a real-time water quality measurement system using Intel microcontroller, Global System for Mobile communications (GSM) module, assorted water quality measuring sensors, Analogue to Digital Converter (ADC), and a liquid crystal display (LCD). Since microcontrollers have more complex architecture, the development time and cost increase due to the complexity of the circuit design. Beri [13] designed an autonomous real-time device to measure the physical and chemical parameters of water such as pH, temperature and turbidity using Arduino Atmega microcontroller and Zigbee wireless module. Hsia [14] developed a water meter system and leakage detection based on Field Programmable Gate Array (FPGA) chip to realize a signal generator, a detection circuit, data encoder and a serial port for the transmission of data. The proposed system consists of pressure sensor, an ADC and FPGA design board. Chi et al. [15] presented a reconfigurable smart sensor interface device for industrial area of WSN in the IoT environment. These interface devices are restricted as they are commonly based on the comparatively complex dedicated electronic boards [16-18]. Vijayakumar and Ramya [19] designed a real-time water quality monitoring system in IoT environment. The system consists of several sensors to measure water parameters and the raspberry PI B+ model as a core controller. For WSN environmental monitoring application, the energy consumption is a critical issue due to the deployment of aWSN based on the IEEE 1451 standard by combining with Complex Programmable Logic Device (CPLD) and the application of wireless communication in IoT environment. The research should be performed to achieve a broad space for development in the large number of energy-constrained sensor nodes in an unattended environment. Therefore, a low-power, low-cost single-chip fully integrated autonomous System On- Chip (SoC) based wireless sensor node is required to solve these problems. In the proposed smart WQM system, the water quality monitoring system consists of a group of sensors to monitor the water parameters such as water level, water temperature, carbon dioxide (CO_2) on the surface of water, turbidity of water and water pH value. Firstly, the sensors detect the water parameters, and then the data is computed on Altera DE1-SoC board using Very High Speed Integrated Circuit Hardware Description Language (VHDL) programming language and C codes. Afterwards, the computed data is transmitted wirelessly to the base station where the user can monitor the water parameters through Zigbee wireless communication module. The block diagram of smart WQM system is shown in Fig. 1.

II. HARDWARE COMPONENTS

In the proposed smart WQM system, a reconfigurable smart sensor interface device that integrates data collection, data processing, and wireless transmission is designed. The hardware experimental set-up of smart WQM system is shown in Fig.2. The hardware of wireless water quality monitoring system comprises the following components:

- Ultrasonic Sensor
- pH Sensor
- Digital Thermometer Sensor
- Turbidity Sensor
- CO_2 Sensor
- Radio Frequency (RF) Module
- FPGA Board

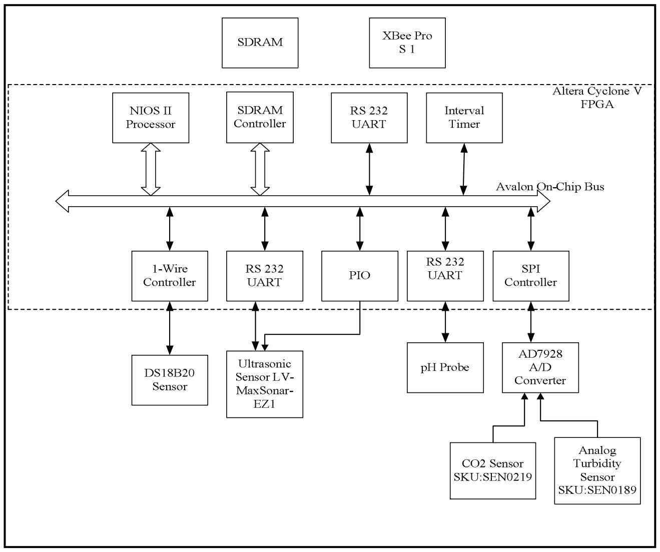

Figure 3: The system block diagram of smart water quality monitoring system

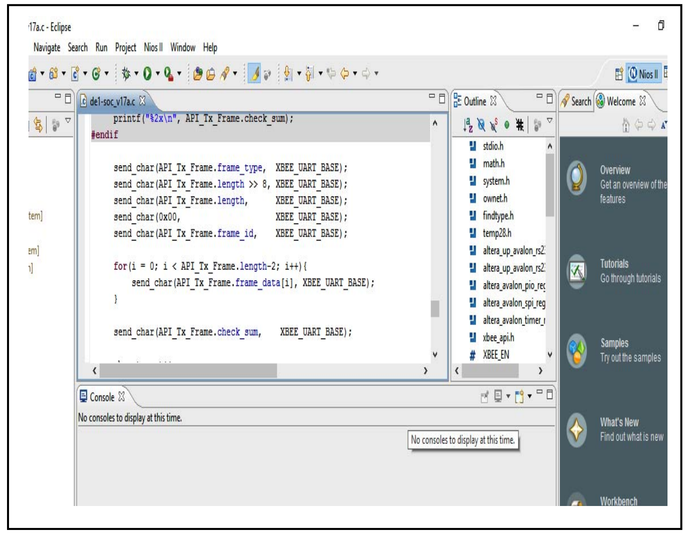

Figure 4: A part of C codes to transmit and receive water parameters wirelessly through XBee module

A. Ultrasonic Sensor

In the proposed smart WQM system, the ultrasonic sensor (LV-MaxSonar-EZ1) is chosen to monitor the water level. This ultrasonic sensor is operated by emitting high-frequency sonic wave at regular time interval starting from the front of the transducer. The sonic waves are reflected by an object and received back in the transducer. The time interval between emitting and receiving sound waves is proportional to the distance between the transducer and the object can be calculated. As the ultrasonic sensor is using sound wave instead of light wave, it is more suitable for sensing uneven surface such as water surface. According to its datasheet, the ultrasonic sensor detects objects from 0-inches to 254-inches (6.45-meters) and provides sonar range information from 6-inches out to 254-inches with 1-inch resolution.

B. pH Sensor

In the proposed smart WQM system, the Atlas scientific pH kit is used to detect the pH value of water. The pH kit consists of three main components: EZO TM class embedded pH circuit, BNC shield, and pH probe. In the process of collecting water pH data, the pH probe is connected to BNC shield. The BNC shield transfers the pH probe sensing data to the embedded pH circuit, and the resulted pH data is then provided to the FPGA board. The embedded pH circuit can be operated in two modes. The pH data is converted into binary by the embedded pH such as UART mode and I2C mode. In this proposed smart WQM system, the UART mode is used for its default mode with baud rate of 9600 bps, 8 data bits, 1 stop bit, no parity and no flow control.

C. Digitla Thermometer Sensor

In the proposed smart WQM system, the temperature of the water is monitored using a 1-wire protocol digital thermometer sensor (DS18B20). The DS18B20 temperature sensor provides 9-bit to 12-bit Celsius degree temperature measurements. The DS18B20 is powered from the data line. The range of power supply 3.0V to 5.5V from data line is needed to power the DS18B20. The accuracy of DS18B20 is ±0.5°C from -10°C to +85°C. The temperature is converted 12-bit digital word in a maximum of 750 milliseconds. The temperature sensor DS18B20 is connected to the configurable NiosII soft processor system which is implemented on the Cyclone V FPGA of Altera DE1-SoC board.

D. Turbidity Sensor

In the proposed smart WQM system, the turbidity sensor SKU: SEN0189 is used to detect water quality by measuring level of turbidity. The turbidity sensor enables the detection of suspended particles in water by measuring the light transmittance and analogue and digital signal output modes, either of the mode can be selected according to the microcontroller unit (MCU). The threshold is adjustable by adjusting the potentiometer in digital signal mode. The operating voltage of the turbidity sensor is 5V DC and the operating current is 40mA (max) respectively. According to the reference chart for the mapping from the output voltage to the Nephelometric Turbidity Units (NTU) depending on different temperature, when the sensor is left in the pure water, that is NTU < 0.5, the output should be "4.1±0.3V" when temperature is 10-50□.

E. CO_2 Sensor

In the proposed smart WQM system, the Gravity: Analog Infrared CO_2 sensor SKU: SEN0219 is used to measure the concentration of CO_2. The concentration of CO_2 is measured in parts per million (ppm). One ppm is equivalent to 1 milligram of something per liter of water (mg/l) or1 milligram of something per kilogram soil (mg/kg). The characteristics of SEN0219 are waterproof and anti-corrosion, high sensitivity, low power consumption, stability, temperature compensation,

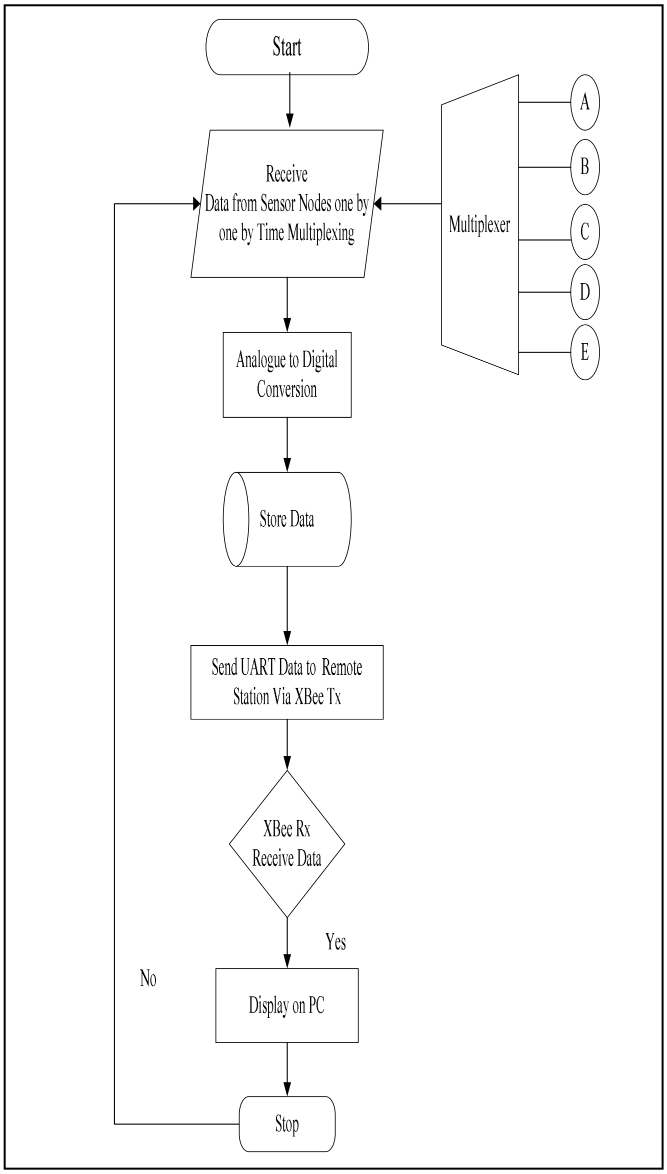

Figure 5: The flow chart of software of smart water quality monitoring system

Figure 6: The experimental result of smart water quality monitoring system shown of Grafana

linear output, high life cycle, anti-water vapour interference and no poisoning. The operating voltage is 4.5-5.5V DC and average current is <60 mA at 5V, the peak current: 150mA at 5V respectively. The effective measuring range of CO_2 sensor is 0-5000 ppm. The accuracy of the CO_2 sensor is ± (50 ppm + 3% reading).

F. RF Module

In the proposed system, protocol based two XBee 802.15.4 RF modules are used to transmit and receive the data between the monitoring device and FPGA board. The Zigbee-based WSN systems are simple to install, and very easy to upgrade. The XBee 802.15.4 is a registered brand name of Zigbee Standard which is manufactured by Digi International. The XBee802.15.4 RF modules include Zigbee/Mesh topologies, and it can support both 2.4 GHz and 900 MHz frequency. The XBee 802.15.4(IEEE 802.15.4 standard) RF module includes two Embedded-Antenna Module, one XBee USB adapter and one voltage adapter. Since the XBee Series Embedded-Antenna Module pins are not exactly same as the normal pin position, the XBee 5V to 3.3V adapter is required to regulate on a normal breadboard or printed circuit board. The XBee USB adapter performs as a connector between the XBee modules and the monitoring device. The voltage adapter converts the 5V to 3.3V under which the XBee Series Embedded-Antenna Modules is operated. The proper configuration is needed before setting up a wireless communication between the monitoring system and the FPGA board. The two XBee Series Embedded-Antenna Modules are the key components to create the wireless communication between the monitoring device and the FPGA board that operates in universal asynchronous receiver/transmitter (UART) mode.

G. FPGA Board

The Altera DE1-SoC board is utilised to control the entire system of the proposed smart WQM system. The DE1-SoC development board includes 85K programmable logic elements, 4,450Kbits embedded memory, 6 fractional phase locked loop (PLLs) and 2 hard memory controllers. For communication, two port USB 2.0 Host, UART to USB (USB Mini-B connector), 10/100/1000 Ethernet, PS/2 mouse/keyboard, IR emitter/receiver, and I2Cmultiplexer are provided. The display of the DE1-SoC board is 24-bit video graphics array (VGA) digital-to-analogue converter (DAC). The power supply of 12V direct current (DC) is needed to power the board. The total resource utilisation to design the FPGA board of the proposed smart WQM system is shown in Table. 1

TABLE I. TOTAL RESOURCE UTILISATION

FPGA Resource Utilisation	
Logic utilization (in ALMs)	1,724 / 32,070 (5%)
Total registers	2662
Total pins	149 / 457 (33 %)
Total block memory bits	83,072 / 4,065,280 (2 %)
Total PLLs	1 / 6 (17 %)
Max Clock Frequency	58.75 MHz

III. SYSTEM ARCHITECTURE

The system block diagram of smart WQM system is shown in Fig. 3. This architecture is used for the entire system of the Cyclone V DE1-SoC FPGA board due to the significant flexibility to deal with a trade off between processing and communication. The sensor nodes are stationed at the bank of the water. The measured data of water parameter are collected by the sensor nodes and sent to FPGA board. The analogue output of CO_2 sensor and Turbidity sensor are digitized by AD7928 Analog to Digital converter. The Ultrasonic sensor and pH sensor are interfaced with RS232 and the default state is UART mode which acts as the transmission (TX) line. The default baud rate is 9600, 8 bits, no parity, no flow control and one stop bit. The temperature sensor DS18B20 communicates over a 1-wire bus which requires only one data line (and ground) for communication with a microcontroller. Serial Peripheral Interface (SPI) bus is used in embedded system to communicate the microprocessor to off-chip sensors, conversion, memory, and control devices. The architecture of SPI is designed for connecting on-chip processors and peripherals together into a system-on-a-programmable chip (SOPC). When the transmitted data from sensor nodes are received by the gateways, SPI transfers the incoming data through the UART interface to the processor. The SPI controller performs nRF24L01 module initialization, receives and sends packets. The Avalon bus is an interface protocol that is designed to connect on-chip processors and peripherals together into the SOPC. The Avalon bus specifies the port connections between master and slave components, and specifies the timing by which these components communicate. The Nios II processor is connected to its embedded peripherals such as parallel input/output (PIO), SPI, on-chip random access memory (RAM), JTAG UART, Timer, UART (RS232 serial port), synchronous dynamic random access memory (SDRAM) controller by means of the Avalon. The multiple slave devices are attached on the Avalon on-chip bus such as SPI, UART, general purpose input/output (GPIO) and custom logic. The Nios II processor is a general purpose configurable soft core processor and it includes a 32-bit central processing unit (CPU) and a combination of peripherals and memory on a single chip. The configuration of Nios II selected the Nios II/fast in order to provide the most effective performance to the processing unit. The SDRAM synchronizes itself with the timing of the CPU. Therefore, the memory controller identifies the exact clock cycle when the requested data is ready. The UART is used to connect Nios II processor to the Zigbee hardware for wireless transmission.

IV. SOFTWARE DESIGN

Since the Altera Quartus II Software is the primary FPGA development tool, the Altera Quartus II Software and the Nios II Embedded Design Suite (EDS) are chosen to build a hardware system design and create a software program that runs on the Nios II system. This programmable logic device design software is produced by Altera and it is compatible with Altera DE1-SoC design board. To display the wirelessly received data of water parameters on PC, the Pythons codes are used to display on the Grafana. The monitoring PC is operated in Linux mode.

A. *Software Program*

The software program consists of the C codes running over the embedded Nios II processor within the FPGA processor and VHDL codes. The Quartus II software is used to create VHDL codes of the interfaces, then the compilation is performed and the system is downloaded into the FPGA device. The Nios II is a soft processor and it is implemented in the FPGA device by using the Quartus II CAD system. The Nios II Integrated Development Environment (IDE) is software development environment of Nios II processor and it is based on the GNU C compiler and Eclipse IDE. The Nios II Software Build Tools (SBT) is used for Eclipse™ and all software development tasks are performed in the Nios II processor system. The Nios II system is generated using Qsys to add the desired components, and to configure how the components connect together. The C software application code is created with the Nios II SBT for Eclipse by using information from the **.sopcinfo** file which is needed to configure the FPGA before running and debugging the project on target hardware. The software programs for sensor nodes and wireless network are written in C and it is run in NIOS II IDE with the NIOS II processor. Finally, the Nios II system is integrated into the Quartus II project. Later, the final FPGA hardware design is created by using the Quartus II software.

B. *Flow Chart*

When the smart WQM system is switched on, the data from each sensor node is collected one after another using time multiplexing. Then, the data of all of 5 sensors is converted to 8 bits binary. The collected data is stored in the integrated SRAM on the interface device. The accumulated data is transmitted to XBee transmitter module in terms of data transmission. The flow chart of the wireless water quality monitoring system is shown in Fig.5. The results of 5 parameters of water quality are displayed on the Grafana which is installed in PC to visualize time series data using the Python codes.

TABLE II. READINGS OF WATER PARAMETERS

Readings on the Grafana				
Water Parameters	**Min.**	**Max.**	**Average**	**Current**
Temperature	31° C	57° C	41° C	43° C
Water Level	356 mm	1.575 m	555 mm	1.575 m
pH	14	14	14	14
CO_2	699 ppm	1076 ppm	766 ppm	718 ppm
Turbidity	4	4	4	4

V. RESULTS AND DISCUSSION

In the smart WQM system, when the sensor board is switched on, the sensors are activated to detect the individual water parameter data. Then, the collected water parameters are transmitted wirelessly to monitoring device which is PC using Nios II software program in the Altera Quartus II software. The data of water level, pH, turbidity, carbon dioxide and temperature are displayed on the Grafana dashboard on the PC using Python codes. The results of water parameters are displayed on the Grafana dashboard as shown in Fig. 6. The reading of water level is changed when the distance between water surface and water level sensor is changed. The readings of water temperature vary according to the increasing and decreasing of the water temperature by using warm water and ice water. The range of the value is displayed for the monitoring of pH, temperature, turbidity, carbon dioxide and level of water. The readings of the experimental result of water quality monitoring system are shown in Table. 2. The data is being monitored continuously and displayed in real time since the default of the system is set in continuous mode. The interval of the sensing time is selected for 1 hour and the data is refreshed every 5s. The proposed smart WQM system reduces power consumption, which outperforms the performance of the conventional microcontrollers-based WSN.

VI. CONCLUSION

The proposed smart WQM system of single chip solution to interface transducers to sensor network using FPGA is presented with wireless method by using a wireless XBee module. The results of the five parameters of water quality are verified that the system achieved the reliability and feasibility of using it for the actual monitoring purposes. The water temperature may vary from 0 to 0.4 Degree Celsius depending on the speed of the ambient air temperature cycles. The time interval of monitoring can be changed depending on the need. By introducing the FPGA board, the proposed system inherits high execution speed and reusable Intellectual Property (IP) design. The proposed system will assist in protecting the ecological environment of water resources. The smart WQM system minimizes the time and costs in detecting water quality of a reservoir as part of the environmental management. The WSN network will be developed in the future comprising of more number of nodes to extend the coverage range.

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