Development of a Low-Latency Wireless Telemetry System for Monitoring Patients Heart Rate

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Abstract – *Telemetry systems provide a means to monitor the physical state of a machine, human beings, and environmental conditions. The need for a telemetry system arises due to the increasing desire to simultaneously monitor, measure and record critical data of patients located in different places at optimal cost. Toward this end, a wireless telemetry system was designed and implemented, especially for small-scale medical applications, particularly, for proper monitoring of the heart-rates of mostly elderly patients. In order to enhance the capabilities of the system, an infrared-based pulse Oximeter sensor was designed and integrated into the telemetry system, and this sends the acquired data to an Arduino microcontroller for pre-processing. The controller sends the pre-processed data to a coordinator PC over a ZigBee mesh wireless network, via a graphical user interface (GUI). For seamless transfer of data from source to destination, a source routing algorithm was applied to route the desired data over the proposed ZigBee network. Thus, an optimized source routing algorithm was evolved, and applied to the telemetry system in order to lower the latency of data transmission of the nodes over the wireless network. Finally, the performance of the optimized routing algorithm was compared with the existing source routing algorithm, and the wired telemetry system. Results show that data routing through the wired telemetry has much lower latency among the investigated routing schemes, and the optimized source routing algorithm transmits data with substantial gains in throughput, and achieved average latency about half the latency of the source routing algorithm.*

Keywords: *Wireless Telemetry System, Pulse Oximeter, Latency, Throughput, Patient's heart rate*

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I. Introduction

In order to monitor the state of a device, an environmental condition, or the physical state of the human body, measurements would have to be taken through physical inspection on a small scale (e.g. a single measuring node) [1]. However, the human inspection method becomes inefficient and unsustainable for medium to large scale measurements scenarios. This fuels the need for a scalable system that allows or supports measurements from multiple sources of interest in real-time, and ultimately, led to the development of the telemetry system [2]. The idea of the telemetry system could be traced back to 1845 where one of the first data-transmission circuits was developed and applied in Russia, and further advancement in the design of a telemetry system was reported in 1874 by French scientists and engineers, and in 1901 by the American scientists [3].

In recent times, the development of remote monitoring systems for data gathering has shown to be an ever-advancing area of research, especially with the advancement in technologies leading to the development of cutting-edge wireless communication protocols [4]-[6]. Most wireless telemetry systems use the point-to-point network topology, which seems to be cost-efficient for a single-user or for very small-scale applications but these often fail reliability tests, and consequently, results in frequent link failure, especially when they are applied to monitor complex infrastructure [7].

Interestingly, recent advancements in the application of Internet of Things (IoTs) in areas like smart metering, smart farms, smart home appliances, patient monitoring systems, has given rise to the development of cost-efficient telemetry systems, which provide the optimal amount of data throughput required for the desired application at the lowest latency [8].

The demand for a telemetry system stems from the ever increasing requirements to accurately monitor, measure or record critical data of patients at multiple locations with great affordability and efficiency [9]. For instance, the old electrical energy metering system in operation before the advent of wireless telemetry-based energy metering systems was done using the electro-mechanical energy meters, which requires an employee of the utility company to physically visit the location of the consumers on a routine basis to inspect energy usage as displayed by the meter, while energy consumed is being calculated. A number of inefficiencies or inconveniences occur as a consequence of this crude system. The meter could be tampered with by a consumer who is willing to reduce his or her energy consumption bills. Also, sending an employee to every consumer premises could be cost prohibitive. Aside from being time inefficient, the traditional system incurs additional travel expenses for the utility company, and some locations may be insecure for the employees to visit. Hence, making it nearly impossible to properly account for the comprehensive energy usage by the consumers. Another drawback of this system is that local fault detection like black-out conditions is relatively difficult to determine instantly because utility consumption is not adequately measured in real-time.

Today, the use of wireless telemetry system has enabled smart electricity system metering. This implies that consumers' electricity usage could be well monitored in real-time, and faults like black-out would be easily detected and resolved. Therefore, it becomes very difficult for consumers to alter the readings of the meter, the utility company also save enormous cost in terms of travel expenses for the employees, and unnecessary risks to the life of the employees is totally avoided.

In this paper, we present a design deploying ZigBee communication protocol by using a mesh topology to provide redundant network paths in case of failure of the primary link to the telemetry system coordinator, whilst applying routing strategies to improve throughput and latency. The system basically takes measurements using pre-designed sensors connected to a microcontroller, which converts the analog signals to digital signals, and then sends the signals to the ZigBee module, which in turn sends the data to the systems' coordinator. In this scenario, the patients' information are organized and reported using suitable data analytic tools. In order to achieve the complete system design, a wireless telemetry system using a ZigBee module is constructed, and then a wireless telemetry system for a pulse Oximeter that uses infrared rays for detection is designed with an Arduino microcontroller for processing. Second, a ZigBee wireless module is deployed for wireless communication, and a Python-based program was written for displaying the results in a robust graphical user interface (GUI).

In addition, a wireless mesh ZigBee network using the source routing algorithm is implemented, and the source routing algorithm was optimized in order to reduce the data transmission latency over the wireless network. Finally, the performance of the system is demonstrated, in terms of data transmission using statistical analysis, and the impact of the source routing algorithm, and the optimized source routing algorithm on the data throughput of the network were observed and tabulated.

The remaining part of this paper is organized as follows. Section 2 reports the related work and theoretical background. Section 3 presents the materials and design methodology. Section 4 displays the results and discussions. Finally, the conclusion and future perspectives are given in Section 5.

II. Related Works

In order to monitor the status of stroke risk patients, Hofmann *et al.* [10] implemented a telemetry system, which comprised of five autonomous sensors capable of measuring ECG using a VitaSENS® sensor, breathing using a nasal cannula, which is worn under the patient's nose, pulse oximetry using a VitaSENS® sensor, movement using a per minute three-axis motion sensor attached to the chest of the patient, and temperature sensor. The sensors are connected using the Bluetooth communication protocol and this communicate with the remote collector using the Zigbee communication protocol.

Also, Zhou *et al.* [11] designed and constructed a wireless telemetry system to monitor and control the environmental values in a greenhouse. The network architecture contains sensor nodes, a ZigBee router node, a coordinator node, and a remote computer. The architecture is designed such that the sensor nodes are connected to the ZigBee router in a star topology while the ZigBee router is then connected to the coordinator node, and an ad-hoc node as a redundant network path in the case of failure. The coordinator node then connects to the remote computer over the internet using a GPRS network. The sensor node contains humidity and temperature sensors connected to a JN5121 microcontroller. The coordinator and sensors nodes are designed with screens to display the numerical readings taken in real-time. However, the system could not support multiple applications for large-scale infrastructure.

Frehill *et al.* [12] reported the impact of using the Zigbee communication protocol for wireless telemetry applications for medical devices. The impact was analyzed in terms of power consumption, throughput, mobility and co-existence with other telecommunication devices. In terms of power consumption, the ZigBee device tested was found to have a suitable power consumption rate as it supports a sleep mode that consumes current up to 1.0 μA. In terms of throughput with the ZigBee module offering data throughput of about 2.5Mbps, it meets the specified requirements of the system at full operational status. Since the Zigbee modules are very small in size, the mobility requirement was satisfied. Although the Zigbee module operates in the 2.4GHz ISM band, caution had to be taken on frequency selection in order to avoid interference with other adjacent and co-channels.

In another related report, Cao *et al.* [13] proposed and designed a telemetry system for a remote meter reading. The system uses the hybrid ZigBee network topology, which is a combination of the mesh and star ZigBee network topology. The network consists of sensor nodes (meter, microprocessor unit, and ZigBee wireless modules), data collectors, and servers. Data from the digital meter is transmitted to the data collector using a ZigBee transmission network, and the frequency of transmission depends on the system requirements. The ZigBee hybrid network was designed using an enhanced LEACH protocol system [5]. The protocol system chooses the best number of cluster heads to ensure the lowest exhausting energy of the network at each transmission, hence, increasing the data receive rate up to 93.11%. The maximum distance allowed for data transmission was also increased and the complexity of the wireless network was greatly reduced.

Watthanawisuth *et al.* [14] designed a wearable pulse Oximeter that utilizes a Zigbee mesh to collect data from multiple patients, simultaneously. The sensory module uses two LEDs and a photo-detector with an amplifier and a low pass filter to detect the heart rate and oxygen saturation of the patients. The analog signal collected is converted to a digital signal using the PIC18F87JI0, and transmits the data to the doctor's node using a Zigbee module. At the doctor's node, a Zigbee module which is used to collect data from the patient's node is connected to the doctor's PC using a serial to USB converter. When the wireless Oximeter's performance was compared with the commercially available Rossmax pulse Oximeter, the telemetry system proposed by the authors was found to have an accuracy of about ±2%.

Moreover, Adochiei *et al.* [15] designed and implemented a wireless telemetry system for a pulse oximeter. The system consists of an eZ430-RF2500 pulse oximeter board, which measures the heart rate of the patients and the data is then sent to an MSP430F2274 microcontroller, which analyzes the data and sends the data to the doctor using the CC2500 wireless transceiver. The circuit is powered using two 1.5V AAA alkaline batteries, which provides a life expectancy of about 205 hours. The SimpliciTi communication protocol was used in the design of the telemetry system, while the GUI on the doctor's end was designed using C# in Microsoft visual studio. The accuracy of the system was measured using the Metron SpO2 simulator, and it was found to have an accuracy of about ±1%.

Furthermore, Wang *et al.* [16] designed and implemented a wireless telemetry system to monitor forest fire using a ZigBee mesh and GSM network. The proposed system contains a number of measuring node clusters connected to a distribution node, which is then connected to a coordinating node using a GPRS network connected to a monitoring host over the internet. The measuring node contains an ultraviolet radiation sensor, temperature sensor, a humidity sensor, and a smoke scope, all connected to a CC2430 microcontroller, which converts the analog signals to digital signals, and transmits the signal to the cluster distribution node using a 2.4GHz ZigBee module. The ZigBee node cluster forms a sort of mini mesh network with the distribution node using a cluster-tree protocol. The data is transmitted to the distribution node using a per-hop system and data from the distribution node to the coordination node is transmitted using the multi-hop routing scheme. The coordinator node collects data and transfers them to the GPRS network. The monitoring center uses File Transfer Protocol (FTP) server to collect the data received from the monitoring nodes, process and analyze the data for appropriate inference.

Similarly, Primicanta *et al.* [17], Shahid *et al.* [18], and Veettil *et al.* [19] designed and constructed different forms of telemetry systems for automatic electric energy metering, using ZigBee and GSM networks. The designs collect data from the energy meter either the digital or analog type, where the analog meter is used and an Opto-coupler could be required to electrically isolate both circuits. The major difference among the three designs presented in [17], [18], and [19] is in the ZigBee network topology. The star topology is used in [17] with a ZigBee router acting as the coordination node, and this was connected to the central server over the internet through a GSM network. Specifically, the design implemented by [18] is a one-node network with the ZigBee transmitter connected to a GSM network to allow the digital meter to be monitored over the internet. In particular, the design in [19] utilizes a peer to peer network topology and the telemetry of the consumer node controlled by the LPC 2148 microcontroller, the wireless communication to the energy company is fully provided by the ZigBee network with the GSM module used only to provide necessary short message services alerts to the consumers.

Haefke *et al.* [20] proposed and implemented a smart sensing system for recording environmental parameters like temperature, humidity, pressure, and light in order to measure current weather conditions and predict the future trends. The system is made of several measuring nodes and the coordination station. The measuring nodes collect data by using four measuring sensors: The temperature sensor, which uses the DS600 integrated circuit (IC) and produces an analog output, the humidity sensor, which uses HIH-4010 IC to produce an analog output, the light sensor, which uses the BPW21 photodiode to measure light intensity, and the pressure sensor, which uses the MPX-4100 IC to produce an analog output, and then converts the data, using the C8051F020 microcontroller to convert the analog signals from the sensors to digital signals, and then sends them to the coordination station using the XBee S2C pro ZigBee module. The coordination station comprises of a ZigBee module, and a computer system to accept, validate, and parse the received data. Since the XBee module does not support checksum to ascertain the validity of the data received, data correctness is validated using the first three characters of the twenty-seven character send string, and the measuring node is used as its unique identifier address as a means to provide some sort of data validity.

Zulkifli *et al.* [21] designed and implemented a centralized heart rate monitoring telemetry system that wirelessly monitors the heart rate of multiple patients, simultaneously over a ZigBee mesh network. The system is divided into the patient node, and the network coordinator, which is at the doctor's end. The patient's node contains an Oximeter, which measures the patients pulse in real-time, and the data obtained is then passed to an Arduino Nano microcontroller, which converts the signals analog from to digital, attaches its unique address to each data stream, and sends it to the ZigBee transmitter module, which then sends the acquired data to the coordinator node. This contains a ZigBee receiver and a computer, which interprets and displays the data collected from the patient to the doctor. The use of a mesh network, in this case, means the data coming from each node needs to be uniquely identified and this is done by assigning each node a unique address using the Arduino Nano microcontroller. Also, the collected data would either transmit directly to the coordinator node or to the nearest patient node as an indirect route to the coordinator node.

On the design of a wireless telemetry system for an ECG (Electrocardiography) machine, Hashim *et al.* [22] use a PIC 16F877 microcontroller to convert analog signal to digital, and then transmit the signal over a ZigBee point to point network using the XBee S2C pro module to the receiving end of the network, which in this case, is the doctor's end. The received data is then parsed by the microcontroller at the doctor's end and display on the doctors' computer. The input signal from simulation using a voltage regulator circuit was observed in [22], whereas, a similar system was reported in [23] where the input signal from a human body was obtained using electrode probes. There were also differences in the outputs display in [22], which used a Graphical User Interface (GUI) and [23], which uses an analog graphical format to display the output of the measured signal.

Dai and Luo [24] designed a wireless pulse Oximeter that uses a Bluetooth 4.0 module. The pulse oximetry sensor was designed using red and infrared LED lights, and a photo-detector, in which the signals collected are amplified and are made rid of noise, using a low pass filter with a cutoff frequency of 8Hz. The signal is passed onto the 12-bit ADC (Analog to Digital Converter), which is integrated into the CC2540 Bluetooth module, which in this design performs the function of transmitting the oximetry data to a smartphone. The oximetry data acquired from the designed telemetry system was compared to a commercially available pulse oximeter to test for its accuracy and after sampling with 35 patients, the system was observed to maintain the accuracy of +1.8% for oxygen saturation measurements, and 2.7bpm for heart rate measurements.

Panicker *et al.* [25] reported a design to monitor the heartbeat and temperature of a patient. The proposed system conprise of a transmitting device, which is at the patient's end, and a controller, which is at the doctor's. The system uses temperature sensor IC (LM35) and a LED and LDR type heart sensors to measure the patients vitals and sends the collected data over a ZigBee point to point network, using the AT89C51 microcontroller to parse the data sent or received. The data collected is then sent to a computer to be presented in a readable and visualizable form. The system also contains a Global System for Mobile Communication (GSM), which is used to enable the user to communicate with the hospital network when in a distant location.

Jaiswar [26] designed and implemented a telemetry system for monitoring the status and location of soldiers on the battlefield. The system consists of a soldier unit, and an army control unit. The soldier's end comprises of a temperature sensor, heartbeat sensor, Global Position System (GPS), Liquid Crystal Display (LCD) display, Panic Switch, and a Zigbee module, while the control room unit comprises of a Zigbee module, and a personal computer. The network adopts the ZigBee star topology, and the LPC2148 microprocessor was used to process the data obtained from the soldiers and sends it to the NORDIC nRF24L01 Zigbee module for further processing.

In a related study, Kaur [27] designed and implemented a telemetry system for energy metering. The system was implemented using a ZigBee mesh network. In the design, the energy meter is connected to a ZigBee module, which is regarded as a user node, and is connected with a number of other nodes to form a mesh network connected to a ZigBee coordinator node, which serves as an intermediary between the mesh network, and the user node controller, which in this case, is a personal computer. The connection between the user node in the mesh, and the coordination node could either be direct like a peer to peer connection or via a closer node in the form of indirect routing of data. Test results from the author's design show that the average latency of communication for user nodes connecting directly to the coordination node is about 4-5 seconds, while the average latency of the user nodes connecting via the network mesh is about 11 seconds.

Adiputra *et al.* [28] designed a low-cost telemetry system used for the measurements of oxygen saturation and heart rate. The system was designed to be dimensionally small and wearable with high mobility. Hence, the finger oximetry module was designed with a photo-detector, and a low-pass filter and an AVR microcontroller to convert the analog oximetry signal to digital signals, and send the signal to the Node MCU which is a Wi-Fi module, and also serves as a gateway to the internet. The gateway to the internet is needed because the data is sent and stored in a database. The database is parsed to a website, which grants the doctor access to the patient's oximetry data remotely at any time. The telemetry system was observed to operate at a bandwidth of 10Mbps and a latency of 3 seconds. Measured data collected by the telemetry system show accuracy of approximately ±3.0 bpm for the heart rate and over ±1.0% for oxygen saturation.

Banerjee *et al.* [29] designed a telemetry system used to monitor the heart rate, temperature, and the FABP3 levels of patients in real-time. The system design was divided into three units: The sensory unit, the analyzer unit, and the interaction unit. The sensory unit contains an LM35 temperature sensor that measures the temperature of the patient, and the AFE4490 pulse Oximeter kit, which contains the FABP3 level sensor and a ZFM-20 fingerprint sensor. The sensor unit is connected to the analyzer unit containing an Arduino Uno, a storage unit, which in this case is a database and a Wi-Fi module. This unit analyzes the data which the sensors provide to do the fingerprint scanner checks if the patients are registered in the database, and once the patient's identity is validated, the patient's heart-rate and oxygen saturation is monitored for inconsistent readings, and the body temperature is also checked using the data obtained from the temperature sensors, and the FABP3 levels, and check the data sent to the interaction units using the Wi-Fi module in the analyzer unit as an internet gateway. The interaction units consist of smartphones and other internet-enabled devices. It makes use of the data sent to it to inform medical professionals of any emergencies with the unique id of the patient which was initially validated using the fingerprint of the patient.

Mamoun *et al.* [30] design a telemetry system for non-invasive glucose monitoring, and self-medication system for diabetes patients. The system uses a pulse oximeter for the non-invasive monitoring of the person's glucose levels, and send the data to the Arduino Uno microcontroller board, which in turn processes the data and sends it to a self-medication kit connected to the patient. The self-medication kit consists of an Arduino Uno microcontroller board, buzzer, GPS, an Insulin pump, an Infusion set, and an insulin reservoir. The microcontroller on the self-medication kit is a program with nine thresholds of which some have certain actions attached to them. Hence, when the glucose level collected matches a certain pre-defined threshold, the self-medication kit injects a certain amount of insulin based on the threshold to the patient. When the glucose level is at certain threshold, an ambulance is alerted of a possible medical emergency of which at that time, the GPS on the self-medication kit is activated and the exact position of the patient is provided to the ambulance. The system is programmed to send telemetry data every 30 seconds and was observed to operate with an accuracy of up to 89%.

Furthermore, Merkepci *et al.* [31] designed a telemetry system for remote non-invasive monitoring of blood pressure and oxygen saturation using a photoplethysmography (PPG) over a Zigbee based network architecture. The sensor uses a red and an infrared LED to sense the blood volume of the patient and then, uses a color sensor to transform the PPG signal to a pulse signal for amplification and filtering. The signal is then sent to the PIC16F877A microcontroller for evaluation, analysis and visual display. The microcontroller also sends the oximetry data collected from the patient to the doctor via the

Zigbee module connected to it. Upon implementation of the design, the sensors were observed to maintain percentage errors ranging between ± 2–4%.

Nagar and Bhatnagar [32] observed the performance of the ZigBee communication protocol in the design of a telemetry system for monitoring the health status of a patient in order to inform a person's medical service vendors about potential physiological illnesses based on pre-created illness profile reported by the medical service vendor. The telemetry data of the person's physical status is compared with the created profile to determine if the medical service vendor needs to be altered to a potential problem that might warrant further investigations. The data is collected using sensors like temperature sensors, glucometer, and pulse oximetry sensors. The authors observed that an increase in the number of consumer nodes decreases the packet delivery ratio (PDR) and throughput, and the energy consumption and latency of the telemetry system were seen to increase when the number of nodes increases.

III. Design Methodology

The proposed telemetry system uses a mesh topology which offers a cost effective solution as the scale of the system increases. The topology for the proposed telemetry system comprises of three sub-units: The measuring sensors: GY-MAX30100 module, micro-controller unit: ATmega328 processor AVR, and the wireless communication module: XBee s2c ZigBee module. The hardware components required for this implementation are the Arduino Nano V3 (ATmega328 AVR) microcontroller unit, 5V 5000mAh LiPo Battery, XBee S2c ZigBee module, and XBee USB mini adapter. The processing microcontroller (Arduino ATmega328 AVR) controls all processing operations at the Oximeter node. The Arduino Nano is powered by ATmega328 AVR microcontroller, and its specifications are obtained from the manufacturer's data sheets. The wireless communication unit (XBee S2c module) is responsible for transmitting telemetry data from the oximetry node to the coordination unit, and the ZigBee communication protocol is used to establish and maintain communication in the telemetry system.

A. Design Considerations

The design considerations covers (1) power dissipation, (2) power supplies to the system circuitry, (3) pulse Oximeter circuit design, (4) Low pass filter design, and (5) Amplifier circuit design.

1. Power Dissipation

a) Arduino Nano microcontroller board:
Operation Voltage = 5V
Current Consumption (at 25°C) = 40 mA
Power dissipation = 5 x 40 = 200 mW

b) Pulse Oximeter circuit:
Operational Voltage = 5V
Current Consumption = 1.2 mA
Power dissipations = 5 x 1.2 = 6 mW

c) XBee S2B Zigbee module
Operational Voltage = 2.1 V
Current Consumption = 45 mA
Power dissipations = 2.1 x 45 = 112.5 mW

The total power dissipation for the telemetry system in an operational state gives

$$200 + 6 + 112.5 = 318.5mW$$

2. Power Supply

In designing the power supply unit for the telemetry system, some factors were taken into consideration. These include the power supply, which has to supply steady voltage to the circuit, the device has to be portable and autonomous, hence, the use of a dc battery. The dc battery has to be rechargeable, therefore, a charging circuitry is needed, and the battery needs to have the capability to sustain power for at least 24 hours. Based on these design requirements, the optimum power supply viable for the circuit is a rechargeable dc battery but the capacity of the battery needs to be determined, and based on the individual specifications of the devices to be used, the total current equals to,

$$40 + 1.2 + 45 = 86.2mA$$

Due to components non-availability constraints, the 5V supply which falls within the safe operating range of all the circuit elements is used, and the total power equals to

$$P_{Total} = 86.2 \times 5 = 431mW$$

Then the energy consumed in 48 hours is

$$431 \times 48 = 20,688\ mWh$$

The capacity of the source is given by

$$Q = \frac{E}{V} \quad (1)$$

where E is the total energy consumption of the telemetry device, and V is the dc supply voltage into the circuit.

From equation (1), the capacity of the source equals to

$$\frac{20,688}{5} = 4,137.6\ mAh$$

Also, the total voltage requirements of the circuit is

$$5 + 2 + 2.1 = 9.1V$$

Based on the calculated values, the choice of dc battery quantity and capacity becomes obvious. Hence, three units of the 3.75V 3000mAh Lithium Polymer (LiPo) battery connected in series would be used to power the circuit. Since the current capacity of the source is approximately 5000 mAh, therefore

$$t = \frac{3000}{86.2} = 35 \text{ hours}$$

3. Pulse Oximeter Circuit Design

The input voltage of the sensor circuit is 5V (obtained from the Arduino terminals). The sensor measures the patients' heartbeat using the infrared (IR) detector. The following calculations are derived based on the data obtained from the datasheets.

$$V_{em} = 1.2V, I_{tem} = 20mA$$

Using Ohms law, $R = \frac{V}{I}$ (2)

$$R_1 = \frac{5 - 1.2V}{20mA} = 190\Omega$$

To calculate the value of the detection series resistor, the purpose of the sensor design is to keep the output voltage from the sensor between the range of 2V and 3V of the 5V supply. In order to calculate the resistance value, the current flowing through the line need to be determined.

$$V_{min} = 2V, R_{em} = 40\Omega$$

$$I = \frac{2}{40} = 50\text{mA}$$

$$V_{res} = 2V, R_2 = \frac{2}{50mA} = 40k\Omega$$

Hence, R_1 = 190Ω, R_2 = 40 kΩ. The peak-to-peak voltage of the IR LED is 0.13 V.

The maximum input voltage from sensors that can be read by the Arduino is 5 V. Hence, the gain to be chosen is to ensure the peak–to–peak voltage does exceed the 5V threshold. Therefore, the desired gain is 10.

4. Low-Pass Filter Design

A low-pass filter has to be designed to block out high-frequency noise from the IR input. A high-pass amplifier has to be designed to increase the peak–to–peak value of the input to enhance the accuracy of the oximetry sensor. The specific filter characteristics are given as follows,

i. the filter has to be a non–inverting unity gain amplifier

ii. the filter has to be a low-pass filter to filter out high-frequency noise

iii. the filter should be a 2nd order filter, specifically, a Butterworth filter using Sallen–key filter topology is used in this design because it meets the specified requirements.

For the Sallen–key topology,

$$R_5 = R \quad (3)$$

$$R_2 + R_4 = mR \quad (4)$$

$$C_1 = C \quad (5)$$

$$C_2 = nC \quad (6)$$

$$f_c = \frac{1}{2\pi RC(mn)^{0.5}} \quad (7)$$

$$Q = \frac{(mn)^{0.5}}{m+1} \quad (8)$$

Filter cut-off frequency for design, f_c, and for the Butterworth filter, Q = 0.707. In order to simplify equation (7), the value of RC = 1.

With f_c is set at 20 Hz, and using above information and equations (3) to (8), the following values are obtained; m = 0.988, n = 64.078 x 10^{-6}, $C = C_1$ = 100 µF, R = 10 kΩ, R_4 = 30.12 kΩ and C_2 = 6.407 nF.

5. Amplifier Circuit Design

The amplifier circuit-design characteristics are as follows. The amplifier is a non-inverting amplifier with a gain of 10. The circuit is a high pass filter, filtering out frequencies below 0.1 Hz. The LM324 operational amplifier is chosen for the implementation of the sensor and its quad op-amp design makes it suitable for the cascade implementation. The transfer function of the circuit is given in (9). Based on the design concept described, schematics for the wireless telemetry node was generated as shown in Fig. 1, and the hardware implementation of the proposed system is given in Fig. 2.

$$sC_3\left(V_{in} - V_{out}\right) = \frac{V^+}{R_5} \quad (9)$$

Based on equation (9), the following values of components for the heartbeat sensor circuitry are obtained; R_6 = 9 kΩ, R_7 = 1 kΩ, R_3 = 10 kΩ and C_3 = 159.15 uF.

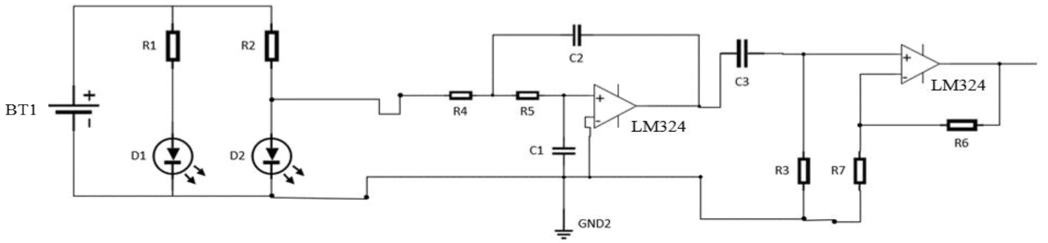

Fig. 1. Circuitry of the heart beat sensor

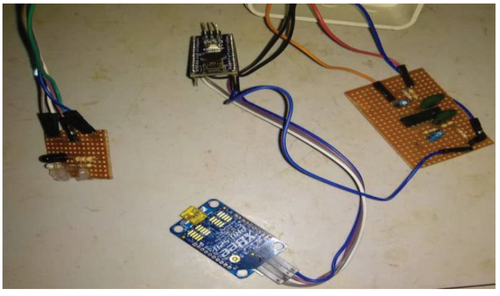

Fig. 2. Hardware implemetation of the proposed system.

B. Wireless Telemetry System Operation

The XBee ZigBee module utilizes the ad-hoc on-demand distance vector (AODV) routing technique, and supports two modes of routing namely the many-to-one routing and source routing.

In many-to-one routing mode, every member node send a broadcast many–to–one message to the central collector or the coordinator node, which in turn forms a reverse route based on path cost. This is then broadcasted to every node as a form of routing table. Hence, data is transmitted using the routing table.

In source routing method, each node maps all possible path to the central collector or the coordinator node after which a single path, which is manually chosen is used. A modified form of source routing is used where instead of the routing path being manually selected it would be chosen dynamically at a predetermined refresh rate based on the latency of each path from the node to a central collector. The microcontroller would leverage on the XBee source route application programming interface (API) in order to manipulate source route creation whilst storing the source route on the microcontroller.

The flowchart of the wireless telemetry system is as shown in Fig. 3. Initially, the oximetry data is collected and transmitted to the microcontroller for pre-processing. The data is converted from analog to digital, and then transmitted and received using the ZigBee module. The received data is further processed with Python based program and the oximetry output is displayed at the coordinator's PC for examination via a suitable graphical user interface (GUI) designed for the proposed telemetry system. If no new pulse is detected, the process is completed, and if a new pulse is found, the whole process is started again. A detailed step-by-step mode of operation of the wireless telemetry system is given in Fig. 4.

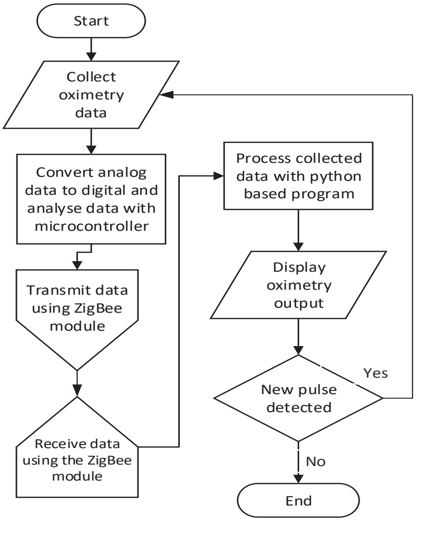

Fig. 3. Flowchart of the wireless telemetry system.

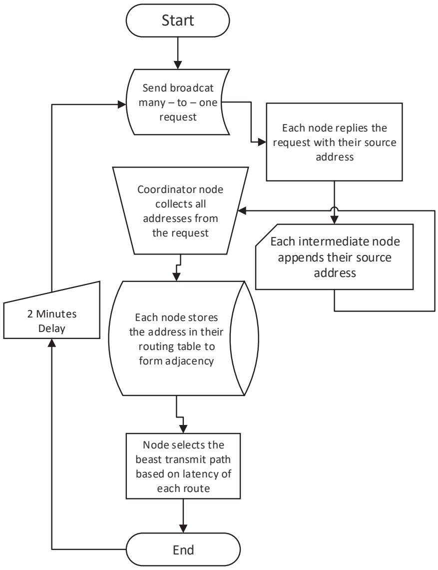

Fig. 4. Operation of the wireless telemetry system.

IV. Results and Discussions

In completing the software design, circuit construction, and implementation of the telemetry system, the associated devices were programmed per their functionalities, and the system was tested against predefined criteria. Results show reasonable agreement with expected outcome. The software implementation includes using the Arduino microcontroller to obtain data from the pulse Oximeter sensors, and sending the information to the coordinator's computer using the ZigBee module, including the C++ codes uploaded to it via the Arduino Integrated Development Environment (IDE).

The GUI displays the evolved wireless mesh newtork as shown in Fig. 5, the received signal strength indicator measurements sample are captured as shown in Fig. 6, and the throughput measurements of the wireless network is recorded as shown in Fig. 7. The coordinator's PC shows the oximetry data for each patient 1, 2, 3, and a composite graph for all patients as depicted in Fig. 8 to Fig. 11, respectively. In addition, the ZigBee module formed a mesh network using the proprietary XBee configuration tool, based on the configuration profile installed on the XBee by flashing its firmware, and this allows for a redundancy based telemetry. A routing path was also formed using the pre-configured source routing method. The source routing algorithm was then optimized to enable faster routing decisions using the most efficient route in the network, hence reducing the latency of data transfer.

The latency of the telemetry routing techniques at various SNR is as shown in Fig. 12, and the throughputs of the source routing, and the optimized source routing algorithms at various SNR are presented in Fig. 13. Table I presents a comparison of the latency of wired telemetry, wireless telemetry using the source routing algorithm, and the wireless telemetry using the optimized source routing algorithm at specific SNR. Finally, the throughputs of the wireless telemetry using the source routing algorithm, and the wireless telemetry using the optimized source routing algorithm at specific SNRs are tabulated in Table II.

The latency of the three pulse oximeter nodes were compared for the data collected (i.e. heart rate and blood oxygen saturation) in real-time for the wired and wireless telemetry systems. The heart beat rhythm as predicated in the design of the system was observed on the GUI of the telemetry system as shown in Fig. 5 to Fig. 7. When the wireless mesh was implemented and effective routing decisions were made using the native source routing algorithm, the network was seen to have a latency of about 7.5 ms for SNR < 52 dB. However, a spike in latency is observed at SNR > 53 dB, taking the average latency of the system to around 25 ms. Although, a temporary reduction in latency is observed at 57 dB, and a minor surge in latency is observed at 65dB asides from which the telemetry system maintains its increasing latency as the SNR decreases. Hence, the observable average latency of the system using this method is 28 ms. However, when the routing algorithm is optimized, the latency pattern was seen to be similar to that of the source routing algorithm with appreciable latency values. Similar to the source algorithm, the latency pattern exhibits linear properties until at 52dB, where there is a spike in latency taking the average latency to about 12 ms. Afterwards, there is an obvious minimal dip in latency observed at 57 dB, and thereafter, the latency of the system continues to increase with respect to a corresponding decrease in the SNR. Hence, the observable average latency using the optimized algorithm is around 15 ms as depicted in Fig. 12 and Table I.

Further to this, the throughput of the data transmission was compared for both the native source routing algorithm, and the optimized routing algorithm as shown in Fig. 13 and Table II. The throughput of the source routing algorithm was observed to decay faster than the optimized source routing algorithm, average throughput for the source routing algorithm is around 2.65 kbps while the average throughput observed for the optimized source routing algorithm is 3.7 kbps. These results are fairly comparable with the results by Adipura *et al.* [28], though the parameters considered are relatively different. Although, it is worth pointing out that due to the processing power required for making routing decisions in the source routing method, it is somewhat unsuitable for large-scale networks. Therefore, the source routing algorithm is restricted to a network size of approximately 40 nodes. Finally, the optimized many-to-one routing algorithm requires even more processing power of the devices. Therefore, it is suitable for only small-scale networks, and for larger networks routing, algorithms like the Ad-hoc distance-vector may be suggested. The implication of the results is that the proposed and implemented telemetry system is usable for only small-scale applications, for example, if the telemetry system is used for medical applications, it would best be applied to relatively small hospitals, clinics and maternity homes, and the system may not be applied to large hospitals with complex infrastructure.

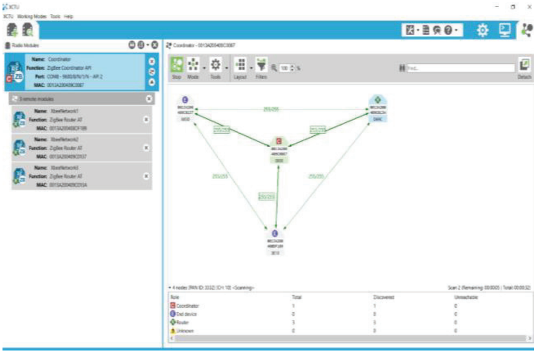

Fig. 5. Wireless mesh network.

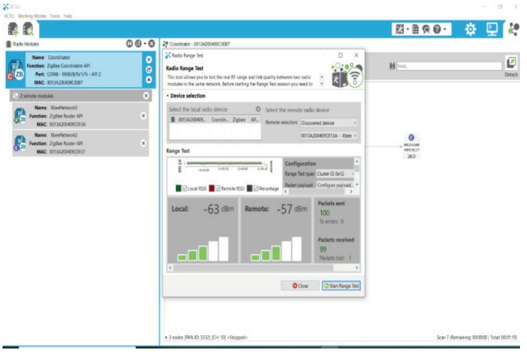

Fig. 6. RSSI measurement sample.

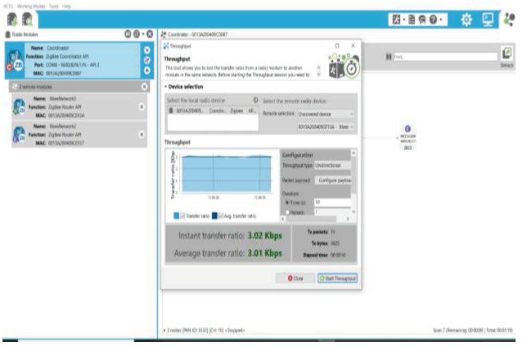

Fig. 7. Throughput measurement of wireless network.

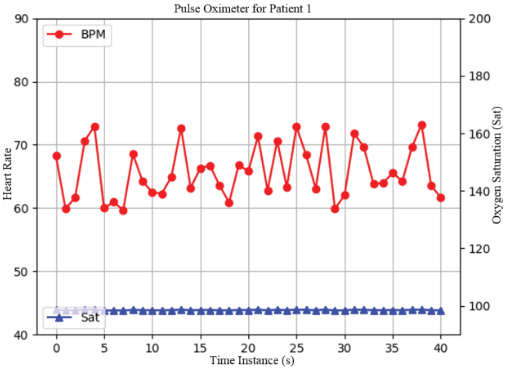

Fig. 8. Pulse Oximeter output for patient 1.

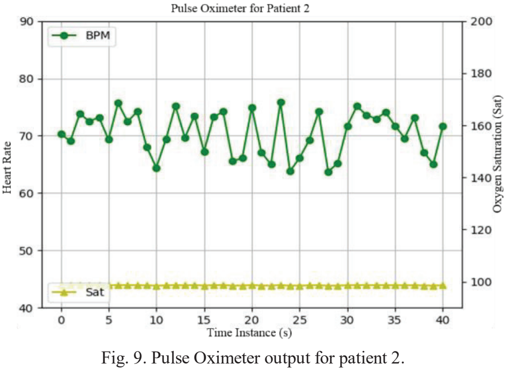

Fig. 9. Pulse Oximeter output for patient 2.

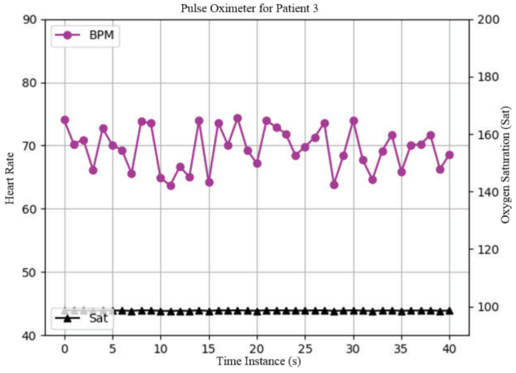

Fig. 10. Pulse Oximeter output for patient 3.

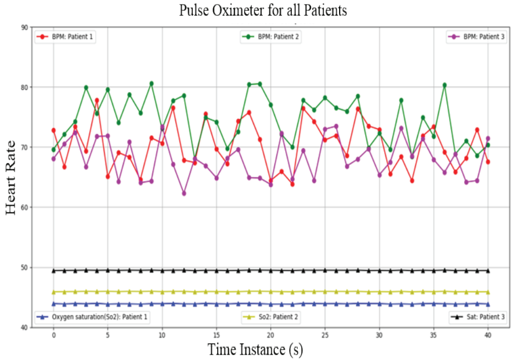

Fig. 11. Composite data points for the three oximetry nodes.

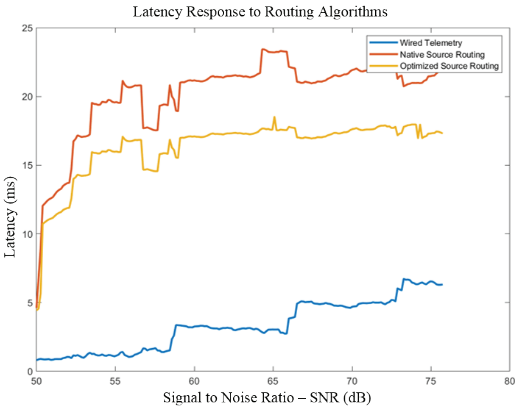

Fig. 12. Latency of the telemetry routing techniques at various SNR.

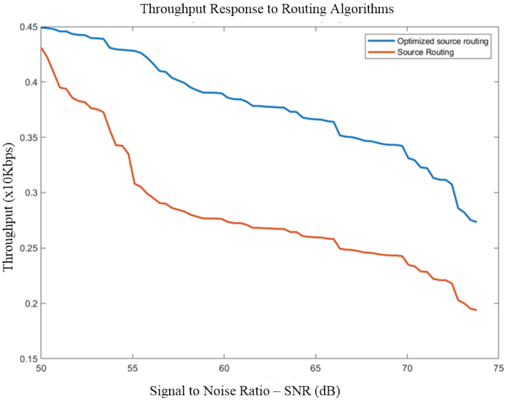

Fig. 13. Throughputs of the source routing and the optimized source routing algorithms at various SNR.

TABLE I
COMPARISON OF THE LATENCY OF WIRED TELEMETRY, WIRELESS TELEMETRY USING THE SOURCE ROUTING ALGORITHM AND WIRELESS TELEMETRY USING THE OPTIMIZED SOURCE ROUTING ALGORITHM AT SPECIFIC SNR.

SNR (dB)	Latency (ms)		
	Wired Telemetry	Source Routing Algorithm	Optimized Source Routing Algorithm
50	2.34	4.12	4.54
54	2.34	19.25	10.85
58	2.38	21.02	11.32
61	2.46	24.95	14.02
65	3.12	25.21	16.28
70	3.35	26.75	18.19
72	3.45	28.22	19.78

TABLE II
THROUGHPUT OF THE WIRELESS TELEMETRY USING THE SOURCE ROUTING ALGORITHM AND WIRELESS TELEMETRY USING THE OPTIMIZED SOURCE ROUTING ALGORITHM AT SPECIFIC SNR

SNR (dB)	Throughput (Kbps)	
	Source Routing Algorithm	Optimized Source Routing Algorithm
50	4.42	4.54
54	4.08	4.14
58	3.96	3.98
61	3.77	3.81
65	3.24	3.76
70	2.56	3.65
72	2.48	3.39

V. Conclusion

In this paper, a wireless telemetry system for a pulse Oximeter over a ZigBee mesh network was designed and implemented. An optimized version of the many-to-one routing algorithm was implemented using existing XBee Python and Arduino APIs. Also, a graphical user interface based on Python libraries was implemented, and a method for storing the patients' historical records was evolved. The performance of the optimized routing algorithm in terms of data transmission latency was compared to that of the wired telemetry system, and the existing many-to-one routing algorithm. The wired telemetry system was significantly faster in terms of latency, than each of the wireless telemetry algorithms tested, whereas the optimized many-to-one routing algorithm was seen to have an average transmission latency nearly half of the native source routing algorithm. However, the performance of the system is only optimal for a small-scale network and shows limited performances in reasonably large networks of greater than 40 nodes. This is perhaps due to certain constraints in the processing power of the microcontroller, and the wireless module used for the design. Future work would focus on improving on the time complexity of the XBee API library in order to reduce the strain, using complex routing algorithms on these devices to increase the maximum node size of the routing algorithm. Finally, the implementation of a text alert system to inform the doctor about the status of the patient when they are not within the range of the telemetry system would require further investigation.

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