REALIZATION OF SOURCE LOCALIZATION WITH SENSOR SELECTION IN A WIRELESS SENSOR NETWORK FORMED WITH LOW COST, ENERGY EFFICIENT SENSORS

by

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ABSTRACT

REALIZATION OF SOURCE LOCALIZATION WITH SENSOR SELECTION IN A WIRELESS SENSOR NETWORK FORMED WITH LOW COST, ENERGY EFFICIENT SENSORS

In a Wireless Sensor Network (WSN), system resources, such as computational resources, the total node energy, need to be utilized effectively while executing the task of interest. Since a number of sensor nodes may be needed in various type of applications, it is also important to develop each sensor node in a cost effective manner. The purpose of this thesis is to develop a custom made, low power and cost-effective wireless sensor node based on a MSP430G2553 microcontroller and nRF24L01+ wireless transceiver module. Then, using these nodes, we form a WSN, and locate the position of a source emitting light. Sensor nodes receive measurements from the light source and sensor measurements are transmitted to the fusion center based on a random access communication protocol. Under this protocol, a sensor node first compares its measurement with a specific transmission threshold. If the measurement exceeds the threshold, then it is transmitted to the fusion center. So that rather than gathering all sensor measurements at the fusion center, we only collect data from the sensor nodes which are close to the light source. Under different transmission thresholds, we obtain the Mean Squared Error (MSE) of source location estimate as a function of the number of transmitting sensor nodes. We also obtain the total number of sensor retransmissions due to collisions with respect to number of transmitting sensor nodes as the value of the transmission threshold varies. Estimates of the source location are also presented in Matlab with real time visualization.

ÖZET

DÜŞÜK MALİYETLİ ENERJİ VERİMLİ DUYARGALAR İLE OLUŞTURULAN BİR TELSİZ DUYARGA AĞINDA KAYNAK KONUMLANDIRMASININ DUYARGA SEÇİMİ İLE GERÇEKLEŞTİRİLMESİ

Bir telsiz duyarga ağında (TDA) hedeflenen uygulamanın başarı ile gerçekleştirilmesinin yanı sıra, duyarga başına harcanan toplam enerji ve işlevsel kaynaklar gibi sistem kaynaklarının etkili kullanılması gerekmektedir. İncelenen sahada farklı uygulamalar için çok sayıda duyargaya ihtiyaç duyulabileceğinden, tüm sistemin maliyet etkin gerçekleştirilmesi için her bir duyarganın da düşük masrafla üretilmesi de önemlidir. Bu tezde, öncelikle özel yapılmış, az enerji tüketen ve düşük maliyetli, MSP430G2553 mikrodenetleyicisi ve nRF24L01+ haberleşme ünitesi tabanlı bir duyarganın geliştirilmesi amaçlanmıştır. Sonrasında geliştirilen bu duyargalar kullanılarak sade bir TDA sınama ortamı oluşturulmuş ve ışık kaynağının konum tespiti yapılmıştır. Duyargalar, ışık kaynağından ölçüm alırlar ve bir rastgele ortam erişim protokolüne göre ölçümlerini tümleştirme merkezine gönderirler. Bu protokole göre, bir duyarga ilk olarak ölçümünü bir eşik değerine göre kıyaslar. Eğer ölçüm eşik değerinin üstündeyse, ölçüm tümleştirme merkezine gönderilir. Bundan dolayı, tüm duyargalardan veri toplamak yerine ışık kaynağına yakın olan duyargalardan veri toplanması sağlanır. Farklı eşik seviyeleri altında, Ortalama Karesel Hata (OKH), veri gönderen duyarga sayısına bağlı olarak gösterilmiştir. Ayrıca, eşik değeri değiştikçe çakışmanın neden olduğu duyargaların yeniden iletim sayısı, iletim yapan duyarga sayısına bağlı olarak gösterilmektedir. Konum kestirimleri Matlab'te gerçek zamanlı olarak da gösterilmektedir.

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LIST OF SYMBOLS/ABBREVIATIONS

D_i	Sensor Measurements
e	Threshold Level
N_A	The Numbers of Active Sensor Node
T	The Total Number of Localization Test
x, y	Actual Target Location
$\hat{x}, \hat{y}$	Estimated Source Location
x_i, y_i	Sensor Node Locations

ACLK	Auxiliary Clock
ADC	Analog to Digital Converter
CCS	Code Composer Studio
CPU	Central Processing Unit
DCO	Digitally Controlled Oscillator
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GPIO	General Purpose Input/Output
GPS	Global Positioning System
I2C	Inter-Integrated Circuit
LDR	Light Dependent Resistor
LED	Light-Emitting Diode
LPMs	Low Power Modes
MSE	Mean Squared Error
RAM	Random Access Memory
RF	Radio Frequency
RISC	Reduced Instruction Set Computing
SMCLK	Sub-Main Clock
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory

TI	Texas Instruments
UART	Universal Asynchronous Receiver/Transmitter
USCI	Universal Serial Communication Interface
WSN	Wireless Sensor Network

1. INTRODUCTION

In recent years, new technological areas arise with development of science. Especially, due to the evolution of the communication systems Wireless Sensor Networks (WSNs) become one of the most important tecnological and research areas. A WSN consists of a lot of sensor nodes communicated with each other and/or a central node called fusion center and responsible to observe the interested conditions in a given environment. The usage of WSNs take an important place in literature and industry [1].

WSN systems are used for different areas in healthcare, environment, industry or infrastructure to improve the life quality of humanity with various types of applications of detection [2], estimation [3], target tracking [4] and area monitoring [5]. WSNs have a wide range area for different applications considering different aims or purposes. For instance, one can use a WSN for border intrusion detection [6], source localization [7] and vehicle tracking [8]. Also, WSNs are used in healthcare applications to detect diseases or monitor physical informations of patients such as daily activity, blood pressure and heart rate [9]. In agricultural or greenhouse applications of WSNs, environmental changes are observed with using sensors such as temperature, humidity and light [10]. Also, WSN are used for pollution or hazard monitoring so air, river or water pollution can be detected to prevent pollution by using different kinds of sensors [11].

While realizing such WSN applications, development of a sensor node is a critical issue for the implementation of the entire WSN effectively in terms of cost effectiveness and energy efficiency. Sensor nodes are tiny simple devices with limited resources such as power, computational capacities and memory requirement [1], [12]. As an example, in order to have long sensor node lifetime, it is important to use energy resources effectively. In a WSN, it is also important to develop each sensor node in a cost effective manner [1], [13], [14], [15], [16]. If large number of sensor nodes are used, it may become expensive and infeasible to form the entire WSN. Various WSN applications can be realized with the commercial products such as TelosB or MicaZ for target localization [17] or power consumption monitoring [18] but these modules have high price so it can be a disadvantage for the WSN projects which have limited budgets. So, using custom design sensor nodes with low cost components may become more suitable instead of using the commercially available WSN products. Specifically, a sensor node basically consists of a microcontroller, a wireless transceiver unit, a sensory device, and a battery. If these units are selected carefully, a sensor node can be formed in an energy efficient and cost effective manner. After that, by communicating such sensor nodes using a suitable communication protocol, the WSN system can be used for any application.

1.1. LITERATURE SURVEY

In this section, we give an overview about the previous works which focus on custom design of a sensor node, its components and their applications.

Microcontrollers are very important for sensor node design to realize the WSN applications. Texas Instruments (TI) MSP430 family microcontrollers are very popular in WSN applications due to their low energy consumption [16], [19], [20]. For example, commercially available TelosB modules use MSP430F series as their microcontroller. MSP430F series processors have been also used for custom design of sensor nodes in [13], [14], [15], [16], [19], [21], [22] but MSP430G Series processors can also be used in WSN applications due to their lower price with sufficient memory and processing speed. Table 1.1 shows the price and technical specifications comparison of several microcontrollers from the MSP430 family. MSP430F148 [16], MSP430F149 [21], MSP430F1611 [14], [19] and MSP430F1612 [13] microcontrollers have more memory and General Purpose Input/Output (GPIO) than MSP430G2553 but their price is above ten dollars while MSP430G2553 is only 2.5 dollars. MSP430FE4272 [22] has less GPIO and Analog to Digital Converter (ADC) channel as compared to MSP430G2553 and price is about five dollars. MSP430F2013 [15] has only 2KB memory and few number of GPIO. On the other hand MSP430G2553 has similar price with MSP430F2013 where MSP430G2553 has more memory, ADC channels and GPIO pins than MSP430F2013. Due to its very low power consumption, low cost, sufficient memory, ADC and GPIO, MSP430G2553 is suitable to design a sensor node for WSN applications.

The wireless transceiver unit of the sensor node also needs to be selected cost effectively and it should operate with low energy. Instead of widely used communication modules

Table 1.1. Price and technical specifications of the MSP430 microcontroller family

MSP430	**F149**	**F148**	**F1611**	**FE4272**	**F1612**	**F2013**	**G2553**
Freq. (MHz)	8	8	8	8	8	16	16
Flash (KB)	60	48	48	32	55	2	16
SRAM (Kb)	2	2	10	1	5	0.125	0.5
GPIO	48	48	48	14	48	10	16
ADC	8ch	8ch	8ch	2ch	8ch	4ch	8ch
Active Power (uA/MHz)	280	280	330	400	330	220	330
Standby Power (LPM3-uA)	1.6	1.6	1.1	1.6	1.1	0.5	0.7
Price ($)	10.99	10.92	19.62	5.51	20.35	2.75	2.50

such as bluetooth devices [23], [24], Xbee [22], [25] and CC2420 [16], [26], [27] using nRF24L01+ [13], [14], [15], [21], [28] has advantages in terms of energy efficiency and low price to design a sensor node.

There are many sensing units that can be deployed on a sensor node such as temperature, humidity, motion, pressure and acoustic sensors. By embedding such sensing modalities, we can monitor different conditions of the interested environment. For example, the light intensity in an area can be monitored using Light Dependent Resistor (LDR) [29]. LDR is low cost, simple to implement and easy to calibrate. So, using LDR as a sensing unit becomes suitable for WSN applications such as localization of a source emitting light.

In literature, by embedding MSP430 series microcontroller, nRF24L01 communication device and sensing units, several WSN applications have been performed in [13], [14], [19], [21]. In [13], due to low energy and low cost, a sensor node is created by MSP430F1612 microcontroller, nRF24L01 communication module and a electrocardiography sensor. In this study, two sensor nodes send data to a central node and data are then transmitted to a website from the central node. In [14], a sensor node is created with MSP430F1611 microcontroller and a nRF24L01 communication module with ultrasonic sensor. In [19], a sensor node is realized with three different sensors, pressure, ultrasonic and GPS (Global Positioning System) with same microcontroller and communication module at [14]. For greenhouse applications a sensor node is created with MSP430F149, nRF24L01, temperature sensor and solar panel [21].

Upon completing the design of a sensor node, a communication protocol is required which defines how sensor nodes communicate with each other. In addition, the communication protocol should also provide energy efficiency for the WSN system. As an example, in a localization application with densely deployed sensor nodes, rather than gathering data from all the sensor nodes, gathering data from specific sensor nodes around the source location performs good localization performance and saves from resources [7]. Note that, WSN communication protocols are different from the conventional Wireless Network communication protocols because Wireless Networks mainly focus on delivering high data rate with some quality of service quarantees, on the other hand, wireless sensors typically transmit short observations and the communication protocol should also consider the energy efficiency of a sensor node in order to prolong the lifetime of the entire WSN [1].

1.2. LIST OF CONTRIBUTIONS

In this project, we design an energy efficient and cost effective sensor node instead of using commercially available sensor nodes to realize a WSN application. For this thesis, a sensor node is created with MSP430G2553 as microcontroller, nRF24L01+ as communication unit, LDR as sensory device and battery (2xAA). Then, using such sensor nodes, we form a WSN to perform localization of a source emitting light with real time Matlab visualization.

Fig. 1.1 shows a WSN system that is realized with designed sensor nodes for this thesis. Sensor nodes receive measurements from a light source and then transmit their light intensity measurements to the fusion center. If the received light intensity value is higher than a specific transmission threshold value then sensor transmits, otherwise it stays silent. In this way, rather than gathering all sensor data at the fusion center, we only collect data from the sensor nodes which are close to the location of the light source.

For sensor node transmissions to the fusion center, we next define a random access communication protocol. Under this protocol, if a sensor node transmits data to the fusion

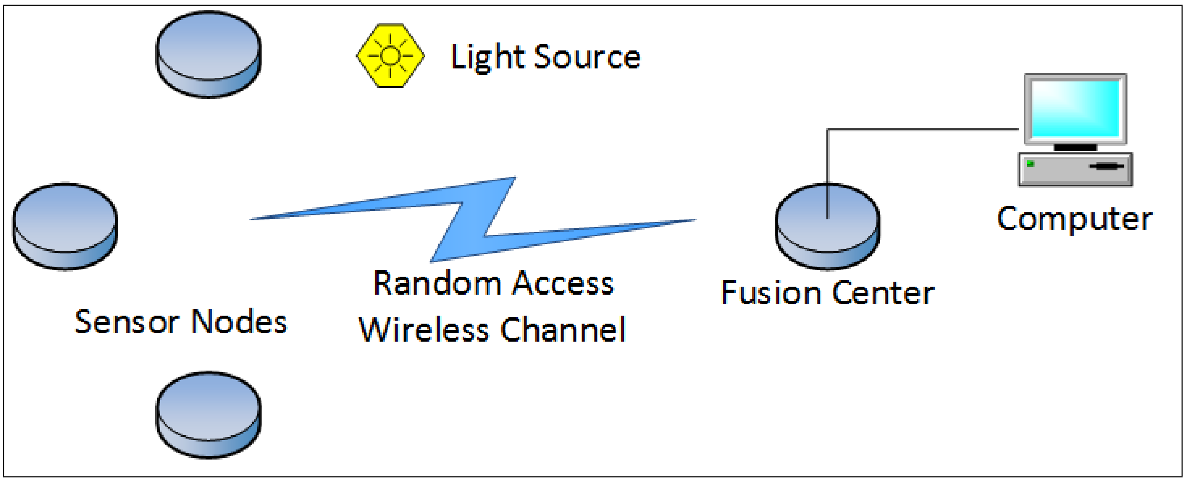

Figure 1.1. Overview of the WSN

center successfully, then the fusion center sends an acknowledgement message back to the sensor node. If a sensor node does not receive the acknowledgement, retransmits its data to fusion center until the reception of the acknowledgement. Fusion center which is composed of MSP430G2553 and nRF24L01+ receives light intensity values from sensor nodes and sends the received sensor data immediately to Matlab. Using Matlab, we perform localization with instantly available sensor data and real time monitor the estimated source location.

In addition, under different transmission thresholds, we obtain the Mean Squared Error (MSE) of localization as a function of number of transmitting sensor nodes. We also obtain the total number of sensor node transmissions with respect to number of transmitting sensor nodes as the value of the transmission threshold varies.

1.3. THESIS ORGANIZATION

The rest of this thesis is organized as follows,

In Section 2, we present the design of a sensor node. We give information about the sensor node components which are microcontroller, communicaiton unit, sensory device and battery. Also, we give LDR calibration method in this chapter.

In Section 3, we explain the communication algorithm which is performed between the sensor nodes and the fusion center. We further explain the network topology, communication packet format and the Matlab algorithm for source localization.

In Section 4, we present the test results. Firstly, we introduce the test area under two different cases, then we present the localization test results under these two cases. In addition, we calculate the energy comsumption and list the component prices of the sensor node.

Finally, we devote Section 5 to our conclusions and address possible future research directions.

2. SENSOR NODE DESIGN

In this chapter, we introduce the designed sensor node and its components which are MSP430G2553 microcontroller, nRF24L01+ communication module, LDR and battery (2xAA). Also in this section, we present the calibration procedure of LDR's.

2.1. SENSOR NODE

Fig. 2.1 shows a sensor node with all its components including MSP430G2553 as microcontroller, nRF24L01+ as communication module, LDR and LDR calibration resistance as sensing device and battery (2xAA). Microcontrollers (MSP430G2553) are programmed in C language using Code Composer Studio (CCS).

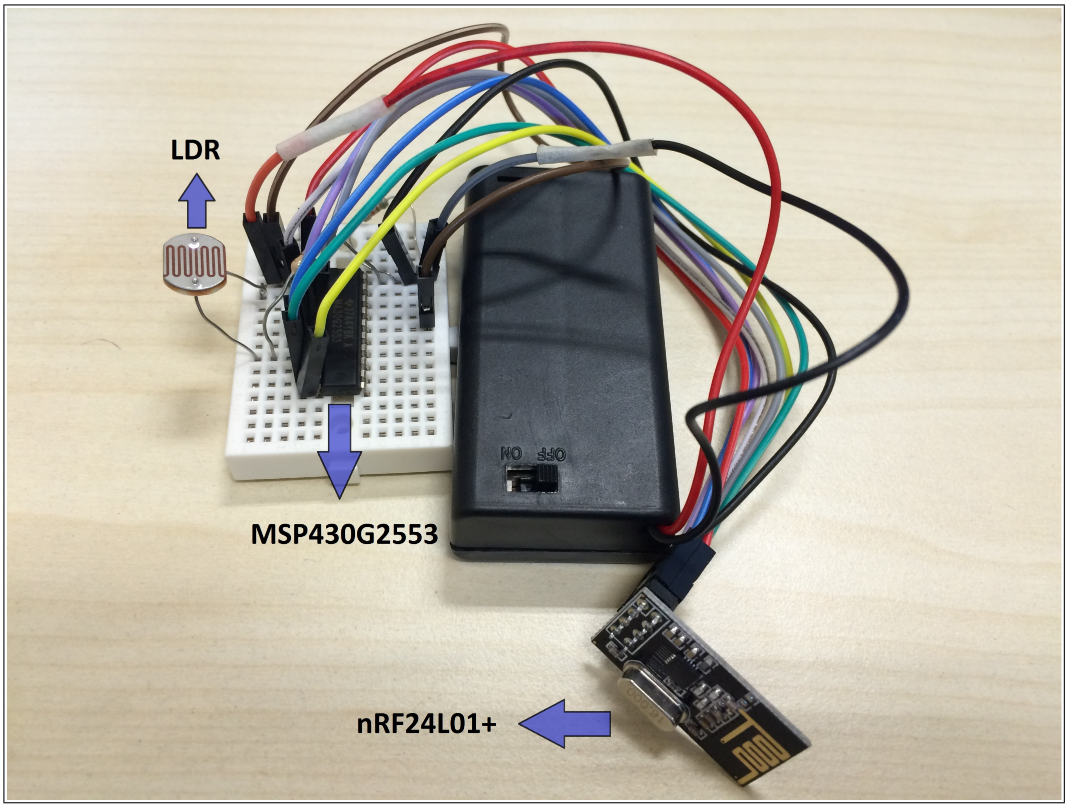

Figure 2.1. Sensor node

2.2. NODE SCHEMATIC

Fig. 2.2 shows the connection diagram of a sensor node. Microcontroller MSP430G2553 and communication module nRF24L01+ are charged from battery. Note that, if there is no data transmission, nRF24L01+ is switched to sleep mode to provide energy saving.

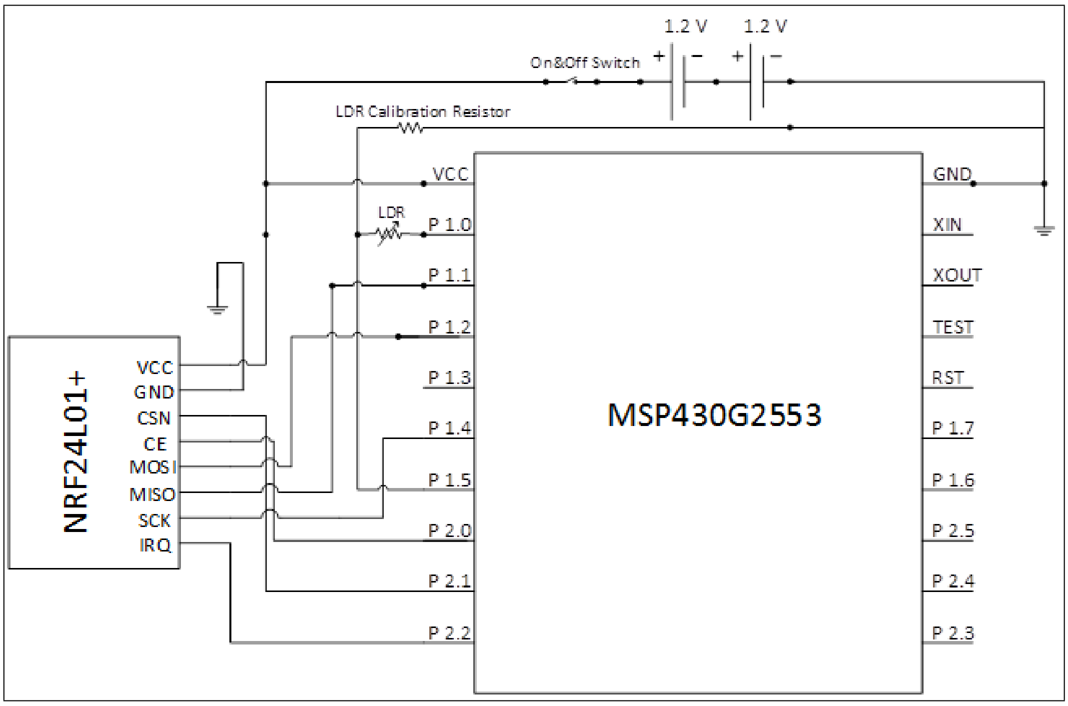

Figure 2.2. Node schematic

LDR is powered from MSP430G2553. LDR is also turned-off for energy saving while data are in the process of transmission to the fusion center. The LDR calibration resistor is used to calibrate different LDRs. Using an on/off switch, the sensor node can be activated or deactivated.

2.3. MICROCONTROLLER

Microcontroller is the most important unit in a sensor node. Due to its technical and financial aspects such that its sufficient memory, GPIO pins, ADC and low cost, we select MSP430G2553 as microcontroller.

MSP430G2553 is built with 16-Bit Reduced Instruction Set Computing (RISC) architecture, activates between 1.8V and 3.6V, and operates up to 16MHz speed. In this thesis, we select 1MHz as microcontroller operating frequency. It has 16 GPIO pins and it has 16KB non-volatile memory with 0.5KB Random Access Memory (RAM). MSP430G2553 has 8-channel and 10-Bit ADC so, for this thesis, light values that are obtained from LDR are limited between 0 and 1023.

MSP430G2553 has also Universal Serial Communication Interface (USCI) with Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I2C) communication protocols to enable communication with peripheral devices. MSP430G2553 has 8-bit communication register but we obtain light intensity value at 10-bit so, we divide the measurement by four to obtain 8-bit light intensity value. It has low power modes (LPMs) for ultra low power consumption and an active mode as shown below [30], [31].

- Active mode (AM): CPU, all clocks and enabled peripheral modules are active. Draws about 230-uA current.
- Low Power Mode 0 (LPM0): SMCLK and ACLK are still active. Draws about 56-uA current.
- Low Power Mode 1 (LPM1): SMCLK and ACLK are still active.
- Low Power Mode 2 (LPM2): ACLK and DCO remains active. Draws about 22-uA current.
- Low Power Mode 3 (LPM3): ACLK remains active (Standby Mode). Draws about 0.5-uA current.
- Low Power Mode 4 (LPM4): CPU, all clocks, and the crystal oscillator are disabled. Only RAM is retained. Draws about 0.1-uA current.

2.4. COMMUNICATION MODULE

nRF24L01+ provides communication between our designed sensor nodes and the fusion center. Communication module nRF24L01+ is connected with MSP430G2553 microcontroller through SPI. Fig. 2.3 shows nRF24L01+ channels where nRF24L01+ operates at the 2.4

GHz band. The 2.4 - 2.525 GHz band is divided into 126 RF sub-channels each with 1MHz bandwidth and nRF24L01+ uses Gaussian Frequency Shift Keying (GFSK) modulation [28]. Fig. 2.4 shows GFSK modulation which is a binary digital modulation technique created by filtering Frequency Shift Keying (FSK) using Gaussian filter which provides better transitions between subsequent transmission symbols and reduces the out-of band spectral interference [32].

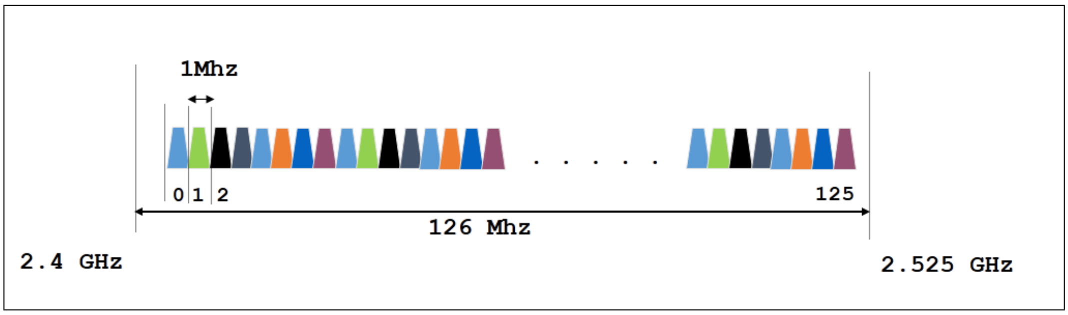

Figure 2.3. nRF24L01+ channels

nRF24L01+ has 250kbps, 1Mbps and 2Mbps air data rates options. In this thesis, we select 1Mbps air data rate. It has 1.9V to 3.6V supply range so we can easily feed it with standard AA batteries. Four different output powers are available respectively 0dBm, -6dBm, -12dBm and -18dBm in nRF24L01+. We select 0dBm as output power for this thesis. It consumes 26-uA in standby-I and 900-nA in power down modes so we conclude nRF24L01+ is suitable for sensor nodes to realize energy efficient WSNs. Also, nRF24L01+ is connected to MSP430G2553 as shown in Table 2.1

Table 2.1. Connection between nRF24L01+ and MSP430G2553

MSP430G2553	**nRF24L01+**	**Description**
P 2.1	CSN	SPI Chip Select
P 2.0	CE	Chip Enable
P 1.2	MOSI	SPI Slave Data Input
P 1.1	MISO	SPI Slave Data Output
P 1.4	SCK	SPI Clock
P 2.2	IRQ	Maskable Interrupt Pin

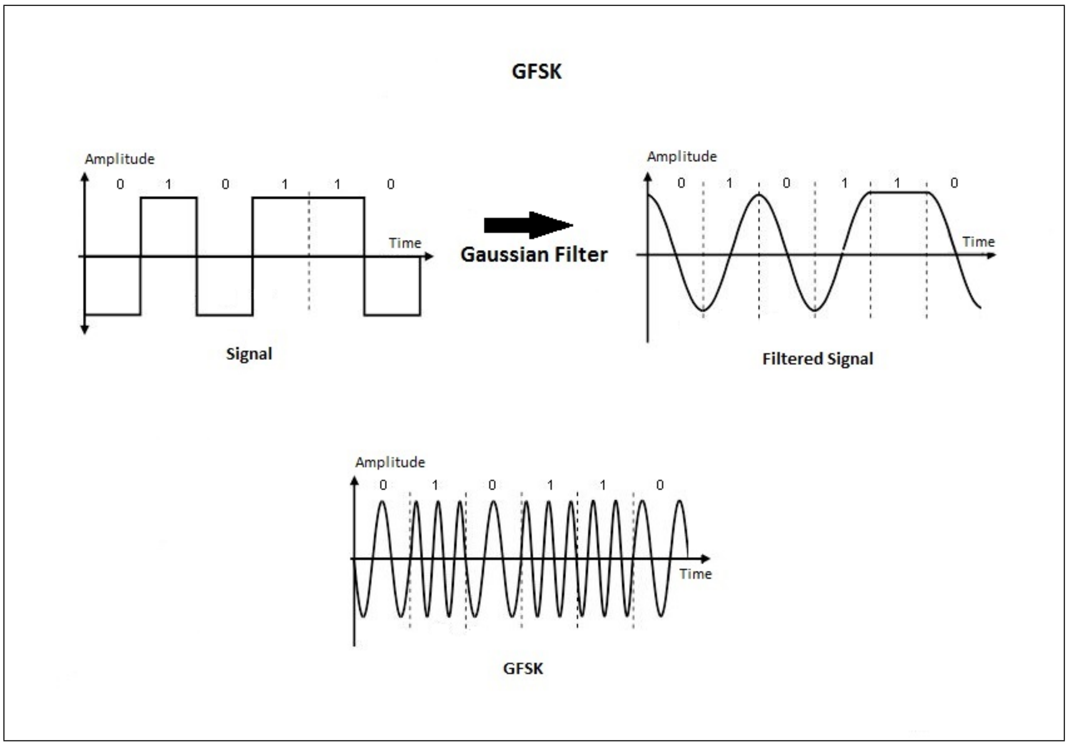

Figure 2.4. GFSK

2.5. SENSORY DEVICE

A sensor node uses a Light Dependent Resistor (LDR) as the sensory device. LDR is charged from the microcontroller so we can turn off it if there are data transmissions between sensor node and the fusion center for energy saving. Also, LDR is connected to Pin 1.5 of MSP430G2553 for ADC measurement.

LDRs of the same product may give different light intensity values under the same light conditions. Therefore we need to apply LDR calibration test. Fig. 2.5 shows the calibration test area. For the calibration test, we use 1W light-emitting diode (LED) light source and opposite of the light source we place the LDRs. Also the distance between LDR and the light source is taken 15 cm and a potentiometer is connected to LDRs to determine the value of the calibration resistors. Firstly, we supply the light source from a power supply and we observe LDRs under low, middle and high light intensity values in order to determine the value of the calibration resistors for each LDR. After that, we select the suitable resistor values for each

LDR. Table 2.2 shows the calibration resistor values for nine sensor nodes.

Table 2.2. LDR calibration resistor values

Sensor No	**Resistor Value**
Node 1	$\sim$ 0.822k
Node 2	$\sim$ 0.989k
Node 3	$\sim$ 0.908k
Node 4	$\sim$ 1.048k
Node 5	$\sim$ 1.315k
Node 6	$\sim$ 1.687k
Node 7	$\sim$ 0.783k
Node 8	$\sim$ 1.416k
Node 9	$\sim$ 0.984k

Then, we test LDRs with the calibration resistors by using CassyLab [33] where the CassyLab interface is shown in Fig. 2.6 to obtain each sensor light values. CassyLab is a software which records measurement data with different CASSY modules [34]. We apply low to high voltage slowly to 1W LED light source and we obtain output voltage values of the LDRs and calibration resistors using CassyLab to determine whether each of the sensor nodes can give same light density values under the same light source. Fig. 2.7 shows LDR calibration test results. x axis shows voltage of light source and y axis shows voltage of calibrated LDRs. Test results show that the sensor nodes approximately give same light values under the same light conditions.

Finally, sensor nodes have battery case and battery (2xAA) which is connected in serial to obtain approximately 2.8V that is suitable to power the sensor nodes.

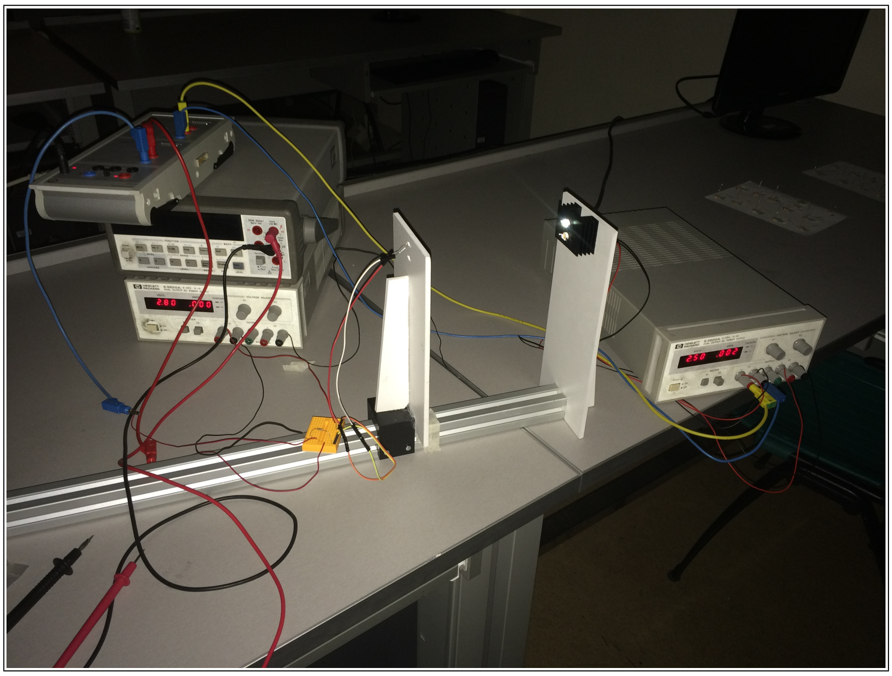

Figure 2.5. LDR calibration test field

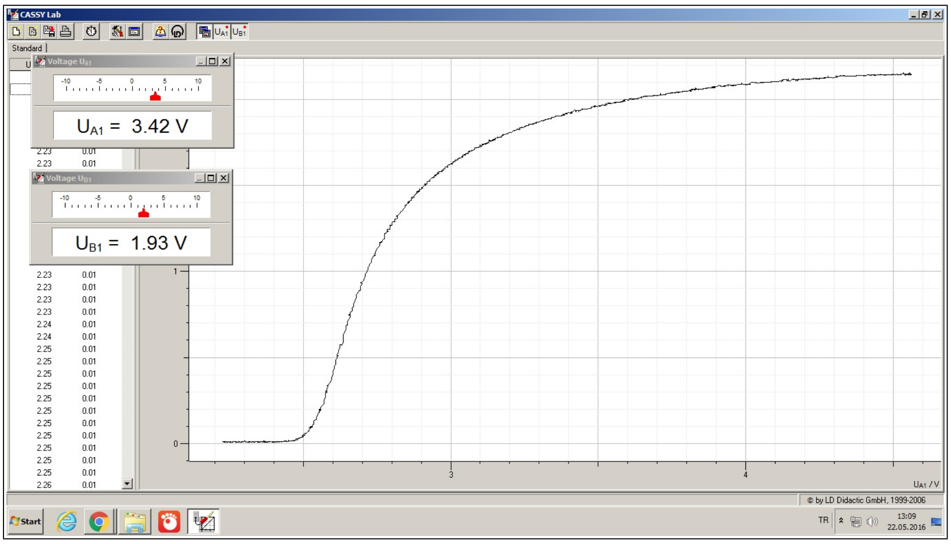

Figure 2.6. CassyLab measurement interface

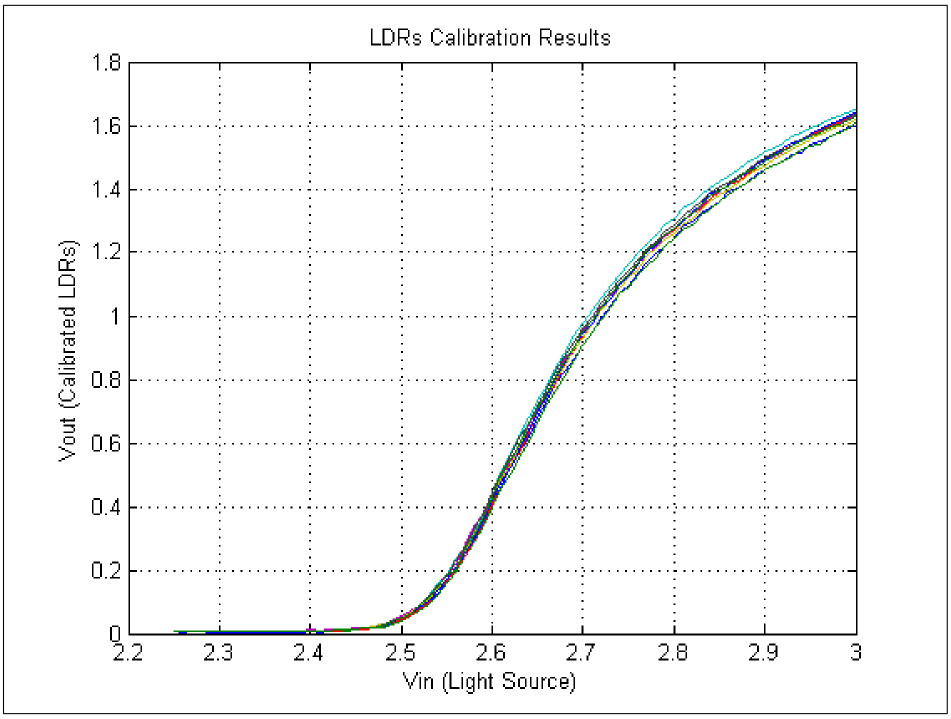

Figure 2.7. LDRs calibration results of nine sensor nodes

3. COMMUNICATION ALGORITHM

WSN applications need energy efficient communication algorithms. Also, the communication protocols should be as simple as possible so that they can be easily implemented on the computationally limited microcontroller. In this chapter, we introduce the communication algorithm which defines the way of transmissions between the sensor nodes and the fusion center.

3.1. NETWORK TOPOLOGY

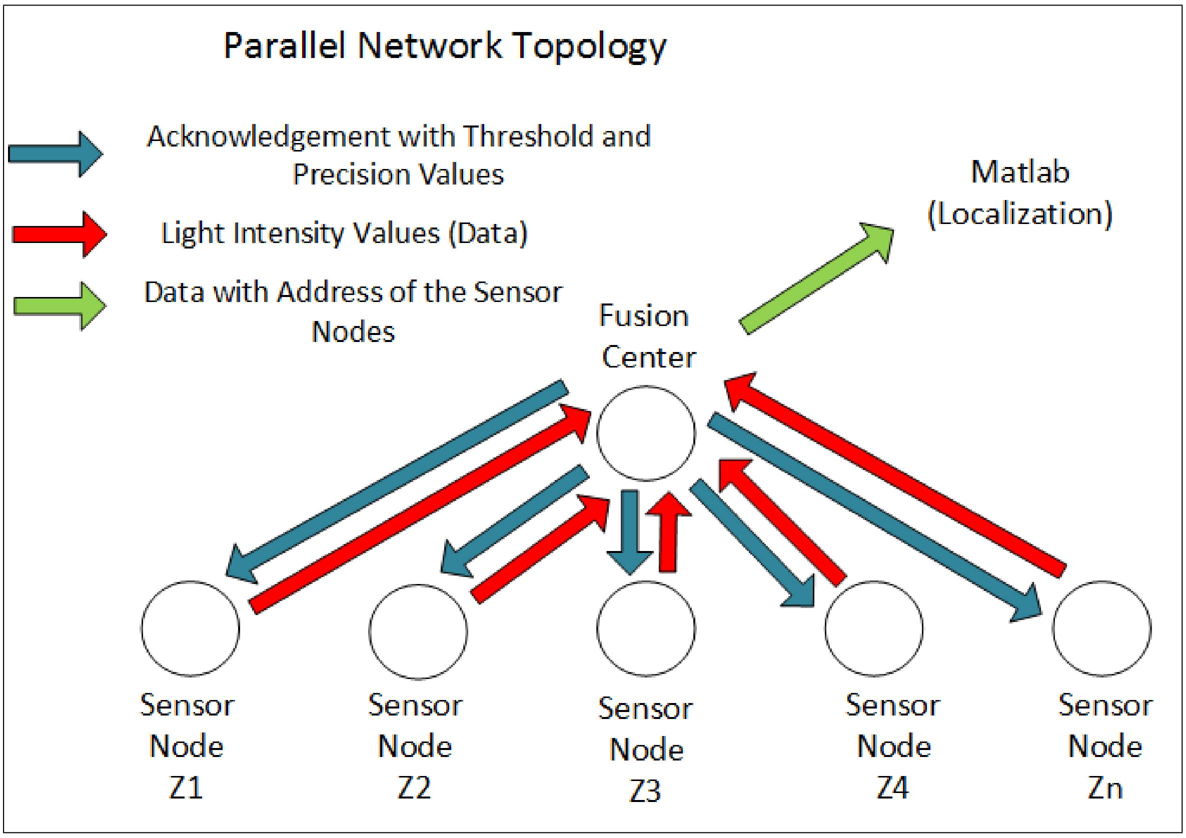

Figure 3.1. Network topology

There are many communication network topologies available for the WSN applications such as serial, parallel and tree topologies [2]. In serial or tree topologies sensor nodes are allowed to communicate with each other. In serial, sensor nodes transmit data to its immediate neighbor and in tree, multiple sensor nodes transmit their data to a cluster head and the cluster heads transmit data to the fusion center. In this thesis, we use the parallel network topology where sensor nodes transmit their data directly to the fusion center as shown in Fig. 3.1.

3.2. COMMUNICATION PACKET FORMAT

Fig. 3.2 shows the packet formats used for the communications between sensor nodes and the fusion center.

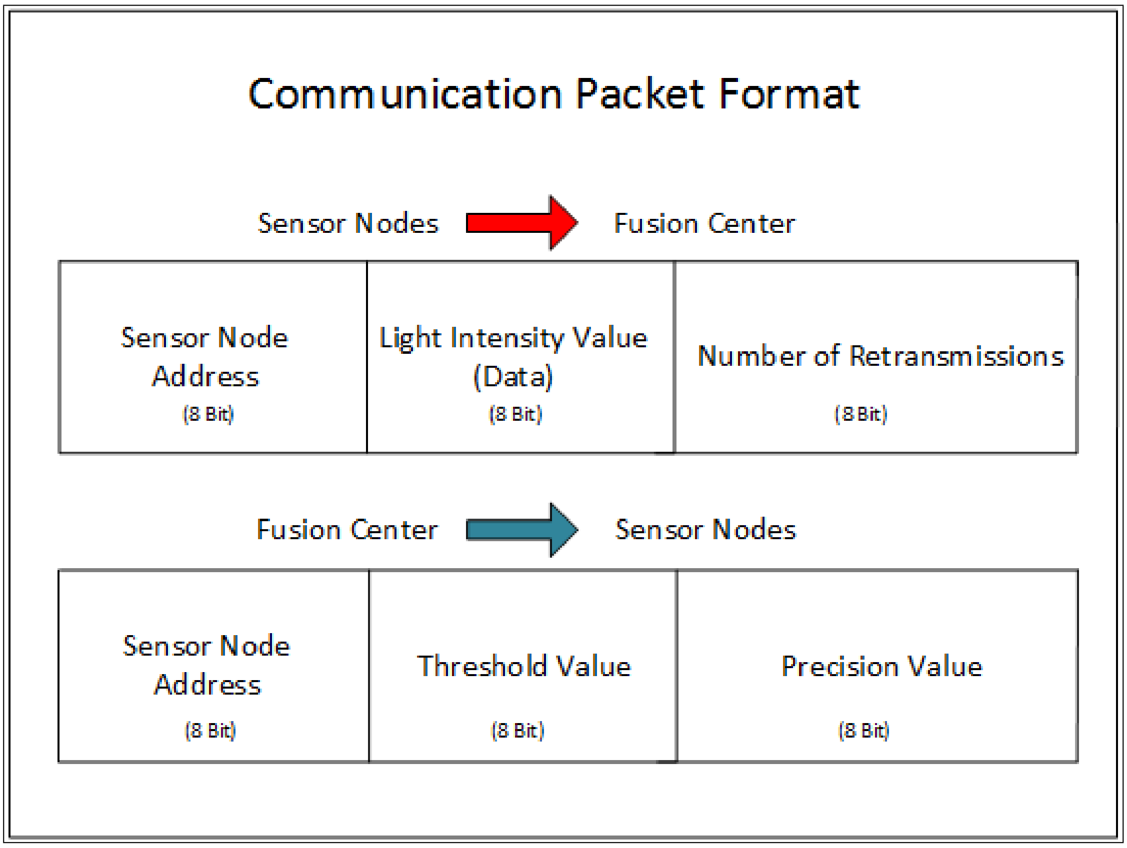

Figure 3.2. Packet format

A sensor node send its address information, measurement and number of retransmission to the fusion center. Upon the reception of the packet, the fusion center sends an acknowledgement to the sensor node. This acknowledgement packet includes the address information of the recepient sensor node, the transmission threshold level and the precision value. A sensor node compares its measurement with the transmission threshold. If the measurement is greater than the threshold, sensor node transmits its measurement to the fusion center. By employing transmission thresholds only a subset of sensor nodes near the source location transmit. If the measurement is above the threshold, by employing a precision value, a sensor node will not transmit continuously if there are minor fluctuations on the light intensity values. Transmission threshold and the precision values are sent to the sensor nodes from the fusion center. This enables dynamic adjustments of the thresholds during operation.

3.3. SENSOR NODE ALGORITHM

Fig. 3.3 shows the flowchart of the operations carried on a sensor node. Before the positioning of the sensor nodes, transmission thresholds and precision values are set in sensor nodes. Threshold value represents what value should be exceeded in order to send the measurement to the fusion center. Precision value determines whether there are any significant changes of the light intensity in the test field.

If the measured value exceeds the transmission threshold, the measurement is transmitted to the fusion center. If the current measurement value is the between [past measurement + precision value] and [past measurement - precision value], we assume that the light intensity value has not changed significantly and sensor node decides not to transmit its measurement otherwise the measurement is transmitted again to the fusion center.

If the light intensity value of a sensor node is outside of the threshold and precision values, sensor node turns on the communication module (nRF24L01+) in order to send the data to the fusion center and turns off the LDR for energy saving. If the sensor node's measurement is under the threshold level, the communication module (nRF24L01+) is switched to sleep mode for saving energy.

After the transmission of the measurement, a sensor node waits approximately 0.01 seconds for the acknowledgement from the fusion center. When the sensor node receives the acknowledgement, it turns off the communication module (nRF24L01+) and continue to take measurements by turning on the LDR. If the nRF24L01+ does not receive an acknowledgement, it retransmits the most recent measurement to the fusion center.

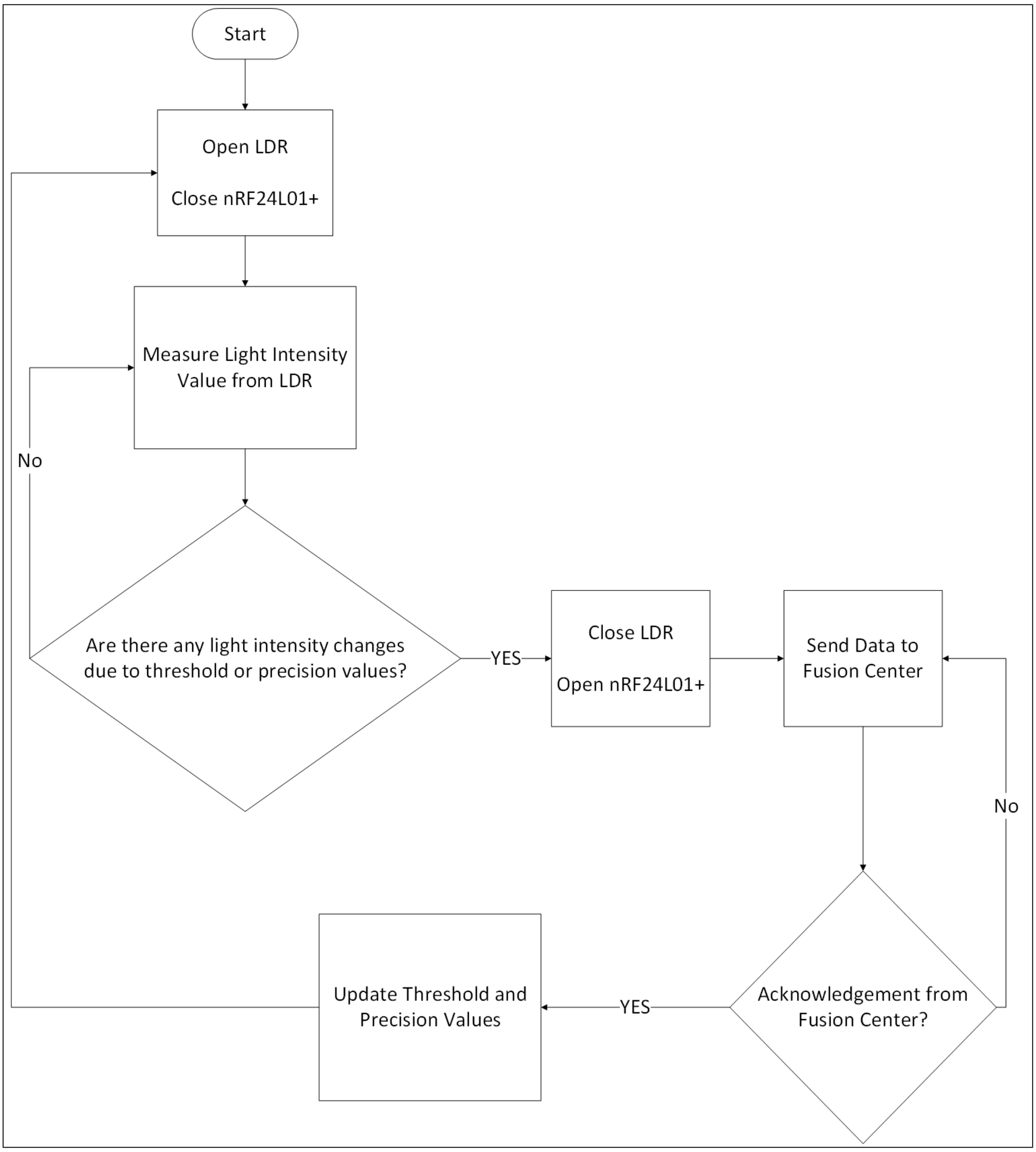

Figure 3.3. Flowchart of a sensor node

3.4. FUSION CENTER ALGORITHM

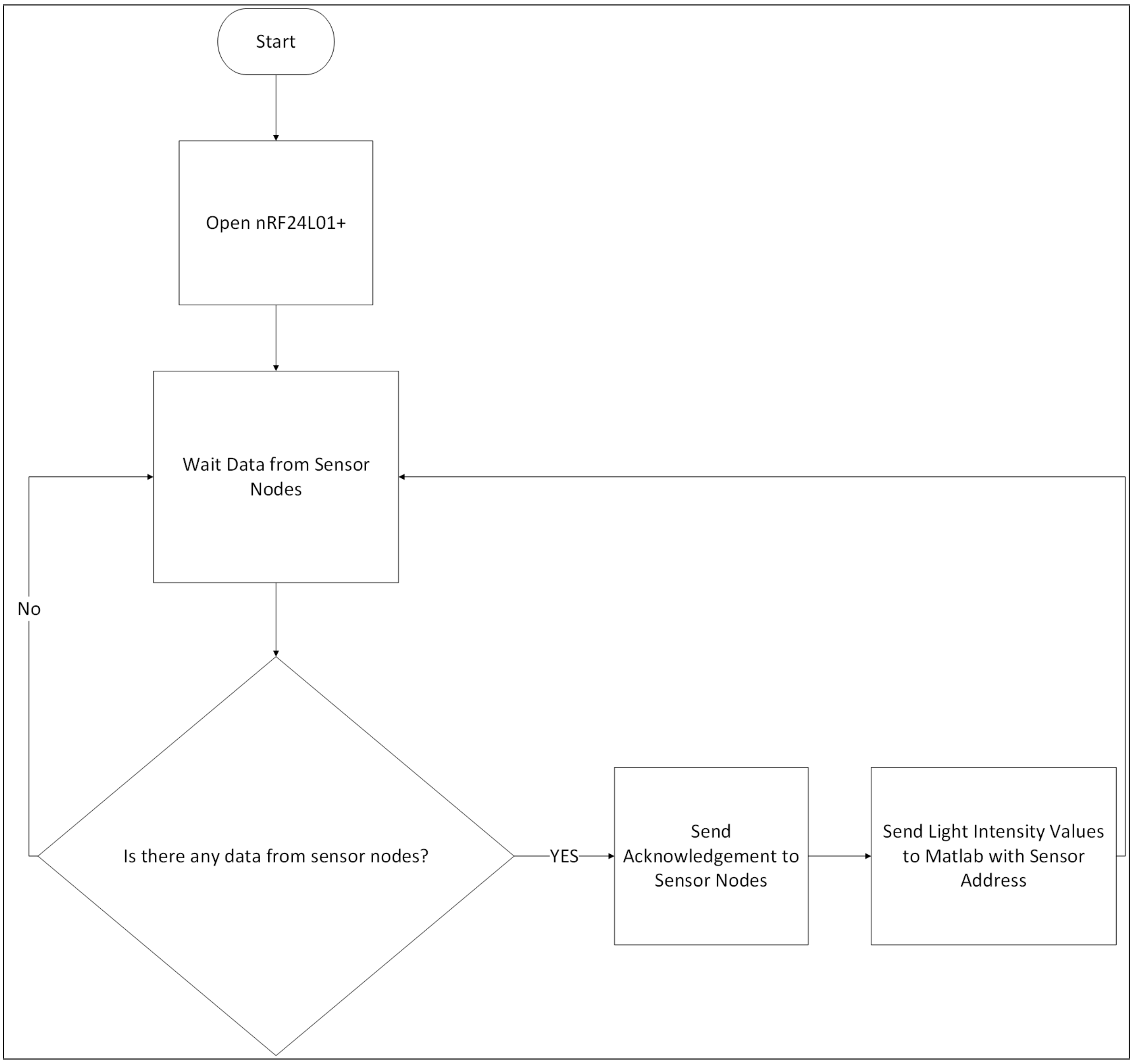

Figure 3.4. Flowchart of a fusion center

Fig. 3.4 shows the flowchart of operations carried out at the fusion center. Fusion center consists of only MSP430G2553 and nRF24L01+, and connected directly to the computer so, the fusion center does not have any concerns about energy saving.

Fusion center permanently the listens environment and receives data from sensor nodes. It transmits acknowledgement including address information of the related sensor node, the transmission threshold level and the precision value. In addition, after every succesful communication with sensor nodes, the fusion center forwards the sensor measurement with their address informations to Matlab. Matlab performs the localization based on the available sensor data.

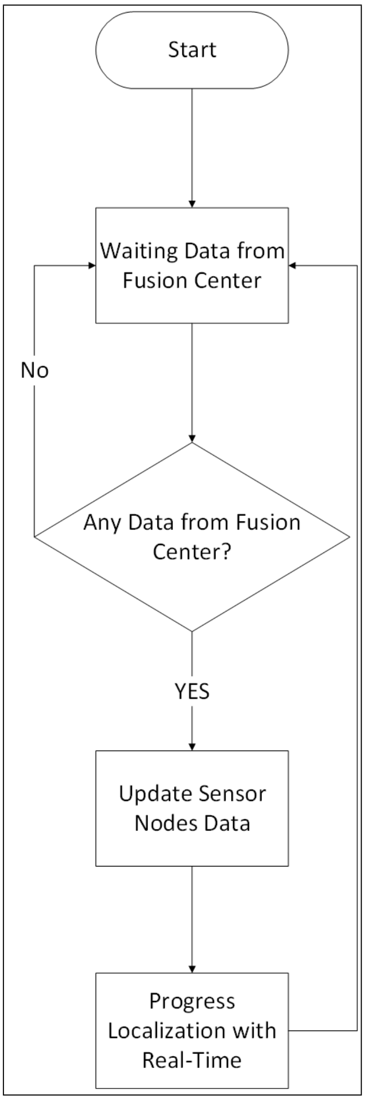

Figure 3.5. Flowchart of Matlab

Fig. 3.5 shows the Matlab algorithm. Matlab collect light intensity values from the fusion center and update the measurement of each sensor node data for real time localization. Source location is estimated based on the weighted average of available sensor measurements. Given the i^{th} sensor node locations, (x_i, y_i), and their measurements D_i, localization is performed as follows [3],

$$\hat{x} = \frac{\sum_{i=1}^{N_A} D_i x_i}{\sum_{i=1}^{N_A} D_i} \tag{3.1}$$

$$\hat{y} = \frac{\sum_{i=1}^{N_A} D_i y_i}{\sum_{i=1}^{N_A} D_i} \tag{3.2}$$

In this formula, $(\hat{x}, \hat{y})$ shows estimated source location, N_A shows the total number of active sensor nodes which send data to the fusion center.

4. MEASUREMENT RESULTS

In this section, we present the localization test results. Also, we present the energy consumption and component prices of a single sensor node.

4.1. LOCALIZATION TESTS

In our tests, transmission threshold level of the sensor nodes is changed between 40 and 200 with spacing of 20 and precision value is set to 12. Under the transmission threshold e, $MSE(e)$ is the mean squared error of the estimated source location and obtained from for each localization test we measure MSE calculated as,

$$MSE(e) = (1/T)\sum_{t=1}^{T}(x - \hat{x}_t)^2 + (y - \hat{y}_t)^2 \tag{4.1}$$

where (x, y) represents the actual target location. In order to determine the actual target location, we locate a sensor node under the light source and we find the coordinate which give the maximum light intensity value. $(\hat{x}, \hat{y})$ represents the estimated target location for test t. Also T represents the total number of tests obtained for threshold level e.

In this section, two different cases are considered for localization. In the first case, we set up five sensor nodes in the area which is shown in Fig. 4.1. As the light source, we use a halogen lamp with approximately 30 cm above from the sensor nodes. In this case, the distance between the fusion center and sensor nodes vary between 350 cm and 450 cm.

In the second case, we use nine sensor nodes which are located approximately between 150 - 250 cm away from the fusion center. As the light source, we use a LED which is fed with 4.2V and located about 80 cm above from the test area. Fig. 4.2 shows the test area for the second case. Next, we present the localization for these two cases.

Figure 4.1. Test area for under case 1

Figure 4.2. Test area for under case 2

4.1.1. First Case

Five sensor nodes are located as in Fig. 4.3 and during the test, the light source is located at the position (36,42).

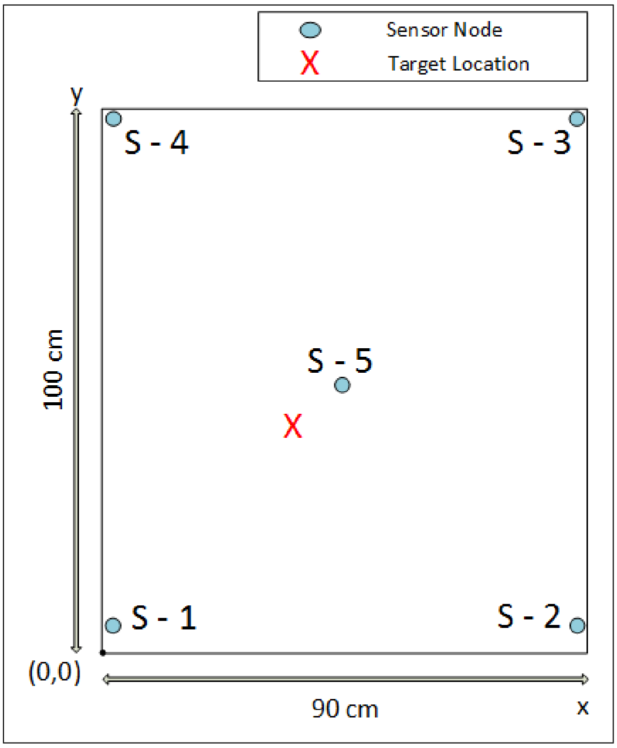

Figure 4.3. Field schematic for first case

Fig. 4.4 shows the MSE as a function of the number of active total sensor nodes and Fig. 4.5 shows the retransmissions as a function of the numbers of active total sensor nodes. As seen in Fig. 4.4 and in Fig. 4.5 if the number of active sensor nodes, which is determined by threshold level, is increased, MSE decreases and also the number of retransmission increases. As the transmission threshold decreases more sensor nodes transmit and more data provides better estimation performance. On the other hand, as the transmission threshold decreases, more sensor nodes transmit which increases the number of packet collisions and the number of retransmissions. As the transmission threshold increases less sensor nodes transmit to the fusion center which also decreases the collisions and hence the number of retransmissions.

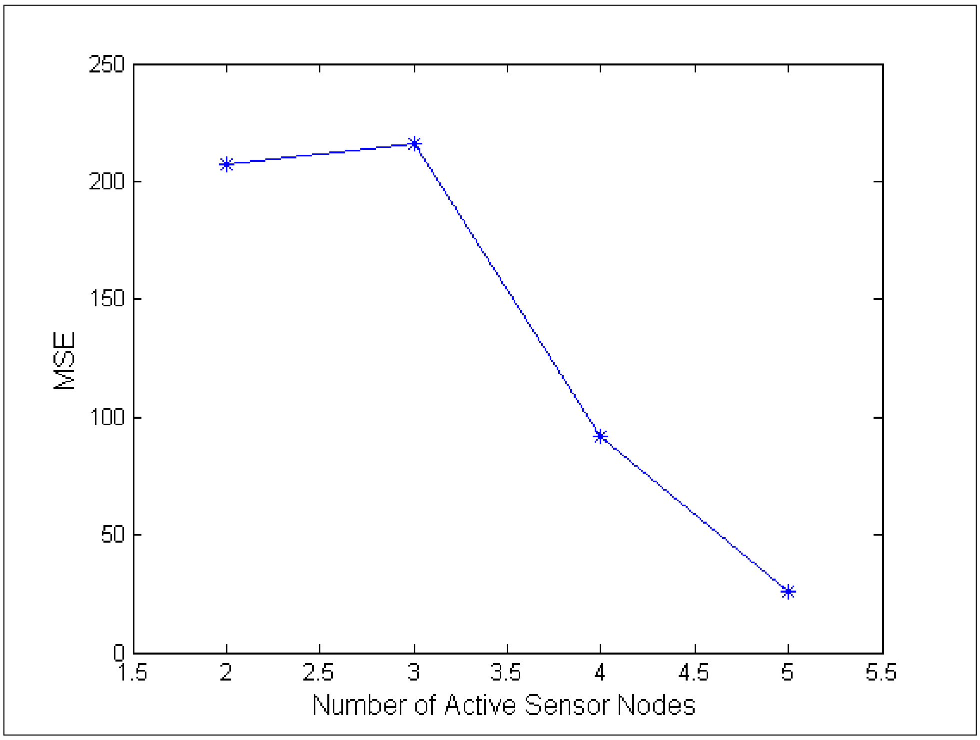

Figure 4.4. MSE due to numbers of active sensor nodes for first case

4.1.2. Second Case

Fig. 4.6 shows the graphical view of the testbed. For this case we use nine sensor nodes and during the test light source is located at the position of (34,42). Similar to the first case, Fig. 4.7 shows MSE as a function of the total number of active sensor nodes. The total number of active sensor nodes which trasmit data to the fusion center at each trial depends on the threshold level defined at the sensor nodes. When the threshold level is high, only few sensor nodes transmit data to fusion center for localization. Therefore, MSE increases while saving energy. If the threshold level is set to a low value, more sensor nodes transmit data to the fusion center which decreases the MSE but increases the total energy consumption.

Fig. 4.8 shows the number of retransmissions as a function of active sensor nodes. Transmission failures occur due to many sensor nodes try to send data to the fusion center. Due to the defined algorithm, sensor nodes send data until an acknowledgement is received from the fusion center. If more active sensor nodes try to send data, retransmissions are increased

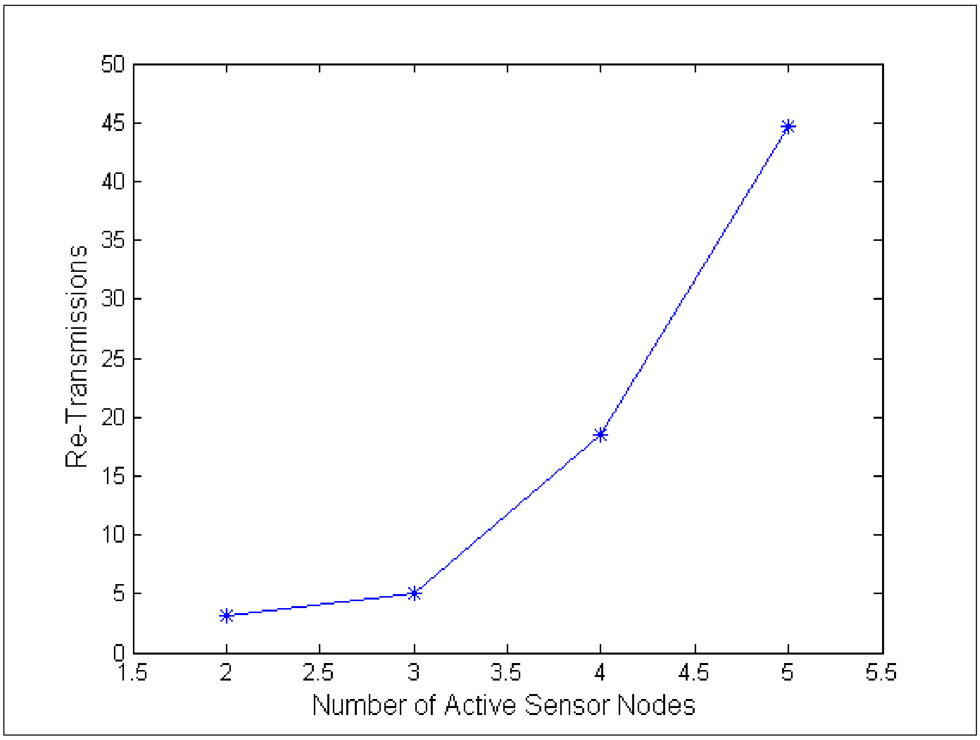

Figure 4.5. Retransmissions due to numbers of active sensor nodes for first case

so total energy consumption also is increased. If we apply the transmission threshold level 60, MSE is obtained approximately under 10 while the number of retransmissions is nearly 15. On the other hand, if we apply the transmission threshold level 160, MSE increases up to 300 and the number of retransmission goes down to 3.

Fusion center directly sends data to Matlab that shows localization results permanently with real time and Fig. 4.9 shows an example Matlab view.

There are some differences between the first and second cases. Firstly, retransmission for the first case results are higher than the second case because in the first case, the distance between sensor nodes and the fusion center is nearly 350-450 cm but for the second case distance is about 150-250 cm which affect the number retransmissions. Under the same number of transmitting sensor nodes the MSE for the first and second cases are different which can be a consequence of different light source, height of the source from the test area and other test conditions.

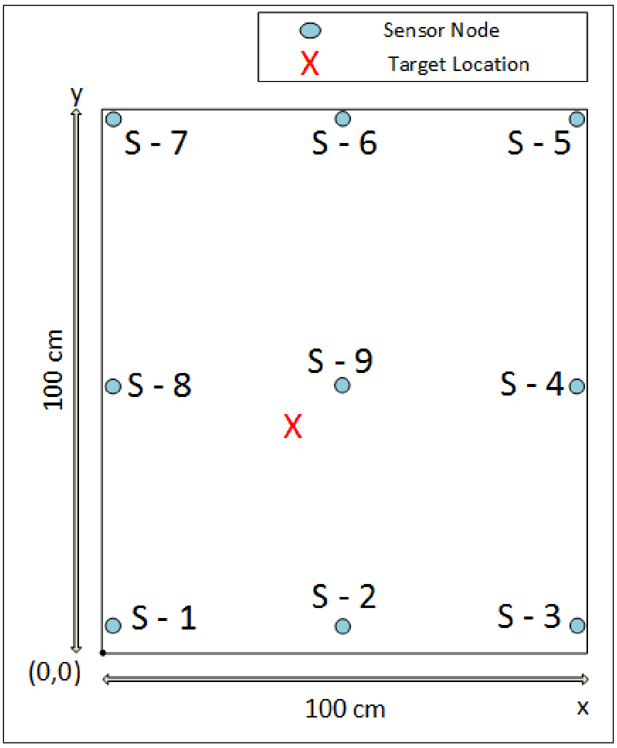

Figure 4.6. Field schematic for second case

So far, we present the source localization performance for a static light source only. Localization can also be performed for a mobile light source as well. When the source is nearly static, an active sensor node near the source sends its measurement and the measurement is then kept in Matlab with the measurements of other sensor nodes for localization. Under this case, the active sensor node does not retransmit its measurement since a new measurement from the light source probably fall within the precision range. On the other hand, when the source moves significantly, the measurement of an active sensor node change beyond the precision range. Therefore, the sensor node tends to transmit its new measurement and the corresponding measurement value in Matlab becomes updated accordingly. Upon completing the localization with updated sensor measurements, the estimated source location is also updated. An example case is visualized in [35].

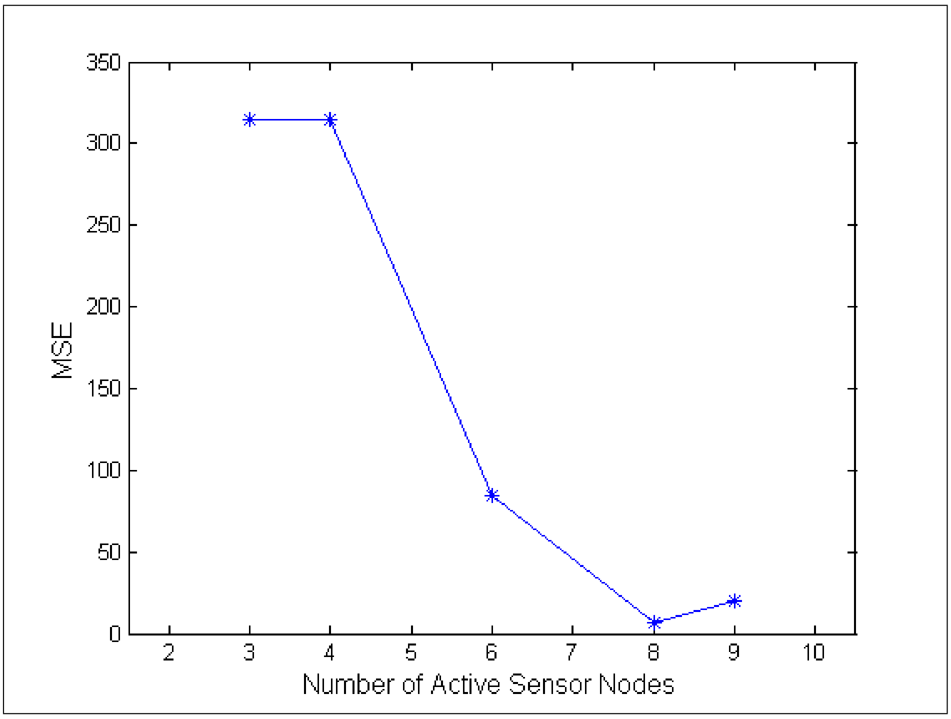

Figure 4.7. MSE due to numbers of active sensor nodes for second case

4.2. ENERGY CONSUMPTION

Table 4.1 shows the current draw. Sensor nodes draw current 1mA while taking measurement from the light source. In designed sensor nodes, communication module nRF24L01+ dominates the current draw as compared to other components. Therefore, the communicaiton modules are taken to sleep mode until the beginning of the communication process. Sensor nodes draw approximately 12mA during of the communicaiton process as data transmission and receiving an acknowledgement.

Table 4.1. Energy consumption

Condition	Microcontroller	Communication Module	LDR	Total
Light Control	$<$ 0.4mA	-	$<$1mA	$\sim$1mA
Sending Data	$<$ 0.4mA	$\sim$11mA	-	$<$11mA
Receiving Data	$<$ 0.4mA	$\sim$13mA	-	$<$14mA

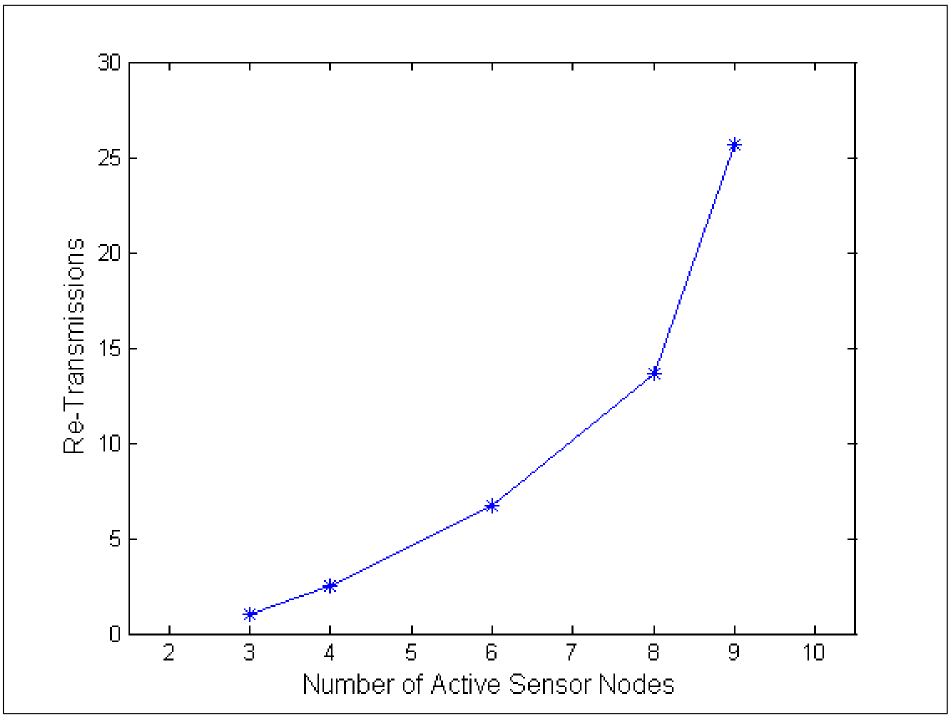

Figure 4.8. Retransmissions due to numbers of active sensor nodes for second case

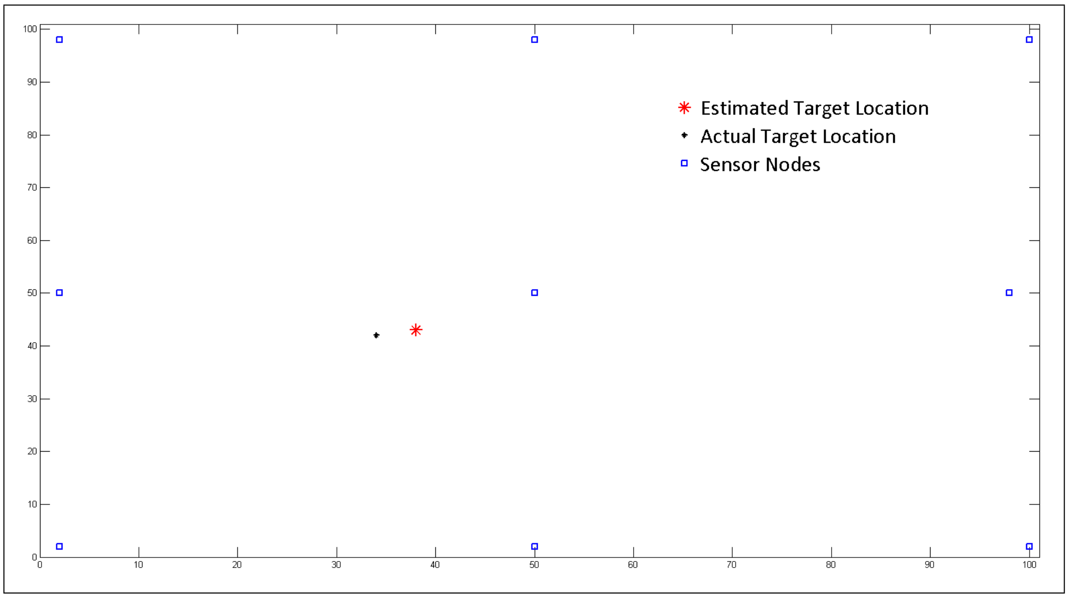

Figure 4.9. Matlab view

Table 4.2 shows the energy consumptions due to retransmissions under different threshold levels in case 2. We apply localization test with different thresholds. If threshold value is low, many sensor nodes trying to send data to the fusion center so number of retransmission and energy consumption increase. Otherwise, if threshold value is high, some sensor nodes try to send data so retransmission and energy consumption decrease. In addition, retransmission period takes approximately between 0.01 and 0.02 seconds.

Table 4.2. Total number of transmissions and energy consumption for case 2

No	Threshold Value 40	Threshold Value 100	Threshold Value 140
Sensor Node 1	9 / ∼12mA	- / ∼1mA	- / ∼1mA
Sensor Node 2	7 / ∼12mA	- / ∼1mA	- / ∼1mA
Sensor Node 3	3 / ∼12mA	- / ∼1mA	- / ∼1mA
Sensor Node 4	3 / ∼12mA	2 / ∼12mA	- / ∼1mA
Sensor Node 5	2 / ∼12mA	4 / ∼12mA	1 / ∼12mA
Sensor Node 6	2 / ∼12mA	4 / ∼12mA	3 / ∼12mA
Sensor Node 7	5 / ∼12mA	2 / ∼12mA	- / ∼1mA
Sensor Node 8	4 / ∼12mA	1 / ∼12mA	2 / ∼12mA
Sensor Node 9	2 / ∼12mA	3 / ∼12mA	3 / ∼12mA

4.3. COMPONENT PRICES

Table 4.3 shows the price of materials that is needed to creating a sensor node. The price is suitable to realize WSN using many sensor nodes.

Table 4.3. Component prices of a sensor node

No	Product Name	Price($)
1	MSP430G2553	2.5
2	nRF24L01+	0.99
3	Light Dependent Resistor (LDR)	0.35
4	Battery (2xAA 2100mah)	1.5
5	Other Products (Cable,Resistance,Battery Case etc)	2
6	Mini Breadboard	0.71
7	Total	8.05

5. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this thesis, we proposed a WSN system which was realized with custom design sensor nodes. Using low cost and low energy components such as MSP430G2553 microcontroller and nRF24L01+ communication module, sensor nodes were created in a cost effective and energy efficient manner. For energy saving, the communication module is switched to sleep mode while taking measurement from LDR and also during data transmission, LDR is turned off. In addition, by communicating such sensor nodes, we formed a WSN and localized a source emitting light. In this study, only the sensor nodes near the light source send data to fusion center instead of all sensor nodes, transmit to the fusion center. Such a sensor selection is approach advantageous in terms of energy efficiency. The number of sensor nodes transmit to the fusion center to minimize estimation error and reduce the number of retransmissions due to collisions depends on the transmissions threshold defined in the proposed communication protocol. Finally, localization results were presented in Matlab with real time visualization. The localization application can be used to locate the any light source in a dark area. As an instance, an individual mine worker whose helmet emits light can be located by such a WSN in a dense dark area.

As a future work, other localization methods such as triangulation can be tested and compared with the localization with respect to the weigted average of the received sensor measurements. Rather than source localization, more complex applications can be realized such as object tracking or area monitoring for field estimation. Different types of sensing units can be added to our node design such as temperature, humidity and pressure to implement different WSN applications. Also other communication topologies such as serial, tree or multihop can be realized. In this thesis, we used MSP430G2553 with its active mode only. To further improve the energy efficiency of the microcontroller, we can develop new algorithms and utilize the rest of the LPMs. In addition, a solar panel can be added to improve lifetime of a sensor node. Depending on the application and communication protocols the microcontroller can also be upgraded to better suit the application needs.

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