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The Development of Wireless Sensor Network for Air Quality Monitoring using Buck-Boost Converter

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A B S T R A C T

Wireless sensor networks (WSN) are increasingly implemented in air quality monitoring with real-time and high spatial-temporal resolution. In this context, current work aimed at designing and testing a cost- and energy-efficient WSN-based air quality monitoring system. The system was assembled principally by wireless sensors, solar cells, microcontroller and network communication. In addition, a new circuit for buck-boost converter was implemented for voltage and current regulations. On-field, testing the proposed air quality monitoring system outdoor and indoor showed efficient real-time readings for the concentrations of carbon dioxide (CO2) and total volatile organic compounds (TVOC). Indeed, it reveals that CO2 and TVOC concentrations at Jwatha Park peaked at 1750 ppm and 200 ppb (550 ppm above the normal limit and 100 ppb for CO2 and TVOC respectively) while it was lower at King Abdullah garden with peak value of 780 ppm and 68 ppb for CO2 and TVOC respectively. However, the air pressure readings at both locations were comparable and ranging from 996.76 to 997.72 hPa with more fluctuations results for pressure results at Jwatha Park. Furthermore, it provided data about ambient temperature, relative humidity and air pressure with good accuracy. In conclusion, actions related to CO2 and TVOC control are recommended to be taken by the stakeholders.

INTRODUCTION

By a steadily increasing emission of greenhouse gasses, the global climate change has become the most prominent global problem [1]. Besides, accumulation of volatile organic compounds (VOCs) and liquefied petroleum gasses (LPS) in the air is an important addition to the spectrum of health hazards [2] [3] [4]. Therefore, intensive research has been directed toward designing systems to monitor the levels of these gaseous compounds [5] [6] [7]. Recently, considerable progress has been achieved in the field of air quality monitoring systems [8] [9] [10]. The progress is exemplified in principle by introducing the next generation air pollution monitoring system, which utilizes advanced sensing technologies, microelectromechanical systems and wireless sensor network (WSN) [11] [12] [13].

The WSN has received considerable attention due to the scalability and mobility of its sensory elements [11]. Using this technology, effective outdoor and indoor air quality monitoring systems have been designed. For example, Liu et al. [14] designed a WSN-based system for outdoor air quality monitoring, which was integrated with the global system for mobile communications. This system was managed by LabVIEW program through data about carbon monoxide (CO) that could be stored into a database. Furthermore, a Bayesian neural network-based system was designed to develop a framework of a functional air quality index, which provided random real-time data through wireless communication [14]. This system included several sensors to measure range of pollutants associated with airways inflammatory diseases. Marques and Pitarma [15] designed an indoor air quality monitoring system based on an Internet of Things paradigm, which included an Arduino and XBee technologies and five micro sensors for ambient temperature, moistness, CO, carbon dioxide (CO2) and glow. In a comparable study, Pitarma et al. [16] designed a low-cost WSN system to monitor an indoor air quality using Arduino, XBee modules and micro sensors. They combined micro sensors to

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monitor CO, CO2, luminosity and other environmental parameters.

Previously, we built a circuit design to measure air quality [17]. The design included Arduino microcontroller, MQ-2 gas sensors and current regulator circuit to monitor the levels of CO and LPG indoor and outdoor. In the current study, we designed a new WSN-based air quality monitoring system encompasses Arduino microcontroller and gas sensors to monitor the levels of CO, CO2, total VOCs (TVOC) and three environmental parameters. In addition, our approach attempts to enhance the durability and cost efficiency of the system by using solar cells. The efficiency of the proposed system was examined outdoor and indoor at different locations at Al-Hasa city, Saudi Arabia. Specifically, the contributions of this paper can be summarized as follows:

- A detailed hardware implementation of air quality monitoring system using efficient modules such as a sensory elements-based microcontroller unit and solar cells.
- A complete mathematical modeling for the buck-boost convertor circuitry using variable duty cycle.
- Three case study experiments with analysis of gas concentrations including CO2 and TVOC, and readings of environmental parameters including ambient temperature, relative humidity and air pressure.

The rest of this paper is organized as follows: Section II will provide comprehensive discussion of the design of buck-boost circuit. Section III presents the proposed system modeling and implementation. Section IV provides the experimental results and discussions followed by the Section V which concludes the presented work.

BUCK-BOOST CONVERTER DESIGN

The circuit operation of buck-boost converter can be divided into two modes. The first mode when the transistor is on and the diode is off, which makes the current flows in the inductor and the transistor as well. The second mode when the transistor is off, which makes the current flows in the inductor, capacitor, diode and the load. Therefore, the stored energy in the inductor at the first mode is now transferred into the load, and the inductor current falls until the transistor is switched on. Here, we propose another configuration that takes the output voltage at the (AB) points. Such configuration may improve the current and voltage regulation processes required. The relationship between the output voltage and the duty cycle is:

$$V_{AB} = \frac{D}{(1-D)V_{in}} \tag{1}$$

Given that: Source voltage (Vs = 2~16 Volt), Frequency (f = 50 KHz), Output voltage (V_{out}= 5 Volt), and Power of fans (Pout=0.2W). The output current (I_{out}) is:

$$I_{AB} = \frac{P_{out}}{V_{out}} = \frac{0.2W}{5V} = 40mA \tag{2}$$

The loud resistance (R) is:

$$R = \frac{V_{out}}{I_{out}} = \frac{5V}{40mA} = 125Ohm \tag{3}$$

For Maximum Vs (16V), the duty cycle of buck-boost converter (D) can be found as follows:

The output current (I_{out}) is:

$$I_{AB} = \frac{1}{(\frac{V_s}{V_{out}})+1} = \frac{1}{(\frac{16}{5})+1} = 0. \tag{4}$$

Assuming that ripple current (ΔI) and ripple voltage (ΔV) are 5%, the ripple current and voltage can be calculated as follows:

$$\Delta I = (\frac{5}{100}) * I_{out} = (\frac{5}{100}) * 0.4A = 0.02A \tag{5}$$

$$\Delta V = (\frac{5}{100}) * V_{out} = (\frac{5}{100}) * 5V = 0.25V \tag{6}$$

The value of capacitor (C) is:

$$C = \frac{I_{out} \times D}{f \times \Delta V} = \frac{0.4A \times 0.2830}{50000 \times 0.25V} = 9.056\mu F \tag{7}$$

The value of inductor (L) is:

$$L = \frac{V_s \times D}{f \times \Delta I} = \frac{16 \times 0.2830}{50000 \times 0.02} = 4.5286mH \tag{8}$$

The critical value of capacitor (Cc) is:

$$C_c = \frac{D}{2fR} = \frac{0.2830}{2 \times 50000 \times 125} = 22.64nF \tag{9}$$

The critical value of inductor (Lc) is:

$$L_c = \frac{(1-D) \times R}{2f} = \frac{(1-0.2830) \times 125}{2 \times 50000} = 896.25\mu H \tag{10}$$

Since C > Cc, L > Lc, the values of Cc and Lc can be as follows:

$$C = Cc = 22.64nF,\ L = Lc = 896.25\mu H \tag{11}$$

For Minimum Vs (2V), the value of D is:

$$I_{AB} = \frac{1}{(\frac{V_s}{V_{out}})+1} = \frac{1}{(\frac{2}{12})+1} = 0. \tag{12}$$

Assuming that ripple current (Δ I) and ripple voltage (Δ V) are 5%, the ripple current and voltage can be calculated as follows:

$$\Delta I = (\frac{5}{100}) * I_{out} = (\frac{5}{100}) * 0.4A = 0.02A \tag{13}$$

$$\Delta V = (\frac{5}{100}) * V_{out} = (\frac{5}{100}) * 5V = 0.25V \tag{14}$$

The value of capacitor (C) is:

$$C = \frac{I_{out} \times D}{f \times \Delta V} = \frac{0.4A \times 0.7}{50000 \times 0.25V} = 22.4\mu F \quad (15)$$

The value of inductor (L) is:

$$L = \frac{V_s \times D}{f \times \Delta I} = \frac{2 \times 0.7}{50000 \times 0.02} = 1.4mH \quad (16)$$

The critical value of capacitor (Cc) is:

$$C_c = \frac{D}{2fR} = \frac{0.7}{2 \times 50000 \times 125} = 56nF \quad (17)$$

The critical value of inductor (Lc) is:

$$L_c = \frac{(1-D) \times R}{2f} = \frac{(1-0.7) \times 125}{2 \times 50000} = 375\mu H \quad (18)$$

Since C>Cc,L>Lc, the values of Cc and Lc can be as follows:

$$C = Cc = 256nF,\ L = Lc = 375\mu H \quad (19)$$

Based on the calculations, the value of L and C should be 375 µH and 56 nF, respectively. The possible values of output voltage were obtained, and finally, a block diagram of the design was drawn using Ms-Visio 2016 and simulated by Multisim 14.0.

SYSTEM IMPLEMENTATION AND PARAMETERS

The proposed air quality monitoring system was assembled by connecting the Arduino Microcontroller with all other sub-systems. The major part of the designed air quality monitoring system was based on the sensors connectivity and calibration accuracy (MQ-series specifically). For accurate readings, the sensors were operated for 1-2 hours, as warm-up stage, prior to the calibration stage.

Based on block diagram and circuit simulation, we selected the hardware to assemble the proposed WSN-based air quality monitoring system. The major units used were as follows:

- Adafruit CCS811 air quality sensor breakout - CO2 and TVOC: MQ-2 gas sensors series were used to measure CO2 and TVOC concentrations within a range of 400-8192 ppm and 0-1187 ppb, respectively. The inter-integrated circuit (I2C) communication protocol was used. Based on circuit simulation, we drawn a block diagram of the proposed air quality monitoring system. The system was composed mainly of sensor elements, rechargeable batteries, solar cells and Arduino microcontrollers.
- Adafruit BME280 I2C/SPI temp-humidity-pressure sensor: To measure additional environmental parameters, we used this sensor to measure ambient temperature with a ± 1.0 C, relative humidity with ± 3 % accuracy and barometric air pressure with ±1 hPa. The I2C and communication protocol and serial peripheral interface bus (SPI) interfaces were used.
- Arduino Uno Microcontroller: This microcontroller was used due to its capacity to perform many control applications using 16MHz ATmega328P microprocessor. Arduino Uno has 14 digital I/O pins, utilizing PWM with 6 I/O pins, 6 analog input pins, USB connection, a power jack, an ICSP header and a reset button and its operating voltage is 5V DC.
- Solar cells: A number of PV cells were interconnected to form a panel. The 12V panel, which includes 36 cells, was connected in series. Finally, the panels were connected in series to form a PV array.
- 3.5 TFT touch Screen with SD card socket for Arduino board: An Arduino TFT touch screen display (2.8") with 18-bit 262,000 different shades and 240x320 pixels was used.
- Other hardware: In addition to the main hardware, we used wireless connection (mini Wi-Fi cards), analog-to-digital converter (ADC), batteries (AAA Batteries, 9-12 volts) and a portable computer.

To examine the efficiency of the designed air quality monitoring system, we measured the greenhouse gas CO2 and TVOC at two outdoor and an indoor location at Al-Ahsa city, Eastern Province, Saudi Arabia. The locations included Jwatha Park and King Abdullah Garden for outdoor examination, and the Microprocessor Laboratory of King Faisal University for indoor measurements. Ahead of examining the effectiveness of the designed air quality monitoring system, gas sensors were calibrated by several readings. A GPS and digital camera were used to determine the locations. As a reference, the measured gas levels were compared with the normal levels and the obtained data were plotted using MATLAB.

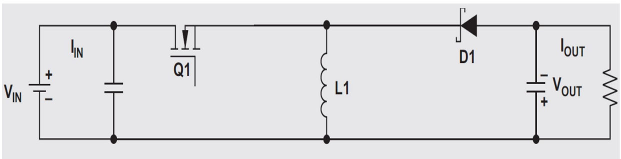

Figure 1. Schematic illustration of the designed circuit

Finally, to examine the output voltage of the designed circuit, we first obtained possible values at duty cycle limit by a means of tuning up the duty percent along with the operational frequency (typically 10 KHz and 50 KHz) using Multisim simulation platform. Data in Table 1 show the relationship between the duty cycle & output voltages, suggesting potential application of the designed circuit in the buck-boost converter, which clearly illustrate the proportional relationship of duty cycle with respect to output voltage level.

Table 1. Output voltage vs different duty cycle values.

D	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Vout	0.00 V_{in}	0.11 V_{in}	0.25 V_{in}	0.43 V_{in}	0.67 V_{in}	1.00 V_{in}	1.50 V_{in}	2.33 V_{in}	4.00 V_{in}	9.00 V_{in}	—

RESULTS AND DISCUSSION

According to the relationship between the output voltage and the duty cycle, the values of L and C were 375H and 56nF, respectively. Subsequently, we drawn the designed circuit using Multisim 14.0. As shown in Figure 1, the current flow travels from input (i.e. V_{in} side) to the output (i.e. V_{out} side) passing through capacitance (C), general

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purpose transistor (Q1 or 2N22222) and inductance (L1). The general-purpose diode (D1 or 1N4001) was used to avoid reverse current from accessing in reveres way.

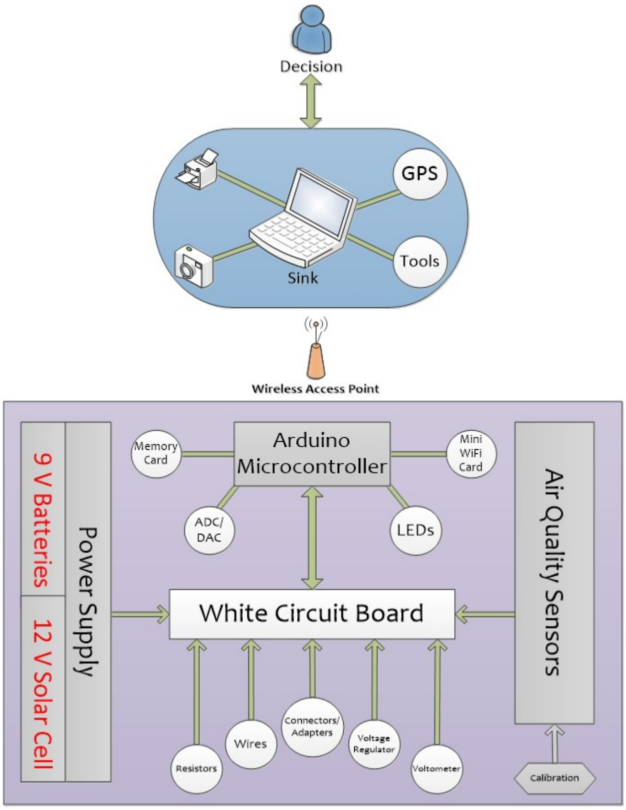

Figure 2. WSN-based air quality monitoring system: All stages & circuits were supplied with renewable energy source composed of rechargeable batteries equipped with solar cells. In order to obtain the required amount of voltage supply for each sub-system, the buck-boost converter was configured to voltage/current regulation purposes. The proposed air quality monitoring system was supported by other accessories at the administration level, which included mainly a GPS module, printer & imaging service.

Based on circuit simulation, we drawn a block diagram of the proposed air quality monitoring system. As depicted in Figure 2, the system was composed of sensor elements, rechargeable batteries, solar cells, Arduino Microcontrollers, voltage/current regulator (buck-boost), mini Wi-Fi cards, connectors and adapters, GPS System, computer, voltmeter, and other accessory hardware. The measurement process starts from the sensor elements side, the end terminal peripherals, which continuously calibrate the values of gas concentrations as an analog voltage. The recorded values were stored into memory cards to be processed by the ADC circuit before being processed by the Arduino microcontroller. The processed values of gas concentrations, i.e. digital values, could be accessed by the administrator's computer via Wi-Fi wireless connections. Furthermore, the circuit could be provided by a GSM module in order to be accessed by a smart phone application at home or out the field. Finally, the obtained data were used for decisions and recommendations about air quality.

To test the designed air quality monitoring system, we operated the system and obtained readings for CO2 and TVOC concentrations and three environmental parameters at two outdoor and an indoor location as case studies. The outdoor locations included Jwatha Park and King Abdullah Garden, the two major parks at Al-Hasa city. The indoor location was the Microprocessor Laboratory of King Faisal University, a laboratory used by students on daily bases. The readings of the parameters were taken for 35 min after warming up and calibration processes. The results were as follows:

- Carbon dioxide (CO2): As shown in Figure 3A, the readings of CO2 concentration obtained by the CCS811 sensors at Jwatha Park were 400-1750 ppm, which was higher than the acceptable limits (1200 ppm). This could be explained, at least partially, by the nearby car racing arena. In contrast, the readings at King Abdullah Garden showed lower levels of CO2 (400-780 ppm) that fall within the acceptable limits (Figure 3B). The acceptable concentrations of CO2 at King Abdullah Garden could be justified by the distance from city center. Notably, the readings were less fluctuating compared with those obtained at Jwatha Park.

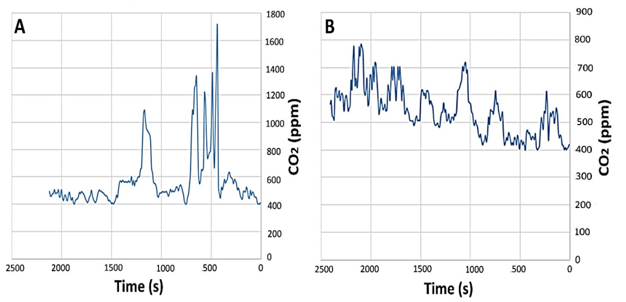

Figure 3. Readings of CO2 concentration (ppm) obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden

- TVOC: The readings of TVOC concentrations obtained by the CCS811 sensors at Jwatha Park were relatively higher (0-200 ppb; Figure 4A) compared with the acceptable limit (100 ppb). The nearby car racing arena could be one of the reasons contributed to the high TVOC concentrations. In addition, plants are one of the main sources of TVOC in the atmosphere. Therefore, the surrounding huge palm farms could be another reason contributed to the higher levels of TVOC. At King Abdullah Garden, the TVOC concentrations (0-68 ppb) was lower than that of Jwatha Park, and it was less than the acceptable limit (Figure 4B).

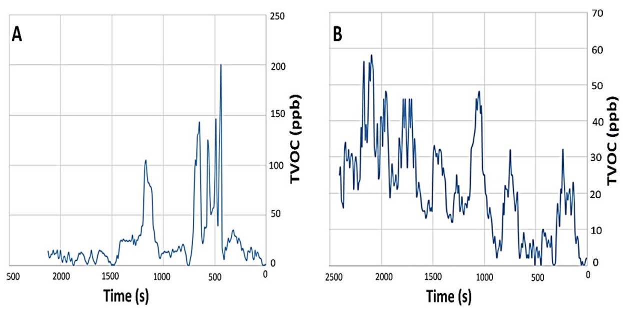

Figure 4. Readings of TVOC concentration (ppb) obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden

- Environmental parameters: Consistent with the reciprocal correlation between temperature and humidity, the readings of BME280 sensors showed that the drop-in temperature was accompanied by an increase in humidity at Jwatha Park and King Abdullah Garden (Figure 5 and 6). The air pressure readings obtained by the BME280 sensors at Jwatha Park and King Abdullah Garden were comparable, which were ranging from 996.76 to 997.72 hPa (Figure 5.a). However, the readings at Jwatha Park showed more fluctuations. Moreover, we provide the air pressure (hPa) measurements obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden in Figure 7.

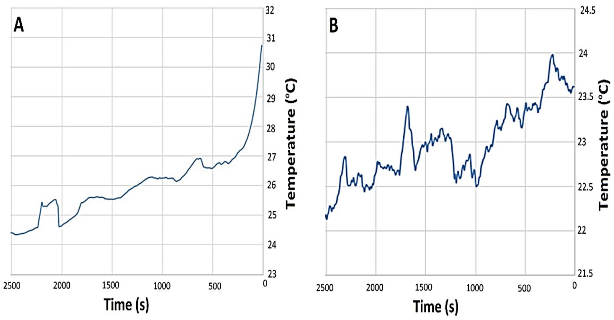

Figure 5. Readings of temperature (◦C) at obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden

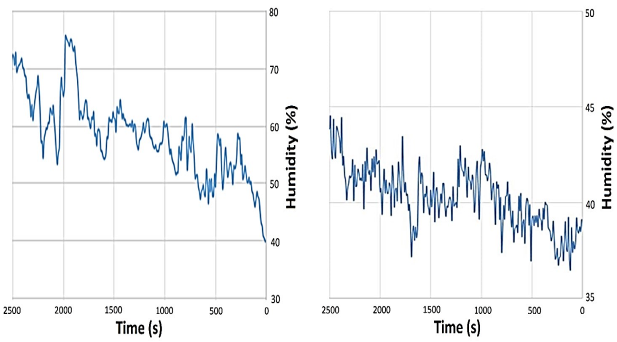

Figure 6. Readings of relative humidity (%) obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden

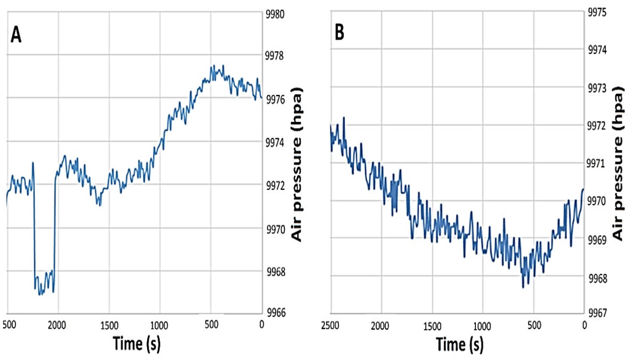

Figure 7. Readings of air pressure (hPa) obtained by the proposed air quality monitoring system at (A) Jwatha Park and (B) King Abdullah Garden

Finally, for indoor testing of the proposed WSN-based air quality monitoring system, we measured the concentration of CO2 and TVOC during lecture time 95 min after warming up and calibration processes. The obtained readings showed that the concentrations of CO2 (410-605) and TVOC (2-31 ppb). The concentrations of the measured gases were acceptable, which most likely due to efficient air ventilation. Such results are plotted in Figure 8.

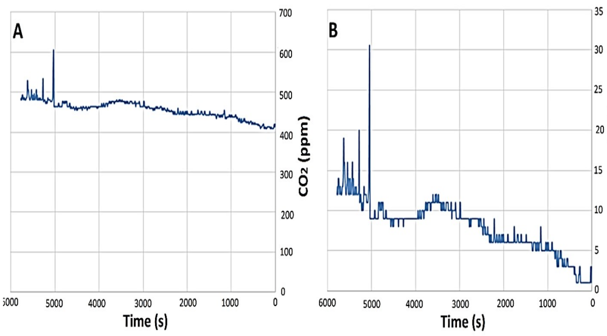

Figure 8. Readings of (A) CO2 (ppm) and (B) TVOC (ppb) obtained by the proposed air quality monitoring system at Microprocessor Laboratory

CONCLUSIONS

The study proposed an enhanced design for air quality monitoring system based on WSN and solar cells. The system was built mainly using wireless sensors with Arduino Mega microcontroller, buck-boost convertor and solar cells with rechargeable batteries. The circuit was used to test concentrations of CO2 and TVOC as indicators for air quality, and ambient temperature, relative humidity and air pressure as indicators for environmental conditions. Also, we performed an on-field testing for the air quality parameters using the proposed system. In addition, the system can be enhanced by adding more wireless sensors to measure other parameters such as LPG, smoke and dust.

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