Design and Experimentation of a Wi-Fi-based Low-Power IoT System for Environmental Conditions Sensing

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ABSTRACT
This paper intends to provide a state art of Wireless Sensor Network(WSN) design using open source hardware platforms. that can be deployed in different weather conditions to monitor factors such as temperature, humidity, and wind speed. WSNs being flexible and scalable systems consisting of several individual sensor systems are favored in these extreme weather and environmental conditions b because of them requiring significantly less wired connections, hence making the system less susceptible to damage. The sensor units, that use Wi-Fi technology to connect to the central processer of the WSN due to Wi-Fi having a long-range of communication and a high-speed of data transmission under Wireless Local Area Network (WLAN), become advantageous when implementing this WSN on a larger scale, with hundreds of sensor nodes. This paper focuses also on designing of a DC-DC power supply for sensor nodes thus sensor nodes consume less power due to its low ripple, high stability.

Keywords
Wireless Sensor Network, Wireless Local Area Network, Wi-Fi, Step-down converter, MATLAB, IoT Systems

1. INTRODUCTION
A Wireless Sensor Network (WNS) is an interconnection and integration of a multitude of sensor units called 'sensor nodes' which incorporate wireless technologies for data transfer. These infrastructure-less networks consist of small sized and easy maintenance components, capable of information processing as well as data communication. The application in this experiment being the arrangement of a number of some detection stations to observe, record, and monitor environmental condition such as temperature, humidity, pressure, wind speed, wind direction, and sound intensity, will mainly focus on the communication among the network using Wi-Fi and the conversion and control of the power supply to these stations, which are the sensor nodes of the system. These lightweight and portable sensor nodes are spatially dispersed. The nodes are set up to sense and retrieve the data and to transmit the data to a main station, which is referred to as the base station or the sink node. The WSN comprises sensors components, radio nodes, WLAN access points, and evaluation software. The sensors in the sensor nodes will capture the intended attribute and convert the sensor signal to an electrical signal. The radio nodes of the WSN system, which contain a microcontroller transceiver, external memory, and a power source, will transmit this data wirelessly to an access point in the network. The processing will be done by the evaluation software to present the received data in a useful and perceivable form.

A WSN where data is transferred from sensor nodes directly to the base node is called a Single-hop network. Since the implementation of a network as in this experiment causes the dispersion of the sensor nodes in a wider area, the data transmission will be long distance, which in turn will consume more energy. It is in such situations that intermediate nodes are used to form a multi-hop, low energy consuming WSN. A base station too can connect or communicate with other networks through the internet, hence expanding the system further. Among the two possible architectures in setting up a WSN, flat-network architecture and Hierarchical network architecture, a multi-hop network will involve the flat-network architecture, where a command sent by the base node to all sensor nodes will be responded to only by sensor nodes with the matching query in multi-hop paths. Hierarchical network architecture on the other hand will have the sensor nodes formed into clusters, where the sensor nodes will send data to a cluster head, which will then transmit the received data to the base station. [1][2] The power consumption in the implementations of this architecture will depend on the sensors, nodes, and the area of implementation.

The connections among the nodes of a WSN may it be a single-hop, multi-hop, flat-network, or a hierarchical network can be arranged in one among the many different topologies, star, tree, mesh etcetera, depending on the desired design and outcomes if the implementation. In fact, since this research aims to build a Low-power consuming WSN to sense and monitor environmental conditions for applications such as agricultural areas, it is essential to consider the power supply when deciding the architecture and components of the network[3],[4].

The power consumption and power supply requirements of a WSN though is dependent on the architecture and topology to a certain extent, the components used in the nodes, the number of nodes, and the processing done by the nodes can be considered to have a much larger effect in the power factor of a WSN. Since the purpose of having individual sensor nodes is to be able to place them in a vast area, especially in applications as this, it is most suitable for the nodes to have a battery for power supply. It is also most essential to keep these nodes alive for as long as possible without failure, to keep the network functioning smoothly. It is due to these reasons that the efficiency of the power supply, sensor node energy consumption, and the execution of operations and algorithms with the ability to consume minimum energy of

the microcontroller should be given consideration. When converting and manipulating the supply power of nodes, to meet the optimum power-saving state, it is also important to make sure that the power supply provides a smooth voltage and current, because of the protection of the sensors, which can often be quite expensive[5].

This paper intends to speak further of building a reliable system which collects environmental data and transmits them accurately and efficiently to complete a compliant self-sustainable Wireless Sensor Network". The components, WSN protocols, and the power supply adjustment and conversion will be discussed in the chapters to come.

2. BACKGROUND STUDY

It is by now understood that the individual sensor nodes of a network, that are responsible to sense and transmit the data, must self-sustain their power requirements from an internal power supply. In this application to monitor environmental factors, the nodes shall consist of temperature and gas sensors and shall follow an architecture to form clusters, adhering to WSN protocols. The clusters will be able to communicate with the ThinkSpeak server, where the data processing shall take place.

When deciding upon the most suitable components, it was necessary to do a thorough analysis of the possible components to select the most efficient and power-saving components to build a better WSN.

2.1 DHT11 – Temperature Sensor

Figure 1: DHT11 Temperature and Humidity Sensor

The figure (Figure 1) depicts a DHT11 Temperature and Humidity sensor which consists of a capacitive humidity sensor and a thermistor to obtain the readings. The sensor has an 8-bit microcontroller to output the temperature and humidity readings as serial data, where to measure the temperature the sensor has a dedicated Negative Temperature Coefficient. The sensor coming factory calibrated makes its interfacing with other microcontrollers much easier.

The DHT11 sensor can measure temperature within the range of 0°C to 50°C with a ±1°C accuracy and the humidity from 20% to 90% with an accuracy of ±1%. The operating voltage for the sensor is within 3.5V to 5.5V and the operating measuring current of the sensor is 0.3mA. [6].

2.2 MQ135 Gas Sensor

Figure 2: MQ135 Gas Sensor

The MQ-135 Gas sensor shown in figure 2 is a sensor used to detect and measure the concentration of NH3, NOx, Alcohol, Benzene, Smoke, CO_2 in the air. Air quality control uses these sensors to determine the air quality and composition. This sensor module with its Digital Pin enables this sensor to function even without a microcontroller which comes useful and cost-saving when it is only to detect a specific gas. The sensitivity of this digital pin can be varied using a

potentiometer. The MQ-135 Gas sensor gives the gas concentration in Part Per Million (PPM) as an analog reading through the analog pin which is Transistor-Transistor Logic (TTL) driven. The sensor operating on 5V makes it easily compatible with most microcontrollers. The wide range of sensing, fast response, and high and variable sensitivity of this sensor makes it a suitable and convenient choice in most applications. [7]

2.3 NodeMCU (ESP8266)

Figure 3 : NodeMCU (ESP8266)

Figure 3 illustrates a NodeMCU board being a development board especially designed for applications based on the Internet of Things (IoT), uses an open-source firmware based on Lua and a hardware based on the ESP-12 module. This board can be set to either station mode or access point mode, where in Station mode, it functions as a wireless sensor node and connects to available Wi-Fi networks, while in Access Point mode, it works as an access point to which other devices can connect. The device follows the standard IEEE 802.11 b / g / n protocol for Wi-Fi communication. Running on an ESP8266 microcontroller, the NodeMCU board has a 3.3V operating voltage and 16 digital input/output pins. The NodeMCU comes with a micro-USB jack and an external power supply pin (Vin), where either can be used to power up the board. The NodeMCU (ESP8266) board also supports interfaces such as Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I2C). [8]

Many related works in IoT system design have used NodeMCU as their main platform [9][10]. Having decided upon the most efficient and effective components, it is equally essential to consider the sensor placements and node routings in order to implement an error-free system. Therefore, the WLAN and network topologies are referred to and analyzed for the implementation design.

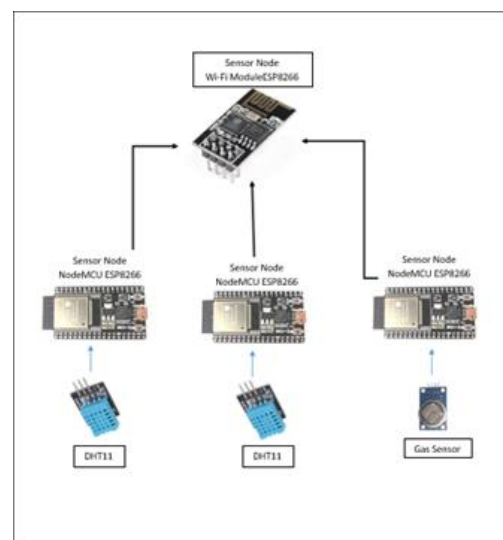### 2.4 Wireless Local Area Network (WLAN)

Figure 4 : WLAN Arrangement of the System

WLAN is one of the fastest growing technologies in the telecommunication industry. A WLAN can be created by connecting the sensor nodes to the base station as per the flow diagram of WLAN for the designed system portrayed in Figure 4. A Wi-Fi module is set as an access point of this WLAN, where all the sensors relate to each sensor node (NodeMCU ESP8266) and to the base-node (Wi-Fi module) using WLAN.

2.5 Mesh Network Topology

In this topology, apart from being responsible to transmit its own data, the nodes are also required to act as relays to transmit other nodes' data. Based on the transmission and reception of data among nodes their topological arrangements can be categorized as fully, or partially connected. While each node is connected to every other node the topology is known as fully connected, if some nodes are connected to one or more other nodes it is a partially connected mesh topology. Hence, it carries data over a long-range splitting it into a series of short hops. Figure 5 below demonstrates the partially and fully connected mesh topologies.
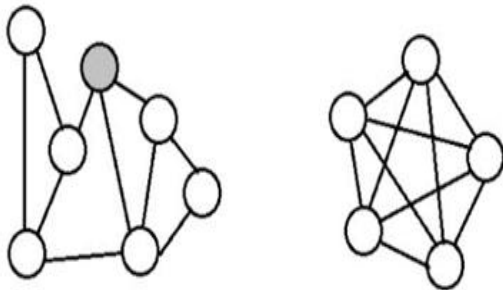

Figure 5: Partially Connected (Left) and Fully Connected (Right) Mesh Topology

2.6 Energy Source

Having chosen the most suitable components for the WSN, and the best topology for its arrangement, it also necessary to consider the power consumption by the system and each node separately to decide upon the best power supply for the stations. After a thorough evaluation and analysis, the lithium battery was chosen as the energy source for the nodes. Considering the sensor nodes, though most sensors demand a supply voltage of only 3.3V or 5V, some special cases such as industrial level sensors may require 12V – 24V DC as their operating voltage. It is considering this possibility, that 12VDC was selected as the optimum operating voltage.Batteries were set to provide power to the sensor nodes as well as the base node of the system.

3. METHODOLOGY

3.1 Overall design

Considering the desired outcomes of the system along with the thorough research on WSN it is decided to implement the following setup shown in figure 6 below.
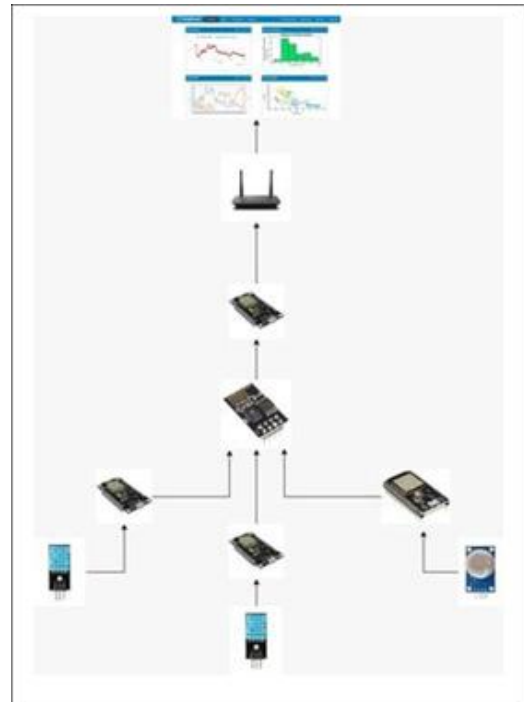

Figure 6: Overall design of the system

Looking at the above figure, it can be seen that NodeMCU is used as the processing unit of a node that is connected with the relevant sensor (temperature and humidity or gas sensor). These three nodes will be connected as well as to an intermediate Wi-Fi Module. This module is then connected to another NodeMCU that acts as the base station for the WSN. Then the whole system is accessed to the internet through the Wi-Fi connection of the router to connect to the ThingSpeak Server where the collected data will be further processed and output information in an understandable manner.

3.2 Power Supply Design

The microprocessor selected for the sensor nodes and the base node of the WSN, which is an ES8266, has a low power consuming system with a Tensilica L106 Diamond series 32-bit processor along with built in Wi-Fi functionalities, hence its application in this experimental system.

3.2.1 Load Calculation

The power consumed by the controller for each sensor node was calculated using the datasheet for the microcontroller, assuming all sensor nodes to be of similar composition. The microcontroller board has a power regulation between 5V to 3.3V, which demands any power converter to the board to have an output voltage of 5V.

$$Battery\ capacity = \frac{Load\ voltage \times Load\ Current \times Working\ houts}{Cell\ Voltage \times Depth\ of\ Discharge \times 0.8}$$

$$Battery\ capacity = \frac{5v \times 0.25A \times 8 * 2}{12 \times 0.8 \times 0.8} = 6.5Ah$$

$$(1)$$

The power consumption specifications of the ESP8266 controller were referred, to calculate the current requirements of the nodes. The tabulated data regarding the Power consumption of the ESP8266 controller are as follows (Table 1).head.

Table 1: Power Consumption of ESP8266

Mode	Min	Typ	Max	Unit
Transmit 802.11b, DSSS 1 Mbps, POUT = +19.5 dBm	-	240	-	mA
Transmit 802.11g, OFDM 54 Mbps, POUT = +16 dBm	-	190	-	mA
Transmit 802.11n, OFDM MCS7, POUT = +14 dBm	-	180	-	mA
Receive 802.11b/g/n	-	95 ~ 100	-	mA
Transmit BT/BLE, POUT = 0 dBm	-	130	-	mA
Receive BT/BLE	-	95 ~ 100	-	mA

It is evident by the above data analysis, that the maximum current for the controller at 19.5dBm wireless power is 240mA. But, a considerably good Wi-Fi signal controller, which requires much less power, may consume approximately 190mA at 16dBm RF power consumption.

Counting the additional power consumption by the sensors in the nodes to be around 50mA, the output current can be rounded off to an approximation of 250mA. The ESP8266 microcontroller, having a recommended power supply current of 500mA, regarding the datasheet, in turn, provides the power supply a range of current up to 500mA. Hence, the power requirements for the nodes were finalized as follows.

Table 2: Load power consumption

	Min	Typical	Max
Output voltage (1% ripples)	4.9VDC	5.0VDC	5.1VDC
Output current	25mA (sleep mode)	250mA	500mA

3.2.2 Energy Source

As was discussed in the previous chapter Lithium batteries were chosen as the energy source for the nodes of the WSN. Though for generally used sensors the supply voltage is either 3.3V or 5V, a 12VDC optimum voltage was decided upon, in consideration of the possibility of cases where industrial level sensors may be interfaced. Sensors demanding a supply voltage of 12VDC can be connected directly to the power supply if required.

Though the load calculation provided 250mA as the rated load for the nodes, it should be noted that the power consumption will reduce to a minimum, at times when the nodes remain idle, where the controller functions in its Sleep Mode. Therefore, a period of 8 hours was arbitrarily decided as the operation time of a node per day, and the Battery capacity was calculated as follows, for an assumed period of 5 such days, where a node will run without intermediate charging.

3.3 Transmission Modes

This study explored two different transmission modes where the First mode is a common transmission mode that is the so-called raw sensor data transmission mode, the node reads the data and directly transmits them to the base station, and the mean operation is executed on the base station. The second mode transmits data to the ThingSpeak web server in the Base station using Wi-Fi. For each sensor node and base node, the above flow charts (Figure 7) can be considered as the working principle.
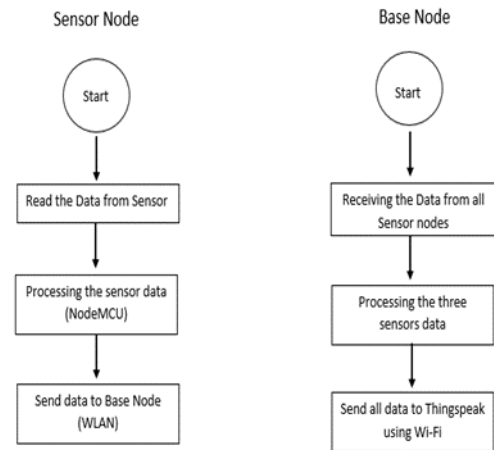

Figure 7: Flowcharts of the Nodes

4. DESIGN AND IMPLEMENTATION
4.1 WSN Design

Since WSNs are networks composed of a large number of sensor nodes that are defined to collect data it is configured to wake-up, self-test, and establish dynamic communications among the nodes that are installed over a desired area. In that case, it is found that the WSNs are characterized by, Limited voltage supply, Limited communication abilities and Computing power

To access the information accurately and time, we must rely on the collaboration of the nodes. Which is defined by the protocols and algorithms. Each sensor node consists of four components,Sensor Unit to Monitoring regional information collection and data conversion, Processor to Controls the entire operation of sensor nodes, storage and processing of data collection itself, as well as other data sent to the nodes Wireless Communication Module to Operates wireless communications, information collection and exchange control data acquisition Energy Supply Unit to Powerup the sensor nodes. usually, batteries are used.

In our design we have used the above-mentioned sensors of DHT11 and MQ135 as sensors, NodeMCUs as processing units, ESP8266 as the wireless communication module, and Personal Computer (PC) power-up as the energy supply unit.

4.2 Power Converter Design

Related works are existing on designing DC-DC converter for WSNs [12-15]. However, given designs are for different types of microcontroller based circuits and not for ESP8266 also application specific. Based on the requirements of the controllers and components of the nodes, it is clear that the system needs a DC-DC converter with a protection circuit along with the controller. The following was decided as the basic requirements that need to be fulfilled by the design of the power converter.

i.   Higher stability in voltage

ii.   A method to prevent over-voltage

iii.   Maintaining low voltage and current ripple

iv.   Smooth operation in low power level

v.   Efficiency in the system to save battery

vi.   Smaller size in the nodes

To accomplish the aforementioned features in the converter, the main factor considered was the converter's switching frequency. Though the frequency may depend on the application to a certain extent, achieving a higher frequency in the converter will be beneficial by, decreasing the ripple level, improving the dynamic performance, and reducing the inductor and capacitor size, hence decreasing the sizes of the components and in turn the size of the converter physically.

The ESP8266 microcontroller uses a clock pulse which ranges within the MHz range. But a switching frequency in the MHz range may cause disturbances to the power of the controller, due to which a switching frequency of 180 kHz was agreed upon as suitable to both reduce the operating frequency of the controller and to maintain a favorable level of dynamic performance while maintaining a lower rate of switching losses.

Another major factor when building the best power converter is the maintenance of the voltage at a suitable level, to achieve which the experiment incorporates a step-down (buck) converter circuit as shown in the figure below, due to its ability to always produce lower output voltage in comparison to the supply voltage.
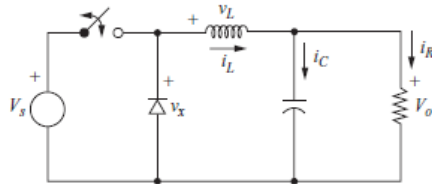
Figure 8: Circuit for a step-down converters

The relation between the input and output voltages of the converter can be depicted as follows.[7]

$$V_0 = V_S\, D \qquad (2)$$

Equation 2: relation between the converter's input and output voltages

When a DC-DC power supply gives a smooth output current, the output current is prone to remain a value greater than zero, hence causing the circuit to operate in a conduction mode continuously.

To decide upon the Inductor value for smoothing in the converter the equation was applied as follows, where 20 percent was considered the acceptable Inductor ripple current, thereby leaving the further smoothening of voltage to the capacitors. The Inductor ripple current was found to lie between 20% and 40%.

$$L = \frac{(V_s - V_0)D}{\Delta\, i_L\, f}$$

$$L = \frac{(12 - 5) \times \frac{5}{12}}{0.2 \times 0.25 \times 180000} = 3.24 \times 10^{-4}\mathrm{H}$$

$$(3)$$

The above derived value for Inductance was increased by 25 percent, to ensure the continuous current flow in the circuit, to get a value of $4.05*10^{-4}$ H which was then rounded off to $5*10^{-4}$ H.

$$C = \frac{(1 - D)}{8L\left(\frac{\Delta V_0}{V_0}\right)f^2}$$

$$C = \frac{(1 - \frac{5}{12})}{8 \times 5 \times 10^{-4}\left(\frac{0.01}{5}\right)180000^2} = 2.25\mu\mathrm{F}$$

$$(4)$$

The capacitance for the component in the converter was determined to be 2.2 µF using the below shown equation, and the consideration of the capacitors' market availability. The voltage ripple was assumed to be 1% at 50V, for the calculation.

The converter was then designed and simulated with MATLAB 2017a   (Figure 9) utilizing the above derived parameter values to obtain voltage and current waveforms (Figure 10).
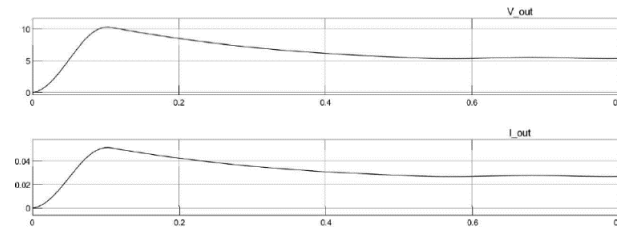

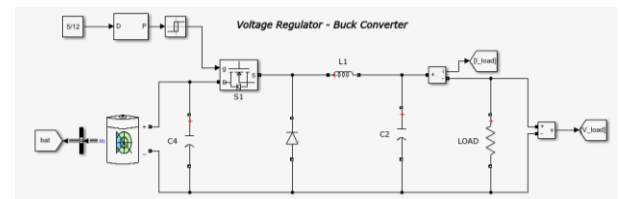**Figure 9: Circuit for a step-down converters**

Figure 10: Circuit for a step-down converters

Though the circuit created so far gives a continuous 5V supply at the steady-state of the waveform, a spike can be observed in both the voltage and current waves at the transient of the period, which given to a real component may even cause the component to get damaged due to overvoltage. To prevent these damages by over-voltage, a few functions were applied to the converter to improve the transient stability as well as to prevent over-voltage due to other reasons.

4.2.1 A PID controller system for a soft starting circuit

By applying a PID controller to the converter as shown below in figure 11, we were able to obtain a waveform with a smoothened transient as follows (Figure 12).
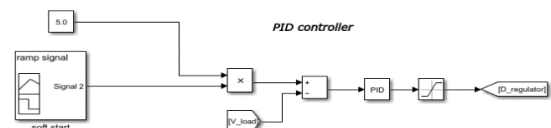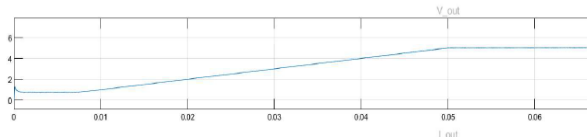

Figure 11: PID Controller

Figure 12: Output waveform after adding a PID controller

4.2.2 Crowbar circuit to prevent overvoltage

The voltage of a circuit though can reach a maximum value is always capable to damage sensitive, costly components in the nodes if reached the said maximum. [12] The crowbar circuit, which uses thyristors and a voltage sensing circuit, being placed at the output of the power supply can be considered an ideal solution for the possible damages by this problem of overvoltage. Here, the SCR which is connected parallel to the output voltage, in the Crowbar circuit will be triggered in the presence of an unnecessarily high power, which will then instantly short-circuit the output, hence saving the sensor circuits from being damaged. The shunt SCR used for the simulation and the output waveform that was received as shown in figures 13 and 14, respectively.
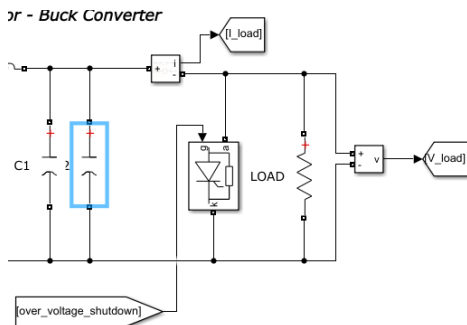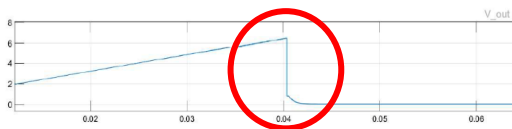

Figure 13: Crowbar Circuit

Figure 14: Crowbar Circuit's function at over voltage

4.2.3 A solution at high ripple frequency

As a solution to the poor response to high ripple frequency of the electrolytic capacitors, ceramic capacitor can be used at the output instead, due to their better performance in high signal frequency.

4.2.4 A battery protection circuit

Damages to the battery due to short-circuiting and other possible faults too were considered when designing the circuit, as a solution for which the protection circuit as shown in the figure was used in the simulation. The battery's over discharge, which may affect the battery's lifetime if occurred during the operation period, and the overheating of the battery were effectively prevented by this protection circuit by suddenly reducing the converter's duty cycle to 0%, had a fault been detected.
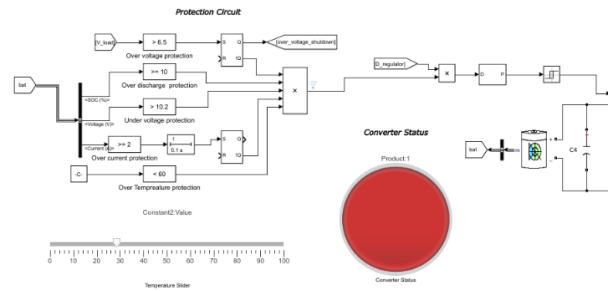

Figure 15: Protection circuit implementation

5. TESTING AND RESULTS

5.1 WSN Functionality

5.1.1 Serial Monitor Results

Once the hardware implementation was completed the results were observed through the serial monitor and compared with the outputs of the Webserver ThingSpeak. Following figures 16 and 17 are the screen captures of the test results.

Figure 16: Crowbar Circuit   Figure 17: DHT11 Sensor B Readings

Figures 18 and 19 below are also screen captures of the test results of the sensor and the generic node's receiving data serial monitor.

Figure 18 : DHT11 Sensor A   Figure 19 : DHT11 Sensor Readings   A Readings

5.1.2 ThingSpeak Server Results

Once the data is sent to the server through the internet the webserver will process data and output the following results.
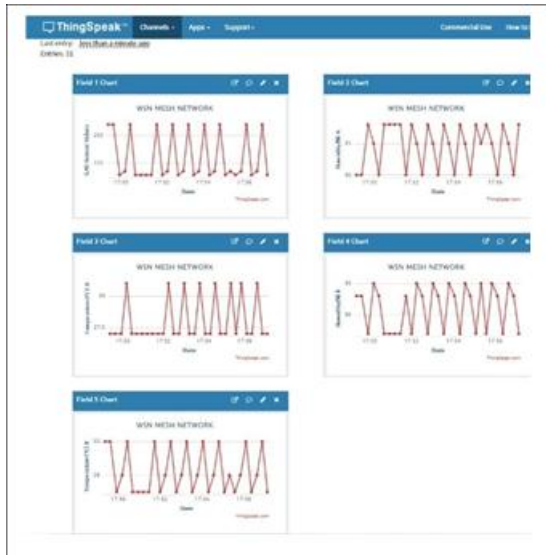
Figure 20: ThingSpeak Results

5.1.3 Input power efficiency

After simulating the power conversion circuit, the voltage ripple and inverter efficiency were evaluated at a few different load conditions, to obtain the following observations, where it could be seen that the converter performs best in 500mA load with an efficiency of almost 94% in typical load.

Table 3: Test result under different load

	25mA (200Ω load)	250mA (20Ω load)	500mA (10Ω load)
Voltage ripples	1.056%	0.66%	0.47%
Efficiency	94.98%	93.78%	98.4%

6. CONCLUSION

In conclusion, the designed system can be considered as a successful implementation comparing with the results give. And also, it is discovered that there are limitations for this system, and it must be further studied to overcome and broaden the usage. Sensor node failures might occur due to physical damages or exhausting energy supply and it is essential to design the system which can minimize the dead nodes or implement a self-routing protocol to continue the communication without any fail. The additional functionalities such as secondary sensors and localization modules increases the cost and energy consumption while making the physical size of the node much larger. Sensor nodes are meant to be powered-up with batteries and nodes can be power hungry. Hence, it is mandatory to supply enough power to the nodes to complement the system and run smoothly. An additional ESP module was used to connect the three nodes because the library clash in the sink node which contains ThingSpeak activating libraries. Hence, the additional module can be disregarded if the nodes are connected to the server directly. Furthermore, the ThingSpeak server results give spikes as the output graphs which can be seen in figure 19. It can be stated as it was because the data wasn't sent to the server constantly. Hence a drop is recorded

when the data is absent. To overcome this issue, it is suggested to use an interpreter to remove the zero in middle. A power supply with a good step down converter at the power input of the node, especially in applications such as this, where sensor nodes can be placed spatially dispersed, can be quite advantageous and cost effective. A converter with best protection adaptations and most suitable components will enhance the operations of the Wireless Sensor Network the most as a whole.

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