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Strategies in the Design of Low Power Wireless Sensor Network for the Measurement and Monitoring of Physiological Parameters

D.Vishnu Vardhan
Department of ECE
JNTUA College of Engineering
Pulivendula-516390-India

Y.Narasimha Murthy.
Department of Electronics
Sri SaiBaba National College
Anantapuramu-515001-India

M.N.Giri Prasad
Department of ECE
JNTUA Collegeof Engineering
Anantapuramu-515001-India

Abstract: This research paper presents the strategies involved in the design of a low power wireless sensor network for the measurement and monitoring of physiological parameters like body temperature, pulse rate and respiration rate of a patient .Ultra low power MSP430F1611 microcontroller from Texas instruments (TI) and the low power transceiver CC2500 ZigBee module from chicon are used in the present design. The TMP100 a digital temperature sensor is used for the measurement of body temperature ,the Free Scale MMA7260Q tri-axial accelerometer is used to measure the respiration rate and a simple pulse rate module is designed using the IR LEDs for the measurement of heart rate. A GUI is developed based on Visual Basic software to display the results. Also the results are displayed on the 2x16 LCD module . In addition , a website with URL www.vishnuhealth.com is designed to display the results .To achieve the low power objective ,an attempt is made to apply the Dynamic voltage and frequency scaling algorithm in addition to all the possible hardware precautions and MAC protocols.

Keywords: Low power wireless sensor, MSP430 microcontroller,Zigbee module ,Accelerometer sensor, Temperature sensor, MAC Protocol.

1. INTRODUCTION

Battery operated wireless sensor embedded system design is the order of the day.But the major limitation for this type of designs is the power consumption which affects the battery life.So,the researchers all over the world are seriously working in this field of low power design to find suitable solutions. The low power architectures, protocols, topologies are the prime concern in the design flow of low-power wireless sensor networks. Especially in the case of battery operated embedded systems which are exclusively designed for bio-medical applications, this fact has utmost importance.

In fact it is not enough if one considers the power consumption for the hardware sub-systems in order to optimize the wireless sensor network, but must consider the power consumption effects of algorithms, network protocols etc[1] i.e it is very essential to balance the power optimized architectures with network algorithms. Hence while designing a low power wireless sensor system for monitoring the bio-medical parameters ,both the software as well as hardware aspects must be equally taken care of.

The transceiver and the microcontroller are the two important candidates in consuming power in a wireless design . So, it is very essential to limit the power consumption of the processor/microcontroller to enhance the battery life. New microcontroller architectures focused in low power systems try to solve this problem by providing hardware support to adapt power consumption to application performance requirements. For example the strong ARM microprocessor from Intel consumes around 400mW of power during the execution of the instruction of the instructions while the ATmega 103L AVR microcontroller from Atmel consumes about 17mW[2,3] .But this low power consumption also affects the performance of the processor drastically. Next, Texas Instruments has released MSP430 family of microcontrollers with five different low power operational modes .They consume around 1.2mW in fully operational mode and 0.3μW in the deepest sleep mode[4].But this change between the operating modes is also a power consuming task ,especially in applications where fast data sampling and data acquisition ,it is not a preferred option.The current consumption of a MSP430 microcontroller in active mode and in other low power modes is shown in Figure 1.below.

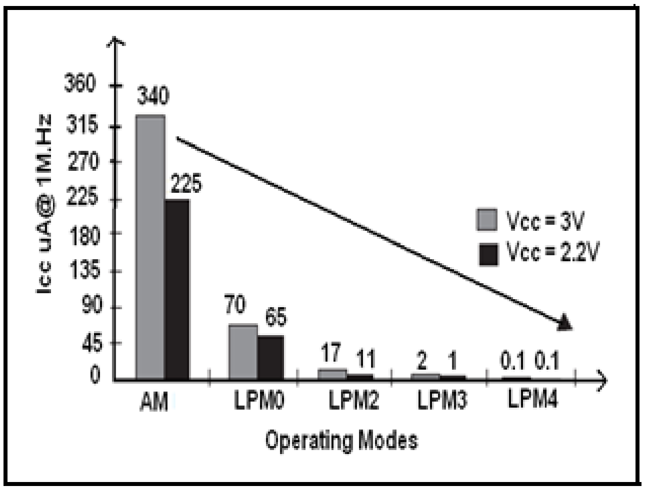

Figure 1. Graph showing the current consumption in different operating modes of MSP430 family.

The power consumed by the CMOS chip is proportional to the frequency and also proportional to the square of the supply voltage as shown below.

$$P \propto f V_{DD} \quad (1)$$

So, it can be observed that ,reducing the supply voltage from 5.0V to 3.3V reduces the power by nearly 55%.Another effect is reducing the clock frequency .The reduced voltage or voltage scaling at the lowest clock frequency of 60M.Hz and with a V_{DD} of 0.9 V is found to consume around 1/5 th of the energy per instruction that is required at peak performance. i.e by properly decreasing the supply voltage and frequency one can reduce the power dissipation in a design. This is the basic idea behind the Dynamic Voltage and Frequency scaling(DVFS)[5].

Coming to the wireless sensor networks, to establish the wireless communication, both a transmitter and a receiver are required in a sensor node. The basic task here is to convert a bit stream coming from a processor or microcontroller and convert them to and from radio waves [6].Now a days a single device is used that combines both these the two tasks in a single entity. Such combined devices are called transceivers. But these transceivers usually consume large power of around 70% of the total power. There are several factors that affect the power consumption characteristics of a transceiver, including the Type of modulation scheme used, data rate, transmit power (determined by the transmission distance), and the operational duty cycle [7].But most of these transceivers can be configured by the user to set the power level by setting them in various distinct modes of operation like Transmit, Receive, Idle, and Sleep modes.An important fact found in most of the transceivers is that, operating in idle mode results in significantly high power consumption, almost equal to the power consumed in the Receive mode. Thus, it is important to completely shut down the transceiver rather than transitioning to idle mode, when it is not transmitting or receiving any data [8]. Some transceivers can support more diverse power levels, for example the CC2500 has Low current consumption (13.3 mA in RX,250 kbps, input 30 dB above sensitivity limit)[9].

A very important feature of followed in wireless sensor network to reduce power consumption, is that the nodes remain sleeping until they need to undertake a specific task. At some defined time, a sensor node will wake up and perform a measurement. An external event also can trigger this wake-up.The node can then decide to communicate the gathered information to a neighbor and send it a message. Unfortunately, the neighbor might be sleeping to save energy. The node must thus keep sending the information until the neighbor awakens and acknowledges receipt of the information. If a node needs information from a neighbor, it can transmit a request until it receives a response. Alternatively, the requesting node can stay awake and wait until the neighbor decides to send the information spontaneously.Also ,the nodes share a single medium for communication and the performance of the network mainly depends on the effective sharing of this medium by the nodes.The MAC protocol controls the communication nodes and streamlines the sharing of the common wireless medium by the nodes. But the limitations of the MAC protocols are packet collision ,idle listening ,overhearing and overhead[10].To overcome the energy consumption and to implement energy efficient MAC protocol the clustered topology techniques are being followed[11].In the present design a fixed TDMA method at the MAC sub layer is adopted. This TDMA provides the advantage of sending the non active nodes into sleep mode. This leads to low power consumption automatically and the battery life is extended[12].

2. HARDWARE DETAILS

The hardware system consists of three sensors , a temperature sensor TMP100 from TI , a pulse rate sensor and an accelerometer based respiration sensor. All the three sensors are interfaced to the MSP430F1611 microcontroller by using suitable circuitry. A 2x16 LCD module is interfaced to the microcontroller for the display of the data and a GUI , based on Visual Basic software is developed to display the measured parameters. A website with URL www.vishnuhealth.com is also designed to display the results. The block diagram of the design is shown in Figure 2 and the photograph showing the hardware arrangement is shown in Fig.3.

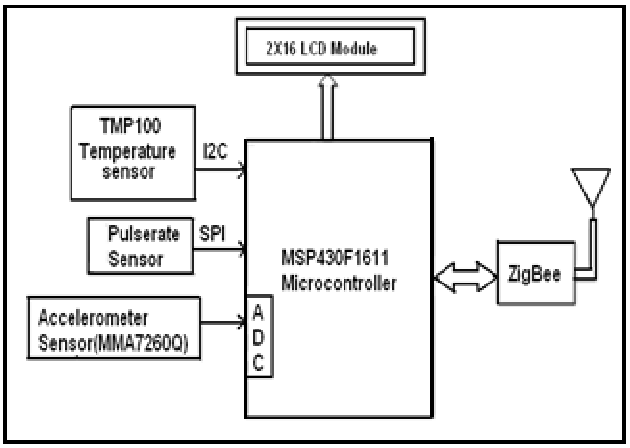

Figure 2. Block diagram of the design

2.1.MSP430 Processor

MSP430F1611 is a 16 bit microcontroller with Ultra low-Power Consumption of 280 µA at 1 MHz, 2.2 V in active mode and 1.6µA in standby mode and 0.1µA in off mode.The supply voltage range is around 1.8 V . . . 3.6 V. and available in 64-Pin Quad Flat Pack (QFP). The architecture of this controller is combined with five low power modes to achieve extended battery life in portable measurement applications. This device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that attribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 6 µs. It is configured with two built-in 16-bit timers, a fast 12-bit A/D converter, dual 12-bit D/A converter, one or two universal serial synchronous/asynchronous communication interfaces (USART), I2C, DMA, and 48 I/O pins. In addition, the MSP430F161x series offers extended RAM addressing for memory-intensive applications and large C-stack requirements. Typical applications include sensor systems, industrial control applications, hand-held meters, etc[13].

Figure 3. Photograph showing the hardware design

2.2.Temperature Measurement

The temperature of the body is measured by using a simple digital temperature sensor TMP100 which supports I2C standard. Actually,this sensor is mounted within the wrist strap ,positioned in such way that it is in contact with the skin,allowing it to measure the external temperature of the skin. From the skin temperature ,the body temperature is estimated. There can be different methods to estimate the exact body temperature from the skin temperature ,but it is observed that the body temperature is nearly 5 ~ 5.2°C higher than the skin temperature when the body temperature is measured at the ear by a standard thermometer by a medical practitioner.[14]

The TMP100 is a digital temperature sensor which can be operated over a temperature range of -55^0 C to +125^{0}C . This temperature sensor does not require any complicated signal conditioning circuitry. This sensor is interfaced to MSP 430microcontroller by using the port pins P2.0 and P2.1 The interest in using this temperature sensor is , when operated in one-shot mode, the TMP100 goes into shut down mode after each conversion is completed and consumes a typical current of 0.1uA between conversions[15]. This will justify the low power system design .This temperature sensor is used for the measurement of body temperature at neck ,wrist and at upper arm as suggested in [16].

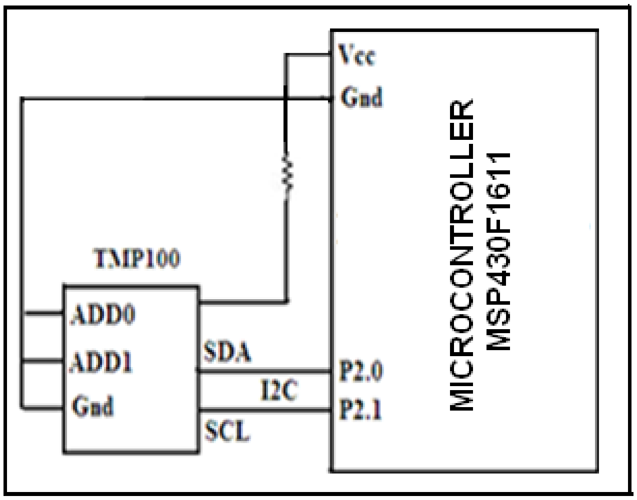

Figure 4. Interfacing of Digital temperature sensor TMP100

The interfacing of the temperature sensor TMP100with the ports of MSP430 microcontroller is shown in Figure 4.

2.3. Pulse rate measurement sensor

Pulse rate denotes the number of heartbeats per second and is usually expressed in beats per minute (bpm). In adults, a normal pulse rate is around 60 to 100 times a minute during resting condition. The resting pulse rate is directly related to the health and fitness of a person and hence is a very crucial physiological parameter. It can be measured at any spot on the body where the pulse is felt with fingers. The most common places are wrist and neck. From this heart rate in bpm is evaluated easily.

To measure the pulse rate a simple low cost pulse-oxymeter is constructed using the arrangement as shown in the block diagram in Figure 5. The main principle of working is based on near infrared spectroscopy using the light of wave length 700-900nm.At these wavelengths most tissues do not absorb light other than hemoglobin.

Basically, the device consists of an infrared transmitter LED and an infrared sensor photo-transistor. The transmitter-sensor pair is clipped on one of the fingers of the patient. The LED emits infrared light to the finger of the subject. The photo-transistor detects this light beam and measures the change of blood volume through the finger artery. The changing blood volume with heartbeat results in a train of pulses at the output of the photo diode, the magnitude of which is too small to be detected directly by a microcontroller. So, a two stage high gain, active low pass filter is designed using two operational amplifiers (Op-Amps) to filter and amplify the signal to appropriate voltage level so that the pulses can be counted by the microcontroller[17].

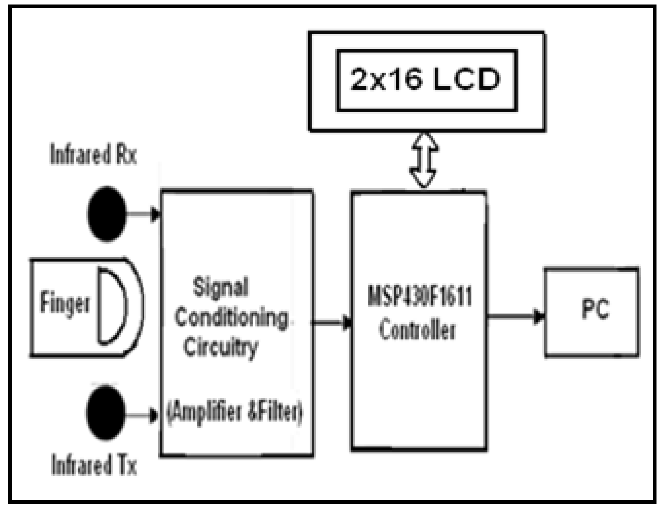

Figure 5. Block diagram of Pulse rate measurement

2.4. Respiration Measurement

Human respiration rate is measured when a person is at rest and involves counting the number of breaths for one minute by counting how many times the chest rises. An optical breath rate sensor can be used for monitoring patients during a magnetic resonance imaging scan. Respiration rates may increase with fever, illness, or other medical conditions. So, the measurement of human respiration is always an important physiological parameter in medical diagnosis.The small rotations at the chest wall due to breathing or during continuous speech provide a valuable information to the doctor . In recent times, the research in the area of accelerometer based respiration techniques gained momentum. This idea as first implemented by Bates et al[18].

In the present design the respiration rate is measured using the Free Scale MMA7260Q tri-axial accelerometer chip .The MMA7260Q is a low cost capacitive micro machined accelerometer features signal conditioning, a 1-pole low pass filter, temperature compensation and g-Select which allows for the selection among 4sensitivities. Zero-g offset full scale span and filter cut-off are factory set and require no external devices. Includes a Sleep Mode that makes it ideal for handheld battery powered electronics [19]. This provides a good solution for XY and XYZ tilt sensing with a sensitivity of 800mV/g in 3.3V applications. All of these accelerometers will experience acceleration in the range of +1g to -1g as the device is tilted from -90 degrees to +90 degrees. A tri-axial accelerometer is a device that measures the acceleration in three orthogonal directions (sensing axes). An accelerometer can be used to sense vibrations (e.g. the vibration of a machine), orientation (e.g. in human activities monitoring) and hence the respiration rate of human beings .

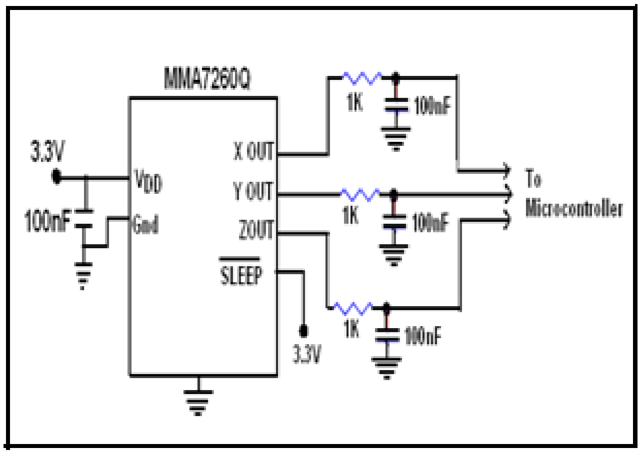

Figure 6.Accelerometer Circuit for respiration measurement

The interfacing circuit of accelerometer sensor MMA7260Q to the microcontroller is shown in Fig.6.The respiration rate is displayed on the 2x16 LCD module. The average resting respiratory rate of an adult is around 24 breaths per minute and of a child is around 18 breaths per minute [20] .The present system is used to measure the respiration rate of adults and children after wrapping the sensor around the chest .The results are found to be satisfactory.

2.5. ZigBee Communication

ZigBee is a low-power, low-cost, wireless networking standard. This low power allows longer life for smaller batteries and provide low cost solutions to many wireless sensor applications. ZigBee operates in the industrial, scientific and medical radio bands (ISM)with 868 MHz, 915 MHz, and 2.4 GHz in different countries. The technology is intended to be simpler and less expensive than other WPANs such as WiFi, Bluetooth and ZigBee . Of these, ZigBee is the most promising standard owing to its low power consumption and simple networking configuration.[v]. Network devices, whether wired or wireless, are commonly described by the Open Systems Interconnection (OSI) reference model. This abstraction model was developed bythe International Standards Organization (ISO), starting in the 1980 description of communication-related protocols and services. The generic seven-layer model is applied to all net work and media types.[vi].In the present work the Zigbee module CC2500 from TI is used. The CC2500 is a low cost true single chip 2.4 GHz transceiver designed for very low power wireless applications. The circuit is intended for the ISM (Industrial, Scientific and Medical)and SRD (Short Range Device) frequency band at 2400-2483.5 MHz.This ZigBee provides the low power features of 400 nA SLEEP mode current consumption, Fast startup time: 240 us from SLEEP to RX or TX mode(measured on EM design) , Wake-on-radio functionality for automatic low-power RX polling and Separate 64-byte RX and TX data FIFOs (enables burst mode data transmission)[21].CC2500 is configured using the SmartRF® Studio software, available for download from http://www.ti.com.

3. SOFTWARE DETAILS

The software development environment of the proposed system is a cross compiler IAR Embedded Workbench which is designed for MSP430 micro-controller by IAR Company[22]. The IAR Workbench IDE is a very powerful Integrated Development Environment that allows to develop and manage complete embedded application projects .It's efficient complier performance and ability to support multiple development tools are its positive points. In System Programming is programming or reprogramming the on-chip flash memory, using the boot-loader software and a serial port. The MSP430 Microcontroller provides on-chip boot-loader software that allows programming of the internal flash memory over the serial channel. Philips provides a utility program for In-System programming called Flash magic Software [23].Visual basic another very useful software which can be readily used to design Graphical User Interface(GUI) to display the measured parameters both in numeric form or graphical forms. This will provide for a good analysis of the results.

4. RESULTS & CONCLUSIONS

The low power wireless sensor network for the measurement of biomedical parameters is designed .The measurement are made over a period of time continuously and the results are displayed on the 2x16 LCD module and also on the Graphical User Interface(GUI) developed using the Visual Basic softwrare. The same results are also made available on the website designed for this purpose with the URL http:// www.vishnuhealth.com.The measurements are made on different persons both male and female at different intervals of time and compared the results with standard clinical instruments. The present readings are found to be satisfactory with in an error of 5%.Since the basic objective of our work is the design of low power ,low cost wireless sensor design, this error is not be taken seriously into account .The body temperature is around 38^0C ,heart beat is 72bpm and the respiration rate is 27 for adults and these values are displayed on the GUI shown in Figure 7.

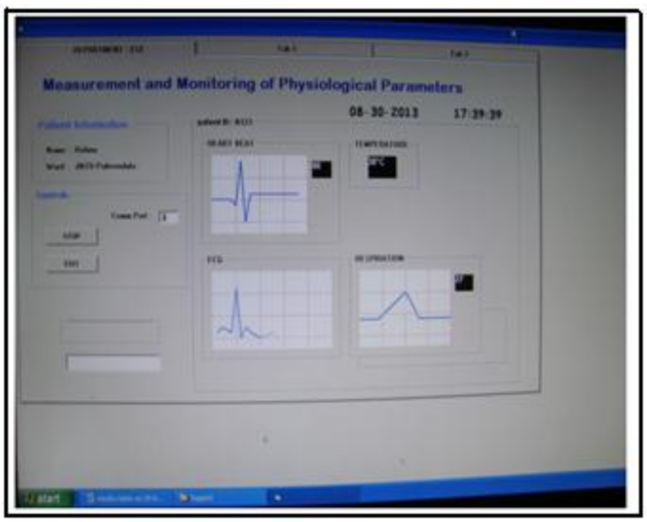

Figure 7. Graphical User Interface (GUI) showing the results

To measure the current consumption, algorithm execution time and the clock frequency ,the methodology suggested by Cebrian[24] is adopted. Though there are certain limitations in this method ,due to its simplicity in implementation ,the authors adopted this methodology. The block diagram used for this implementation is shown in Figure 8.The microcontroller current consumption is obtained indirectly by measuring the voltage drop across a shunt resistor. A precision digital multimeter is used to measure the small currents of the order of few µA at K.Hz clock frequencies to mA at M.Hz clock frequencies. Proper filtering must be done to avoid the noise.

The algorithm execution time is also equally important for low power design.So,this algorithm execution time is measured using the PC DAQ card. The clock frequency of the MSP430 microcontroller is measured using the digital frequency meter.

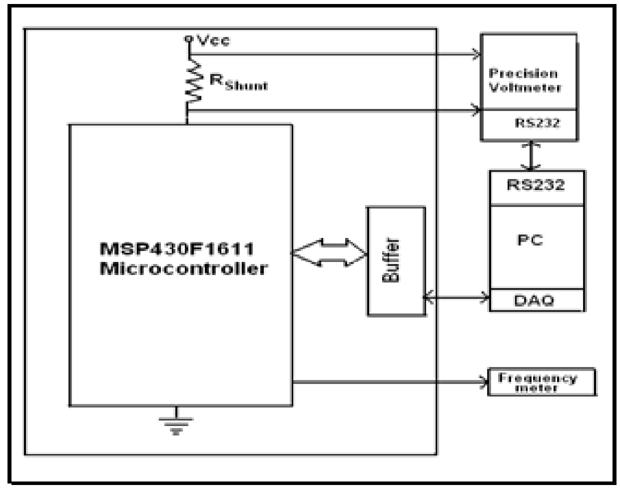

Figure 8. Measurement of current consumption

The power consumed by each subcomponent during the execution is evaluated using the relation

$$\text{Power } P = (I_{mean}.V_{DD}.\tau)/T \quad (2)$$

where V_{DD} is the supply voltage , τ is the effective computation time of the algorithm ,I_{mean} is the average current calculated and T is the maximum time interval of the algorithm execution.

As mentioned in our earlier discussion ,in the total power budget there are two important candidates one is the microcontroller and the other is the transceiver. Between the two , the transceiver consumes around 70% of the total power. By the application of suitable TDMA based clustered MAC protocols the power consumption is brought down considerably to around 62%. Power consumption in a microcontroller during the detection of the signal is more than the power consumed during the sampling of the signal .The variation of power and energy consumption in a MSP430 controller with the supply voltage is shown in the Figure 9.

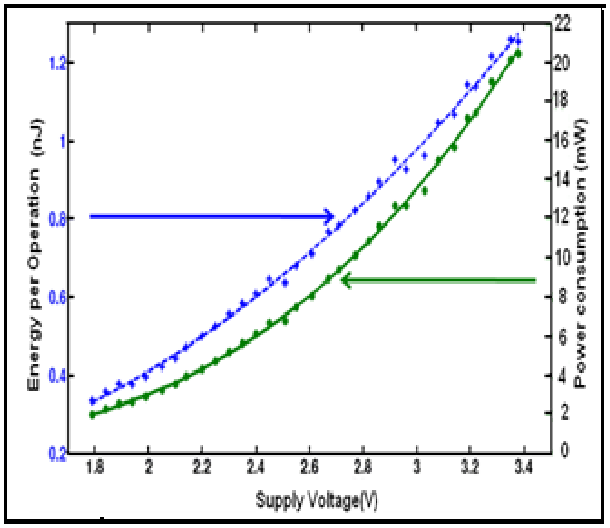

Figure 9. Energy and Power consumption with supply voltage in a MSP430 microcontroller

It is very clear that at higher voltages the power dissipation is more. It is also observed that the power dissipation during the data processing is more than during the transmission of data.So,it is evident that the higher supply voltages lead to larger power dissipation. Hence the dynamic voltage and frequency protocol is applied by operating the microcontroller in LPM3 mode, where the supply voltage levels are decreased during the data transmission automatically using proper algorithm . But, this is achieved at the cost of increased execution time. Similarly the frequency of the oscillator is also suitably modified during the data sensing and transmission as well as during data processing.The total power consumption in the present design is found to be 104mW.

The TMP 100 temperature sensor consumed a typical current of 0.3uA and a power consumption of around 1mW between two conversions in active mode .But when the display is also considered it is about 2.78 uA .In the present design the power consumption of TMP100 sensor is 2.2% of the total power. The commercial pulse oxymeters consume a power of 20 ~ 60mW.In this the LEDs consume a bulk of the total power. The present low-cost pulse measuring device consumed a power of about 6.76 mW. This is about 6.5% of total power consumption. This may not be the lowest power consumption as some body has reported a very low power devices of 4.8mW and also 1.5mW[ ],but in view of the very low cost design ,this is considered as a better option. The CC2500 was chosen because of its smaller size and lower power requirement. (Inspite of its limitations like : the CC2500 device suffered greatly from interference with other 2.4GHz systems, such as 802.11 wireless networks and Bluetooth and also the 2.4GHz band is greatly attenuated by the human body, limiting its suitability for body area networks).This transceiver is the major power consumer .In the present design it consumed nearly 61.9% of total power of 104mW.The MSP430 controller consumed nearly 21.3% of the total power when it is operated mostly in the mode LPM3 .The accelerometer consumption is around 3.1% of the total power i.e it consumed a power of 3.22mW.The other circuitry of the design consumed a power dissipation of about 4.5% of the total power.The entire power consumption is shown in Pi chart in the Figure 10.

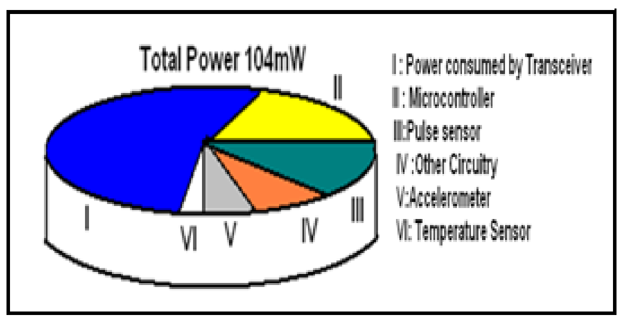

Figure 10. Power consumption in each subcomponent

After measuring the current consumption of different subcomponents of the present design ,it is observed that there is an advantage of nearly 10~11% power savings by this design when compared with normal design without low power modes of the microcontroller and with out application of TDMA based MAC protocols. The

Table.1 below shows the current/power consumed by each subcomponent of the present design.

Table 1.Details of Power consumption in the design

S.No	Sub Component	% of Power	Power consumed (mW)
I	Transceiver(WSN)	61.9	64.48
II	MSP430	21.3	22.25
III	Pulse Sensor	6.5	6.76
IV	Other circuitry	4.5	4.68
V	Accelerometer	3.1	3.22
VI	Temperature sensor	2.2	2.3

5.FUTURE SCOPE

In recent times ,because of inherent advantages of real time embedded systems ,researchers are more inclined towards the design of a real time wireless sensor designs. Currently the most important and widely used operating systems for wireless sensor networks are TinyOS ,Contiki and Mantis.The basic use of these operating systems is to provide a robust and reliable operation and maintain the system in the deepest low power mode so that the battery power life is extended. In view of these facts the authors are modifying the same design with MSP430 Microcontroller using the TinyOS .

6.ACKNOWLEDGEMENTS

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