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Ultra Low Cost Wi-Fi Based Biomedical Kit for Rural Healthcare

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Abstract: Rural health care has always been an important challenge faced by all nations, especially developing ones. There is a large imbalance in health facilities that are available for urban and rural population. There is a pressing need for an inexpensive and reliable biomedical device which can measure vital health parameters on a regular basis and transmit them rapidly over long distances for proper medical guidance. A novel and an efficient biomedical device has been proposed which can monitor the vital signs of large number of people and transmit the information to the doctor present anywhere in the world at an ultra-low cost. The implementation depicts a hub and spoke model with the spokes being sensor nodes consisting of a microcontroller MSP430G2553 and a wireless transceiver nRF24L01 (IEEE 802.15.4). The hub consists of a CC3200 with nRF24L01. The data received at the hub can be transmitted to the doctor through the inbuilt IEEE 802.11 (Wi-Fi protocol) of CC3200. All the hub and sensor nodes can be powered from the coin cell batteries.

Key words: Ultra-low cost, vital signs, biomedical device, MSP430G2553, nR24L01 (wireless transceiver IEEE 802.15.4), CC3200, rural healthcare

INTRODUCTION

India is a unique nation where one can find the most advanced city with all its technological advances and at the same time an impoverished village without even the basic amenities such as water and electricity. In a nation where the already bursting population is continuing to increase and where almost every urban adult has a smart phone, it is an irony that rural India is largely undeveloped. One of the major concerns in the world, especially in developing nations such as India is rural healthcare. More than 55% of the world population live in rural areas (TGCLLC, 2015) while the number is 70% in India. But the alarming fact is that India has a mere 48 doctors per 100,000 patients and most people in rural India do not have access to sufficient medical facilities. Given that the ILO (International Labour Office) has recommended at least 41 health workers per 10,000 people as a minimum requirement for providing universal health coverage (Adlung, 2015) India is clearly far behind. With the tremendous pace at which technology has progressed in the last 40 years, one would assume that this inadequacy would have been taken care of by now. However, this is not the case mainly owing to cost of currently available biomedical technology and lack of infrastructure facilities.

The main issues in the rural healthcare sector for India are low household income, lack of awareness, and limited resources. The average rural household income is just 33 per day which makes it difficult for an individual to take advantage of good healthcare technology. Therefore, there is a very big need to develop a large scale health monitoring system that is accurate, efficient, simple to use and very importantly, affordable to the poor villager.

Telemedicine, one of the earliest efforts in rural health care, enjoyed limited success. However, high cost of infrastructure setup and maintenance due to the large transportation distances involved, poor quality of video and audio reception etc. have made telemedicine a justifiable option only to those areas that are close to major cities. Whitten and Adams (2003) carried out a case study of two rural telemedicine projects. The comparison of two projects resulted in a simple conclusion that the crucial element in determining the success of the telemedicine is the organization in which it is intended to launch. Each organization operates within a larger environment which is often constrained by fiscal, geographical and personnel factors. So for a better implementation of telemedicine (Krishnan and Rangan, 2016) a detailed study on the organization have to be made.

In the past decade, several innovative approaches (Jacob *et al*., 2011) were made to monitor the vital signs of human body. The main vital signs consisting of body temperature, pulse rate, respiration rate (rate of breathing), blood pressure where appropriate and blood oxygen saturation level, measure the body's most elementary functions and are routinely monitored by medical practitioners. When a patient visits any doctor, usually these parameters are routinely monitored before any diagnosis. Normally this happens on a monthly or annual basis as part of regular health check-up or when the patient falls sick as the case may be. Nonetheless, these values are so critical that regular monitoring of these parameters on a more frequent basis can immensely help in prevention or early detection and cure of an ailment or condition. It has been deduced that with the help of these vital signs, up to 80% of the health issues can be detected early (Spruijt *et al*., 2013; Yeo *et al*., 2013). Kini *et al*. (2015) have suggested a device that collects the vital signs using different microcontroller for each sensor end and the data is transmitted by a wireless transceiver placed on the each microcontroller. The drawback of this design is that using multiple microcontrollers to monitor vital signs makes the device more expensive and bulky. Several other proposed designs are similarly bulky and expensive (Stoyanov *et al*., 2015; Daramola *et al*., 2008) and require more number of sensor nodes have to be placed on the different locations of the body.

Jacob *et al*. (2011) have developed a USB-based kit for remote patient monitoring but this model is significantly more expensive and requires a laptop or a PC to work. The model that is proposed here is extremely inexpensive, efficient and can monitor vital parameters of large number of people simultaneously. In addition, it is small and compact and each person can simply wear a 'wrist-band' consisting of the sensors and wireless transceiver chips. No big and expensive equipment are needed and there is no special maintenance involved either.

MATERIALS AND METHODS

Overview of the proposed design: The proposed design consists of a simple wrist band with an embedded sensor node that the patient has to carry to enable monitoring of vital signs. The core motivation for this design is to monitor a variety of health parameters using a single sensor node and transfer the monitored data in a singly fly. The proposed model of the wrist band with the sensors and the Data Acquisition System (DAQ) along with the transceivers has been shown in Fig. 1. This eliminates the necessity composite Biomedical Sensor Network (BSN). However, if more parameters are to be measured, we may need to add different sensor nodes.

The transceiver module used at the sensor node is nRF24L01 which works on basic IEEE 802.15.4 protocol and consumes very less power compared to other propriety protocols like BLE (Bluetooth Low Energy), ZigBee and Wi-Fi. Table 1 summarises the comparison of nRF24L01 with other protocols. In addition, to the power consumption being very low in both the standby and active modes, it is 4-6 times cheaper than the other transceivers while maintaining a descent data rate. One of the important features of the nRF24L01 is the six data pipe multiceiver which helps to create mesh networks.

The readings from the sensors are transferred to the MSP430G2553 which is an ultra-low-power microcontroller. The voltage readings from the sensors are calibrated and converted into their corresponding units (for example heart rate measurements in beats per minute (bpm) and processed in a fashion understood by doctor. Now the data from the MSP430 is transmitted wirelessly to the hub located centrally in the village which is common receiver to 126 people (Fig. 2). The nRF24L01 which operates in 2.4 GHz ISM serves this purpose. The

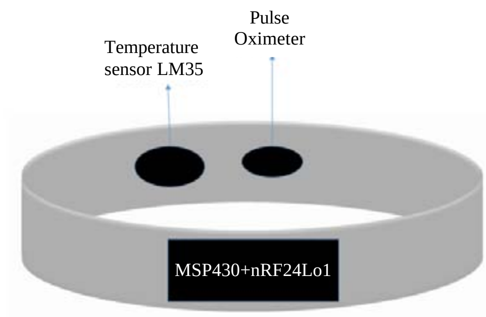

Fig. 1: Proposed model of wrist band (sensor node)

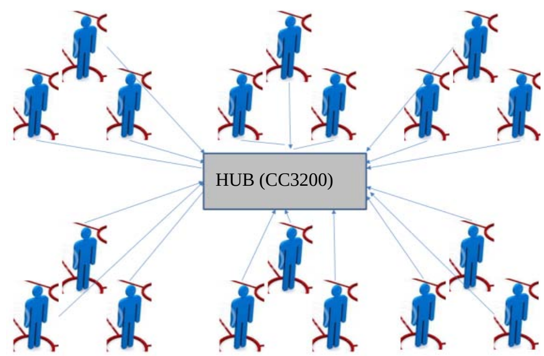

Fig. 2: Hub and Spoke Model

Table 1: Comparison between ZigBee, RF, BLE and Wi-Fi protocol for the sensor node

Criteria	ZigBee	nRF4L01 (IEEE802.15.4)	BLE	Wi-Fi
Cost (Unit price)	$6.4	$1.4	$5.4	$8
Power consumption (Tx/Rx active)	23-39 mA	12.3 mA	16.6 mA	59-229 mA
Standby mode	2-3 mA	20 µA	2-5 mA	825 µA
Data rate	250 Kbps	2 Mbps	1 Mbps	54 Mbps

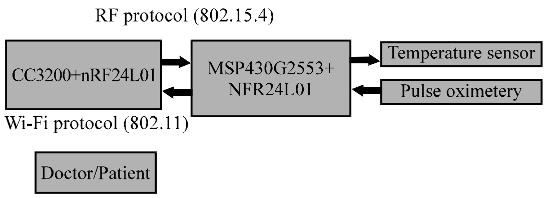

Fig. 3: Architecture skeleton for monitoring a single patient

design of the hub is very critical and a single chip micro controller with built in Wi-Fi connectivity, CC3200 is proposed here. The built in Wi-Fi feature out-performs the other microcontrollers which would require an additional module to enable this feature. In addition to this, one could add nRF24L01 module on to it which helps in communicating with the sensor nodes without any additional hardware or protocol conversion. Using any other microcontroller other than CC3200 would have not enabled us to use the SPI (Serial Peripheral Interface) since the nRF24L01 occupies it and will constrain us from adding other modules.

The advantage of our design is that hub is a simple data transferring device that can be able to do the protocol conversion and push the data to upper layers. For this operation to be done we would require a module that could receive the data in 802.15.4 protocol and push the data to 802.11 enabled devices. Raspberry Pi could have been used as an alternative however in addition to being more expensive (Raspberry Pi costs $50 whereas the CC3200 is available at $10) it also consumes more power (Raspberry Pi consumes 5 V while CC3200 is in the range of 2.1-3.6V). Also, the additional peripherals such as HDMI, Audio out, etc. Present in the Raspberry Pi consume more power which are not required at the hub end. The Raspberry Pi 3 requires a minimum current of 500 mA to transfer the data to a cloud whereas CC3200 can perform the same task by consuming 229 mA.

The usage of two different protocols at the sensor and the hub end would make the design economically feasible and consume less power. The data from the CC3200 can be sent to the doctor/experts present anywhere in the world with the inbuilt 802.11.

The idea of using the CC3200 at the sensor node is also taken into consideration but a simpler and cheaper Personal Area Network (PAN) cannot be constructed by implementing 802.11 protocol as the header weight is much larger and therefore a large amount of data has to be transferred which consumes more power and drains the battery much faster when compared to 802.15.4. (IEEE 802.15.4 is a simple two layer protocol).

Architecture description: The architecture skeleton for monitoring a single patient is represented in Fig. 3. The data can be collected at very low intervals, up to minimum of two minutes. The collected data is transmitted over the standard 802.15.4 protocol to CC3200.

Hardware architecture: The hardware architecture consists of sensors-Temperature sensor, Pulse Oximeter.

Temperature sensor: The normal human body temperature for a healthy adult ranges from 36.5°C (97.7°F)-37.2°C (98.96°F). With the availability of several body locations to measure the temperature, we have chosen the wrist because the target accuracy of the age old axillary location matches with that of the wrist. LM35 is a high precision centigrade temperature sensor that produces an output linearly proportional to the centigrade temperature. The datasheet of LM35 specifies that for every 0.25°C rise in temperature a change of 2.5 mV is absorbed at the analog voltage reading. The full scale of temperatures that LM35 can detect ranges from 55-150°C. The highest temperature corresponds to the reference voltage which is 3.3 V. The resolution of the ADC (analog to digital converter) is 10 bit (for MSP430) and hence a change of 2.5 mV/0.25°C can be identified.

If the temperature and the corresponding digital reading be indicated by T and x, respectively then the value of temperature in Celsius can be calculated as shown in Eq. 1:

$$T = \frac{150 \times x}{1024} °C \tag{1}$$

Pulse oximeter: A pulse oximeter is a non-invasive device capable of monitoring the blood oxygen saturation level and pulse rate of the person. The pulse oximeter consists of an optical transmitter (LED), optical sensor and a band pass filter to remove unwanted signals. The optical sensor that was chosen TSL257 manufactured by Austria Microsystems Inc.

The core theory behind the pulse oximetry is the variability of absorption coefficient of photons going through human tissues at different wavelengths. At the wavelength 500-1000 nm the oxygenated HaemoGlobin (Hb) and deoxygenated HaemoGlobin (deoxy-Hb) have different absorption coefficient. Wavelengths 650 nm and 990 nm have been chosen based on availability and correspond to Red LED and Infrared LED. The ratio of absorption (R) (Eq. 2) of Hb and deoxy-Hb at both these wavelengths can be used to determine the oxygen saturation level in blood by standard methods which then gets transmitted to CC3200:

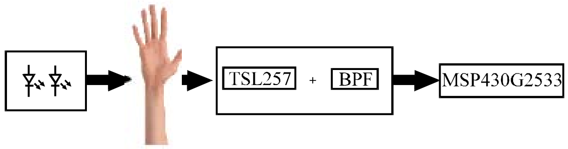

Fig. 4: Design of pulse oximeter

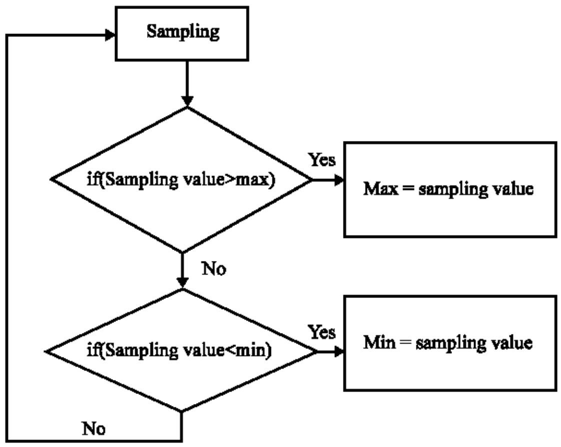

Fig. 5: Algorithm for SpO_2

$$R = \frac{AC_{650}/DC_{650}}{AC_{990}/DC_{990}} \quad (2)$$

Based on the ratio of absorbance determined at the receiver, SpO_2 (saturated oxygen) can be picked out from the existing comparison tables. These tables have been calculated with the help of theoretical concepts and the existing empirical formulae. To obtain an error free calibration, the comparison tables can be generated by collecting the experimental samples from the healthy patients. The design of the pulse oximeter is represented in Fig. 4.

The transmitter is built with a 650 nm (Red) LED and a 990 nm (Infrared) LED that are controlled by the MSP430. Once the light passes through the body, it enters the receiver where the photodetector present in the TSL257 will convert the light signal to current signal. Now to feed this signal as an input to the microcontroller we need to convert the signal to a voltage signal and provide it a small gain. The transimpedence amplifier with an internal resistance of 1MU in the TSL257 serves this purpose. The output of the TSL257 contains lots of other undesired frequency components. A band-pass filter is needed to remove the undesired signal, leaving the desired frequency. The receiver filter is set 0.8-3 Hz as the pass band since the gain is around 20 dB in that region.

The ratio of absorbance can be determined from the receiver circuit by implementing the algorithm represented in Fig. 5. Once the ratio is obtained it can be compared

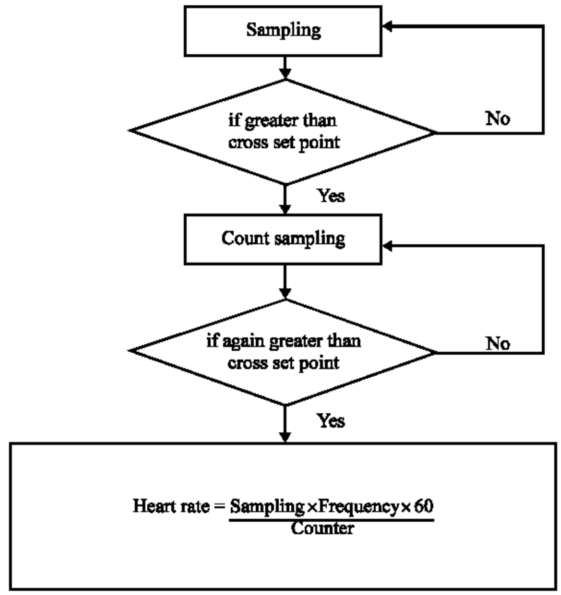

Fig. 6: Algorithm for heart rate

with the standard values and the SpO_2 is transferred to CC3200. The interrupt sampling can also be used to determine the heart rate by implementing the algorithm shown in Fig. 6 in MSP430. Analog read pins A0 and A1 of MSP430 are used respectively to collect the samples corresponding to Temperature sensor and pulse oximeter. In general ADC of a microcontroller can process a single channel at any instant, so a small delay is required between two acquisitions.

Protocol architecture: The two different protocols used in this study are the IEEE 802.15.4 and IEEE 802.11. The IEEE 802.15.4 is a technical standard which specifies the physical layer and the media access control layer. It targets low-power wireless personal area networks (LR-WPANs). The many other advantages of this protocol have been described in Table 1. The nRF24L01 module used along with the MSP430 (Sensor) will enable the 802.15.4 to transfer the data to the other nRF24L01 present on the CC3200 (Hub). The embedded baseband protocol engine (Enhanced ShockBurst™) used in nRF24L01 is designed for ultra-low-power wireless applications. The SPI of the MSP430 can be used to access the register map of nRF24L01 and hence configuring the frequency channel, air data rate and the output power. The transmission of the data has to be initiated from the nRF24L01 on the MSP430 by uploading a new packet to the TXFIFO. The packet contains preamble field (1Byte), address field (3-5 bytes), payload field (1-32 bytes) and a CRC (Cyclic Redundancy Check) field (1-2 bytes). It is important to note that the receiver and the transmitter

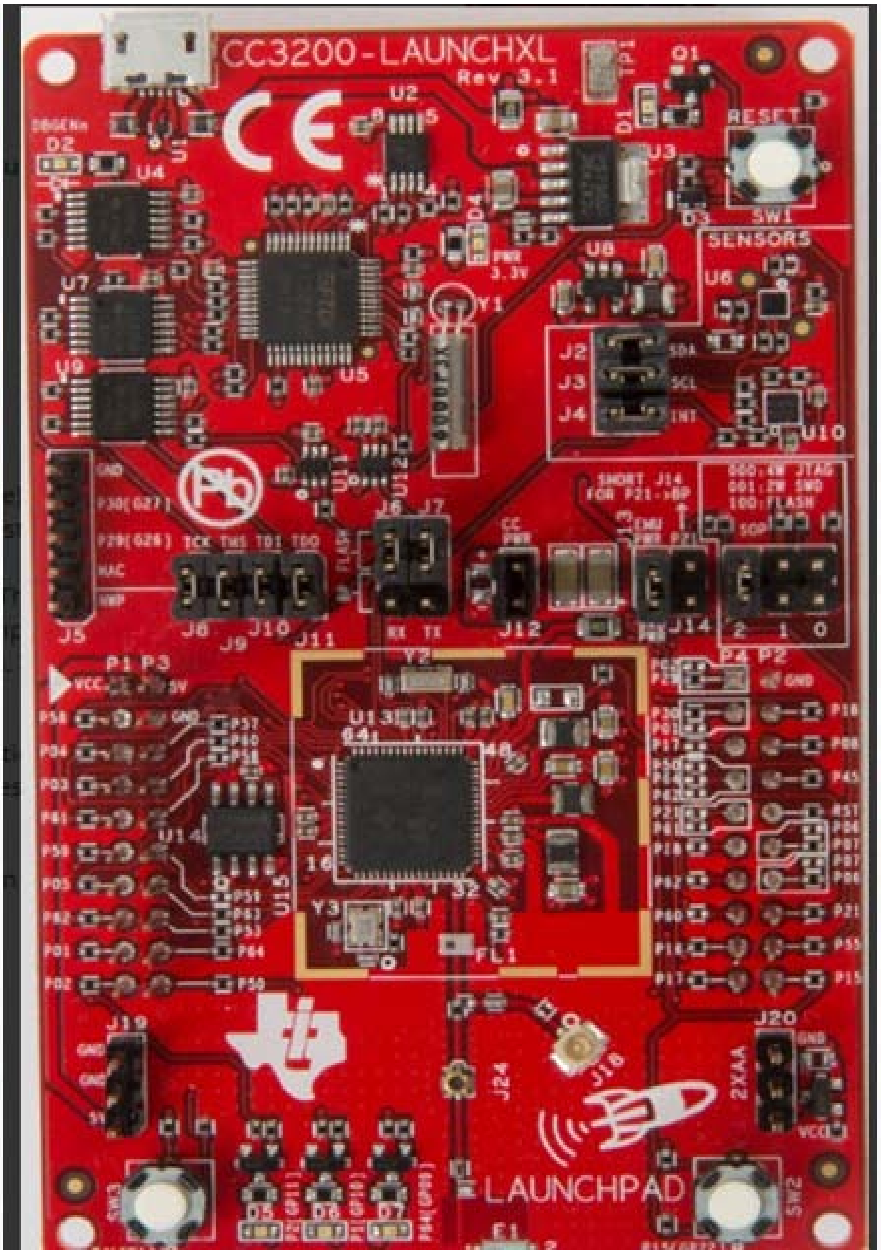

Fig. 7: CC3200 Launchpad

must be tuned in the same frequency and the same data rate has to be programmed in order to communicate with each other. The PA (Power Amplifier) register of nRF24L01 controls the transmission current consumption and therefore the power output. In the receiving mode, the steps followed are the same as that of transmission mode except that they have to be implemented at the CC3200. The nRF24L01 at the CC3200 has to be enabled as receiver by setting the PRIM-RX bit of the CONFIG register as high. Enhanced ShockBurst™ enables automatic packet handling, acknowledgement and re-transmissions of packets.

The data received by the CC3200 (Launchpad shown in Fig. 7) has to be sent to the doctor for an actionable feedback. It cannot be stored in CC3200 as the available memory is only 256 KB which would be filled with the

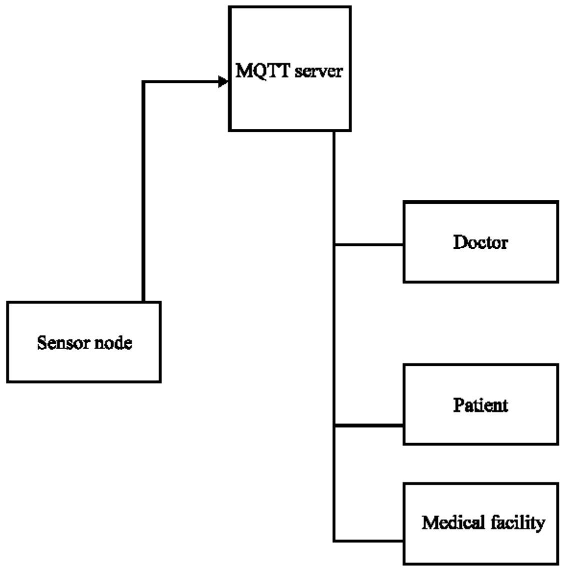

Fig. 8: MQTT overview

programmed code. The built in 802.11 protocol of the CC3200 will transfer the data that is received from the sensor node. The MQTT (Message Queue Telemetry Transport) which is a lightweight messaging protocol can be used to display the sensor readings obtained. The MQTT acts as a middleman between the CC3200 and the doctor/patient. We first populate the server byte array of the MQTT and then connect the CC3200 to MQTT server as a client and publish the data in the cloud. Now once the data is published in MQTT to access the published data doctor should also get connected to the same MQTT server and hence access the cloud in which the data has been stored. The data can also be periodically pulled from the cloud by the hospital databases to store the patient record.

Large scale architecture: The six data pipe multiceiver capability of nRF24L01 will help to create a mesh network of the sensor nodes as shown in Fig. 8 and hence the vital signs of a large number of people can be collected and stored. The sensor nodes present in the network are assigned a unique number ranging from 1-255. The nRF24L01 configured at Person 6 (Fig. 9) in our case forms the immediate hub and hence the primary receiver that can be receiving the data from six different addressed data pipes (in our case person 1-5) in the same frequency channel. To begin with the reception all the data pipes are searched simultaneously by enabling the Enhanced ShockBurst™ of the nRF4L01.

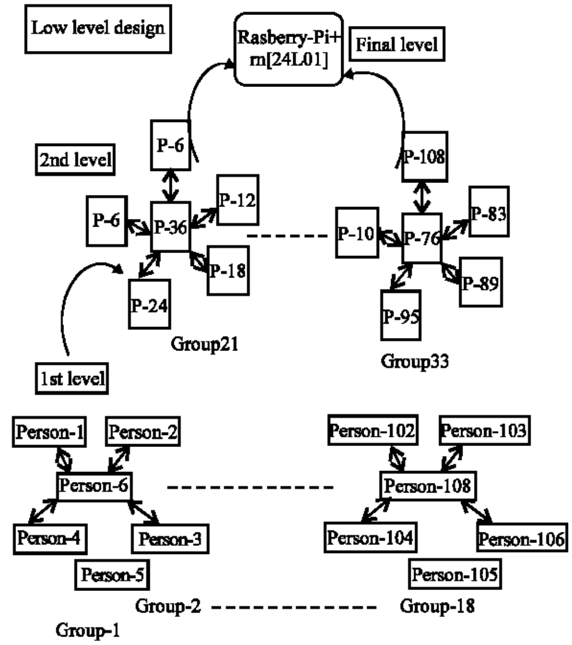

Fig. 9: Mesh network of sensor nodes

Table 2: Size and cost of building the Biomedical kit

Components	Dimension (Length x Breadth) in mm	Cost (in USD $)
LM35	1×3 (Through hole)	2.0
Pulse Oximeter	7×4 (PCB)	2.0
MSP430G553	9.80×6.60 (SMD)	2.4
nRF4L01	33.1089×15.0622 (SMD)	2.0
CC3200	9.3×9.3(QFN)	10.0

RESULTS AND DISCUSSION

Cost analysis and device packaging: The circuits designed can be embedded into a wrist band as shown in Fig. 1. The dimensions of the PCB simulations of transmitter and receiver circuits, the SMD (Surface Mount Device) versions of the MSP430 and nRF24L01, and QFN (Quad Flat No leads) package of CC3200 are mentions in Table 2 along with the cost of developing a single sensor node and a hub. The evaluation boards of the MSP430G2553 and the CC3200 in the working model can be substituted by programmed microcontroller in the real scenario. The overall cost for building a sensor node and hub end for 126 people accounts to accounts to $1068.4 and hence resulting in a cost of $8.47 per sensor node.

CONCLUSION

A new design for an ultra-low cost IoT based Biomedical kit has been proposed which can simultaneously monitor the vital signs of a large number of people at a rapid rate. The kit includes a temperature sensor, pulse oximeter, MSP430 and nRF4L01 for the wireless transmission of the data to the hub which consists of CC3200. The cost per person for a group of 126 people is only $8.47. Hence, we conclude that the proposed design can be definitely implemented on a larger scale in real life at a low cost.

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