DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ENERGY EFFICIENT WIRELESS SENSOR NETWORKS FOR UNDERGROUND MINING APPLICATIONS

by
Emre ÜNSAL

September, 2016
İZMİR

ENERGY EFFICIENT WIRELESS SENSOR NETWORKS FOR UNDERGROUND MINING APPLICATIONS

A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Computer Engineering

by
Emre ÜNSAL

September, 2016
İZMİR

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"ENERGY EFFICENT WIRELESS SENSOR NETWORKS FOR UNDERGROUND MINING APPLICATIONS"** completed by **EMRE ÜNSAL** under supervision of **PROF. DR. YALÇIN ÇEBİ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my supervisor, Prof. Dr. Yalçın ÇEBİ, for his guidance, endeavor and seamless support throughout this study. My cordial thanks and appreciation also extend to my thesis committee members, Asst. Prof. Dr. Gökhan DALKILIÇ and Asst. Prof. Dr. Reyat YILMAZ, for their moral support, thought provoking and invaluable comments.

I would like to offer my special thanks to Asst. Prof. Dr. Özgür TAMER, Prof. Dr. Ahmet Hakan ONUR and Assoc. Prof. Dr. Doğan KARAKUŞ for their help, support and cheerful presence through not only the course of this study but also any course of my life. I would also like to offer my thanks to my friends Mehmet MİLLİ, Mehmet CENGİZ and Selman KAYA for their seamless help and support during this study.

Finally, I would like to express my sincere gratitude to my dear wife, son and parents for their support, patience and love. I could not be able to complete this thesis without their precious support.

Emre ÜNSAL

ENERGY EFFICIENT WIRELESS SENSOR NETWORKS FOR UNDERGROUND MINING APPLICATIONS

ABSTRACT

The harsh environment and challenging working conditions cause certain difficulties in sensing and tracking of significant physical environmental parameters in the underground mining. In order to mitigate accidents, and to ensure a safety monitoring system for underground mining applications, tracking the underground mine galleries, active and abandoned underground mining workplaces are become major tasks. However, in some cases the lack of electrical energy or rapid structure changes in the mining galleries and underground mining workplaces cause impossible to monitor all of these places continuously.

In this study, a low-cost, low-power Wireless Sensor Network (WSN) architecture is proposed to monitor active and abandoned underground mining workplaces. The proposed WSN will monitor the presence of temperature, humidity, methane and carbon monoxide parameters from underground mining workplaces in order to avoid mine accidents. For this purpose, Arduino suitable sensor nodes were developed for underground coal mine monitoring application. The developed sensor nodes were tested in terms of radio signal propagation through different materials. Additionally, the coverage of sensor nodes was measured in closed and open field experiments. Finally, the signal range of the sensor nodes were measured under the soil.

Both MS-Windows and web based mine monitoring applications were developed to control and manage the deployed WSN. In addition, a new adaptive underground monitoring algorithm was implemented to optimize power consumption of the sensor nodes.

Keywords: Wireless Sensor Networks, underground mine safety, Arduino, power management, signal propagation.

YERALTI MADEN UYGULAMALARINDA ENERJİ VERİMLİ KABLOSUZ SENSÖR AĞLARI

ÖZ

Yeraltı madenciliğindeki muhalif çevre şartları ve zorlu çalışma koşulları önemli fiziksel ortam parametrelerinin algılanması ve takip edilmesinde bazı zorluklara neden olmaktadır. Yeraltı maden uygulamalarında kazalardan kaçınmak ve güvenli bir izleme sistemi sağlamak için, yeraltı maden galerilerinin, aktif ve terkedilmiş maden iş sahalarının izlenmesi başlıca bir görev haline gelmiştir. Ancak, elektrik enerjisinin bulunmadığı ya da yapı değişikliklerinin hızlı olduğu bazı durumlarda maden galerileri veya maden iş yerlerinin sürekli olarak izlenmesi imkânsızdır.

Bu çalışmada, düşük maliyetli ve düşük güç tüketimine sahip bir Kablosuz Algılayıcı Ağ (KAA) mimarisi aktif ve terkedilmiş yeraltı maden alanlarını izlemek için önerilmektedir. Önerilen KAA maden kazalarını önlemek amacıyla yeraltı maden işyerlerinde sıcaklık, nem, metan ve karbon monoksit parametrelerinin varlığını izleyecektir. Bu amaçla, Arduino platformuna uygun sensör düğümleri yeraltı kömür madeni izleme uygulaması için geliştirilmiştir. Geliştirilen sensör düğümleri farklı materyaller aracılığıyla radyo sinyalleri yayılması açısından test edilmiştir. Buna ek olarak, sensör düğümlerinin kapsama alanı, kapalı ve açık alan deneylerde ölçülmüştür. Son olarak, algılayıcı düğümlerin sinyal menzili toprak altında ölçülmüştür.

Geliştirilen KAA kontrol etmek ve yönetmek amacıyla Windows ve web tabanlı maden izleme uygulamaları geliştirilmiştir. Buna ek olarak, yeni bir uyarlamalı yeraltı izleme algoritması sensör düğümlerin güç tüketimini optimize etmek için uygulanmıştır.

Anahtar kelimeler: Kablosuz Algılayıcı Ağlar, yeraltı maden güvenliği, Arduino, güç yönetimi, sinyal yayılımı.

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CHAPTER ONE
INTRODUCTION

1.1 Overview

Recent developments in wireless communications, embedded devices and sensing technologies allow real word deployment of Low Power Lossy Networks (LLN) such as Wireless Sensor Networks (WSNs). In recent years, WSNs are getting popular for observing and sensing the physical environment. These networks have wide range of applications such as monitoring volcanic eruption, military surveillance, control in buildings, vehicle tracking and detection, monitoring inaccessible or wild environment, nuclear, biological or chemical attack detection, home automation and health-care applications (Akyildiz et al., 2002).

WSNs are widely used for environment monitoring applications such as, habitat (Akyildiz & Vuran, 2010), air pollution (Rawat et al., 2014), agricultural (Yoo et al., 2007) and underground (Dohare, Maity, Paul, & Das, 2014) monitoring. Wireless Underground Sensor Network (WUSN) is a specialized kind of WSN that mainly focuses on the use of sensors nodes which operates under the earth's surface (Akyildiz & Stuntebeck, 2006). The communication medium is the main difference between WUSNs and the terrestrial WSNs. Actually, the main reason of this difference is caused by the propagation of electromagnetic waves under the ground.

In a WUSN deployment, the sensor nodes are buried below the ground or placed inside the underground mines, tunnels or subways (Akyildiz & Vuran, 2010). The underground mining is one of the most dangerous jobs, and the lack of light, insufficient fresh air and limited electrical energy makes this industrial filed more challenging.

The size and placement of the underground mine is changed frequently. Therefore, the coverage area of the monitoring application is also changed with it. Wired monitoring systems should be redeployed to suit up with these rapid changes, however, the cost of the redeployment of these systems is much. In addition, the wired communication system is cut out by the cave-in or falling materials encountered in the underground mines. In order to widen the coverage area and reduce the redeployment of the monitoring systems cost, using a wireless underground monitoring system is a good solution.

1.2 Purpose and Contribution of the Thesis

In order to mitigate accidents, and to ensure a safety monitoring system for underground mining applications, tracking the underground mine galleries, active and abandoned underground mining workplaces are become major tasks. However, in some cases the lack of electrical energy and rapid structure changes in the mining galleries or underground mining workplaces cause impossible to monitor all of these places continuously.

In this study, a low-cost and low-power WSN architecture is proposed to monitor active and abandoned underground mining workplaces. The proposed sensor network will monitor the presence of temperature, humidity, methane and carbon monoxide gas percentages from underground mining workplaces for preventing the methane explosions and coal combustions.

For this purpose, Arduino suitable sensor nodes are developed for underground coal mine monitoring application. The developed sensor nodes are tested in terms of radio signal propagation with different materials. The developed WSN is tested indoor, outdoor experiments. Finally, the signal range of the sensor nodes are measured under the ground.

Both MS-Windows and web based monitoring applications are developed to control and manage the developed WSN in this study. In addition, a new adaptive underground monitoring algorithm is proposed to optimize power consumption of the sensor nodes.

1.3 Organization of the Thesis

This thesis composes of eight main chapters. In Chapter one, an introduction to the WSNs, underground safety monitoring and purpose of the thesis are given. The remaining chapters of this thesis are explained briefly below;

In the second chapter, a general review about sensor nodes and network architectures, characteristics, protocol stacks, application fields and design challenges of the WSNs are explained. Finally, a classification of WSNs is given.

In the third chapter, underground applications of the Wireless Underground Sensor Networks (WUSNs) are summarized. Underground network architectures and the design challenges of the WUSNs are explained. The recent studies about underground mining applications in the literature are classified into three subcategories and examples of each category is surveyed at the end of this chapter.

In the fourth chapter, design and implementation stages of the sensor nodes used in this study is mentioned. The hardware implementation of the sensor nodes and suitable sensor selection for the underground monitoring applications are explained in detail.

In the fifth chapter, the importance of the power management for battery powered sensor nodes is emphasized. Power saving and management methods for optimizing the power consumption of battery powered sensor nodes are explained. In conclusion, the experimental results of these methods applied to the sensor nodes used in this study is given.

In the sixth chapter, the experimental studies about radio signal propagation in underground mines and the implementation of a WSN for underground mine monitoring are explained. The signal attenuation of the different materials frequently encountered in the underground coal mines is examined. Moreover, the results of the radio module signal range test are discussed for indoor and outdoor experiments. At the end of this chapter, the wireless connectivity of the developed wireless nodes was tested under the ground.

In the seventh chapter, the developed underground monitoring applications to ensure safety of the underground mining workplaces is explained in figures and forms. In addition, the developed adaptive underground monitoring algorithm is also explained.

In the last chapter of the thesis, conclusions and contribution to academic areas is given. Then, future works are discussed.

CHAPTER TWO
WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSNs) comprise of spatially distributed autonomous devices using to monitor physical environment conditions and pass their data through to a main station (Bokare & Ralegaonkar, 2012). WSNs observe the physical environment by sensing mechanical, thermal, biological, chemical, optical, or magnetic events (Hussain, Cebi & Shah, 2008).

A WSN physically consists of densely located sensor nodes, routing nodes and one or more manager nodes, called sink (gateway) node (Akyildiz et al., 2002). After the node processes the information derived from the sensors and makes some decision, the collected data is sent forward to the gateway node. An example WSN architecture is given in the Figure 2.1. Although Ad-Hoc Networks and WSNs have some similarities, the dense of sensor nodes in a sensor network and the communication protocols differs these wireless network types each other (Gomez & Garcia-Macias, 2006).

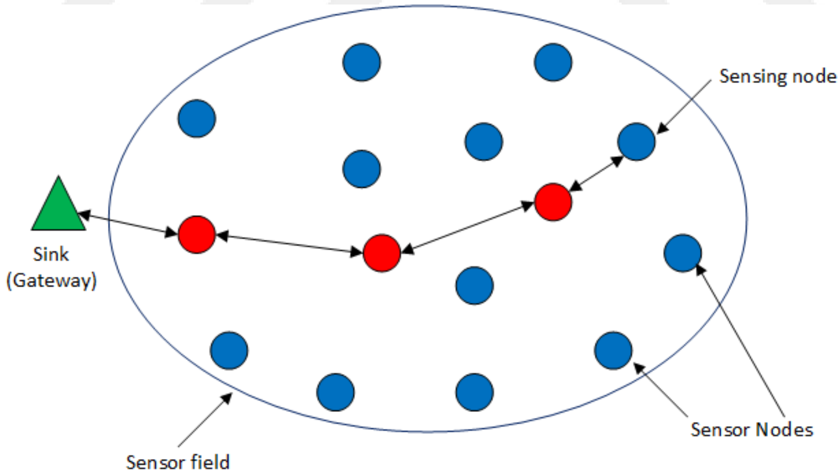


Figure 2.1 An example WSN architecture.

WSNs may include much more sensor nodes when compared with the ordinary wireless networks. Moreover, sensor nodes have limited power, low computational capacity, and very limited memory (Akyildiz et al., 2002). The power management is one of the most important task for WSNs. Therefore, multi-hop communication is expected in sensor networks to consume less power than ordinary single-hop wireless networks (Khemapech, Miller & Duncan, 2007).

Most of the WSNs are using one of the two well-known data flow mechanisms: sensors-to-sink (upstream) and sink-to-sensors (downstream) (Wang, Sohraby, Li & Tang, 2005). In sensors-to-sink approach, sensor nodes periodically send the sensing data to a single or multiple destinations on an event occurs. In contrast, in sink-to-sensors approach, the data is sent to all sensor nodes by the sink node in the sensor network field.

Nowadays, WSNs are used in various types of industrial, academic, medical, mining and military applications (Hussain, 2008). The network architecture and the number of the sensor nodes varies due to the requirements of the applications. One of the main purpose of a WSN is first to sense the physical environment with their sensors, then process the collected data and last deliver the collected sensorial data to the sink node (Romer & Mattern, 2004; Ünsal, Milli & Çebi, 2016).

2.1 Sensor Node Architecture

A sensor node hardware also known as sensor mote is capable of processing and sensing the environment, and communicating with other connected nodes in the network (Akyildiz & Vuran, 2010). A wireless sensor mote consists of a power unit, communication subsystems (receiver and transmitter), storage and processing resources, Analog-to-Digital Converter (ADC) and one or more sensors to gather data from the environment (Kalaycı, 2009), as shown in Figure 2.2.

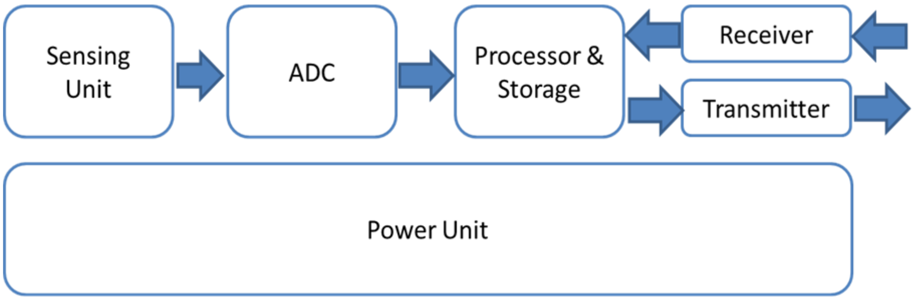


Figure 2.2 Components of a sensor node.

The sensing unit observes and gathers data from the environment. Most of the sensors produce analog information, so that the collected analog data is converted to digital form by using an ADC. After the digitalization of sensor data, microcontroller and the sensor node software analyze the information and the result is transmitted to nearby sensor nodes.

The development of sensor nodes is effected directly by the improvements on microcontrollers, performance of the wireless networking technologies, sensitivity and development of the accurate sensors and the improvement of the developed software tools (Bokare & Ralegaonkar, 2012).

2.2 Wireless Sensor Network Characteristics

The sensor nodes on a WSN are small in size and equipped by sensors to sense environment. Sensor nodes can communicate each other in short distances and transmit their data to the gateway node. When sensor networks are compared against traditional wireless networks, WSN have the following unique characteristics and constraints (Zheng & Jamalipour, 2009; Akyildiz & Vuran, 2010):

- **Dense Node Deployment:** Compared with the traditional wireless networks, sensor networks are usually densely deployed in the sensor filed.

- **Power Consumption of Sensor Nodes:** Sensor nodes are usually powered with a battery. In some cases, it is impossible to recharge or change the battery unites of the sensor nodes.

- **Energy, Computation, and Storage Constraints:** Sensor nodes are tiny embedded micro mechanical embedded devices. Most of the sensor nodes have limited memory, computational and battery capacities.

- **Self-Configurable Networks:** Generally, sensor nodes are distributed randomly in the sensor network field. After the deployment, sensor nodes expected to build up a communication network on their own.

- **Application Specific Networks:** WSN usually application specific networks. The design and deployment of a sensor network relies on the application requirements.

- **Unreliable Sensor Nodes:** Sensor nodes generally deployed in harsh or hostile environments. They are vulnerable against physical damage, security attacks or intruders.

- **Rapid Topology Changes:** Network topologies can be changed due to node failure, battery power depletion and wireless medium access problems.

- **Absence of Global Identification:** Most of sensor nodes do not use a global identification technique such as MAC or IP addresses due to the memory and power constraints. However, most of the sensor nodes have a unique sensor ID in the local sensor network.

- **Data-centric Traffic Flow:** WSNs are usually using sensors-to-sink data flow mechanisms to send their sensorial information. This many-to-one traffic flow cause bottlenecks nearby the manager nodes.

- **Heterogeneity of Sensor Nodes:** In some cases, the requirements of the application or dependencies of the network topology cause sensor nodes to vary from each other.

- **Scalability:** The number of the sensor nodes can be reach to hundreds or even thousands in some sensor network applications. The network management and additivity to the changes is an important task for these networks.

2.3 Protocol Stack of the Wireless Sensor Networks

WSNs use a layered network model similar as in the traditional wireless and wired internet networks. The protocol stack of sensor networks is given in Figure 2.3. The protocol stack consists of independent five layers (Pandey & Tripathi, 2010; Zheng & Jamalipour, 2009). The properties of each layer are:

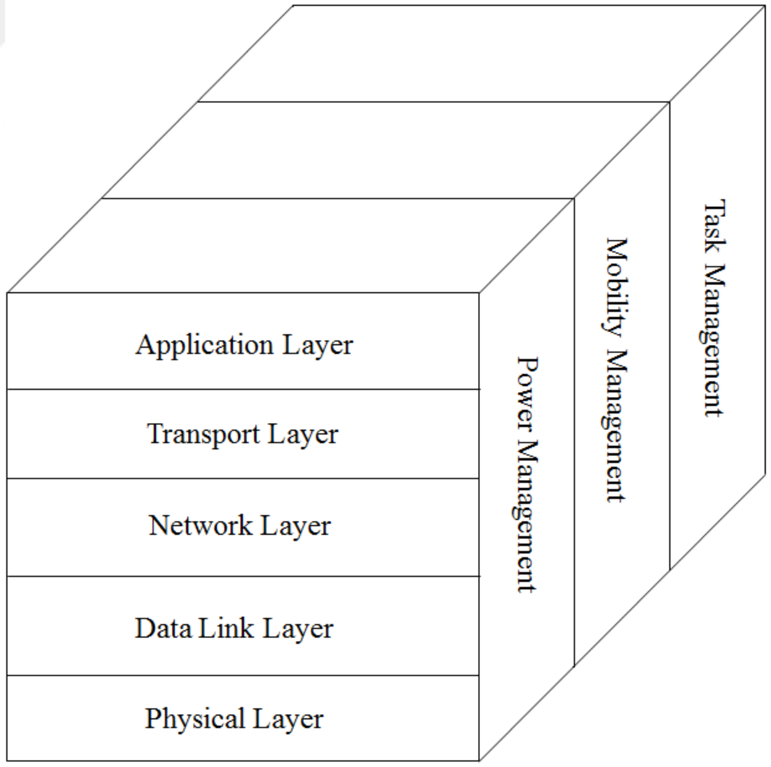


Figure 2.3 Components of a sensor node (Pandey & Tripathi, 2010).

- **Physical Layer:** The physical layer is responsible from the wireless medium access, frequency generation, data rate control, modulation techniques, signal detection and wireless connectivity and data encryption. This layer is related with the electrical signals and wireless antennas.

- **Data Link Layer:** The data link layer is primarily responsible for the communication establishment between the sensor nodes, data stream multiplexing, data frame transmission and reception, medium access, and error control. Moreover, collision detection, collision avoidance and packet retransmission mechanisms are implemented in this layer.

- **Network Layer:** The network layer is responsible for routing the information from sensor node to sensor node, sensor node to sink, or sensor node to cluster head. Moreover, the main purpose of the network layer is to find best path for establishing an efficient routing mechanism.

- **Transport Layer:** The transport layer is responsible for reliable data transmission required by the application layer. Traditional transport protocols cannot be directly applied to the WSN, because of the energy, computation, and memory constraints of the sensor nodes. On the other hand, WSNs are application specific networks, so the reliability requirements of the applications may be different.

- **Application Layer:** The application layer is responsible for the presentation of the final information, query process, time synchronization and network security. The main objective of this layer is to ensure processing of the data through the application software for getting reliable results.

2.4 Application Fields of Wireless Sensor Networks

WSNs have significant advantages compared against to the traditional wired and wireless networks (Romer & Mattern, 2004). WSNs can be deployed into hostile or inaccessible areas with lower cost than the wired networks which are almost impossible to deploy (Zheng & Jamalipour, 2009). Same examples of WSN applications in various fields are:

- **Monitoring Applications:** Environmental monitoring is one of the most well-known use of sensor networks (Mainwaring et al., 2002). Sensors are used to monitor variety of physical environment conditions. Monitoring applications can be classified into subgroups in terms of the application dependencies for instance: Habitat monitoring, chemical or biological hazard monitoring, disaster monitoring, flood detection and forest fire detection (Zheng & Jamalipour, 2009).

- **Health Applications:** WSNs and Personal Area Networks (PANs) are widely used in health care applications (Bokare & Ralegaonkar, 2012). Sensor nodes are used to monitor patients and doctors inside the hospital. Vital sign monitoring, blood pressure monitoring, exercise or dietary monitoring can be given some examples of the health care sensor networks.

- **Military Applications:** WSNs are especially used in military sensing applications. Because of the easy deployment and self-configurability properties, sensor networks are becoming one of the main part of military command, control, communication, and intelligence (C3I) systems (Akyildiz et al., 2002). The sensor networks provide services like battlefield monitoring, targeting, battle damage assessment, nuclear, biological or chemical attack detection exploration.

- **Industrial Applications:** WSNs can be used for machinery control and monitoring and maintenance applications. Harsh environments, inaccessible locations, hazardous or restricted areas can be reached by sensor networks (Bokare & Ralegaonkar, 2012).

- **Security and Surveillance:** WSNs can be used to monitor buildings, subways, airports or restricted areas to identify or track intruders or to ensure personnel security (Zheng & Jamalipour, 2009).

- **Smart Home Applications:** WSNs can be used for intelligent home applications. Wireless sensor and Actor Networks (WSANs) can be applied for buildings, home automation and structural monitoring applications (Zheng & Jamalipour, 2009).

- **Agriculture Applications:** WSN applications for agriculture are increasing in recent years. Building a wired monitoring system is difficult in such environments. WSANs enable farmers to monitor and manage plantation or greenhouse remotely (Bokare & Ralegaonkar, 2012). Water tank levels, temperature and humidity levels, soil moisture levels can be monitored by using WSNs. Moreover, watering systems, air conditioner systems or lighting systems are also controlled by using WSANs.

- **Underwater Applications:** Wireless Underwater Sensor Networks are used to enable wide variety of purposes for instance pollution monitoring, oceanographic data collection, disaster prevention, offshore exploration and surveillance systems (Akyildiz & Vuran, 2010).

- **Underground Applications:** Wireless Underground Sensor Networks (WUSNs) consist of wireless sensor nodes that operate below the ground surface. Sensor nodes are either buried under the soil completely, or placed into an underground space, such as mines, subways, tunnels, caves or under the structures (Akyildiz & Vuran, 2010). WUSNs are especially used for underground monitoring, underground mine safety and tracking applications.

2.5 Network Design Challenges

WSNs have unique network characteristics and hardware constraints which cause a lot of challenges in the design of WSNs (Gungor & Hancke, 2009). Deployment of the sensor nodes into harsh environment or inaccessible places makes the management of these networks more challenging. In addition, shared wireless medium is vulnerable to malicious attacks (Akyildiz & Vuran, 2010). Hidden node problem, over hearing, signal attenuation and reflections makes this shared wireless medium more challenging. The following main topics should be taken into account during the design of sensor networks (Gungor & Hancke, 2009; Zheng & Jamalipour, 2009; Akyildiz & Vuran, 2010).

- **Limited Power:** Sensor nodes are usually battery powered devices, therefore, they have limited energy (Hac, 2003). Traditional wireless network protocols are not suitable for sensor network applications, due to the energy consumptions. In order to prolong sensor nodes lifetime, energy aware networking protocols should be used to save battery life for WSNs.

- **Hardware Constraints:** Sensor nodes are battery powered tiny embedded devices. They have limited storage, processing and memory capacities, thus, the computation capacity of these nodes are also very limited (Akyildiz & Vuran, 2010). These hardware constraints should be taken into account during the software development of sensor networks and network protocol designing process.

- **Unreliable Environment:** Most of the sensor nodes are deployed into hostile or unreliable environments. In addition, the network topology is changed frequently because of the node failures (Zheng & Jamalipour, 2009). On the other hand, sensor nodes are connected to each other in a wireless medium which is vulnerable against signal fading, attention, reflection and jamming. These connectivity properties make the implementation of WSNs more challenging.

- **Application Specific**: The design and implementation of the WSNs are usually depended on the application (Gungor & Hancke, 2009). The environment properties and the application requirements form the design of network protocol and software. There is not any network protocol which can provide the requirements for all applications. As a result, WSNs are application specific wireless networks.

2.6 Classification of Wireless Sensor Networks

WSNs may have various characteristics due to the application requirements. According to the different requirements of WSNs, they can be categorized in terms of hop type, network topologies, sensor node types, mobility, sink count or configurability properties (Al-Karaki & Kamal, 2004; Romer & Mattern, 2004; Abbasi & Younis, 2007; Zheng & Jamalipour, 2009). Some of these classifications according to the various properties are:

- **Hop Count:** WSNs can be classified by hop count between the sensor nodes and the sink. These types are sing-hop and multi-hop networks. In single-hop networks each sensor node has a single-hop distance to the sink. In multi-hop network sensor nodes should perform a routing path and forward their data to the sink.

- **Network Topology:** WSNs can be classified in to two subcategories by the network topology: Flat or hierarchical topology. In flat topology all the sensor nodes have the same privileges and properties (Figure 2.4). In contrast, hierarchical topology allows various privileges to the different sensor nodes by their tasks. In hierarchical topology sensor nodes are divided into sup groups called clusters and each cluster has a master node called cluster head. All the sensor nodes in the cluster should communicate only with the cluster head. Sensor network data is transmitted over the cluster heads to the sink. An example of a hierarchical network topology is given in Figure 2.5.

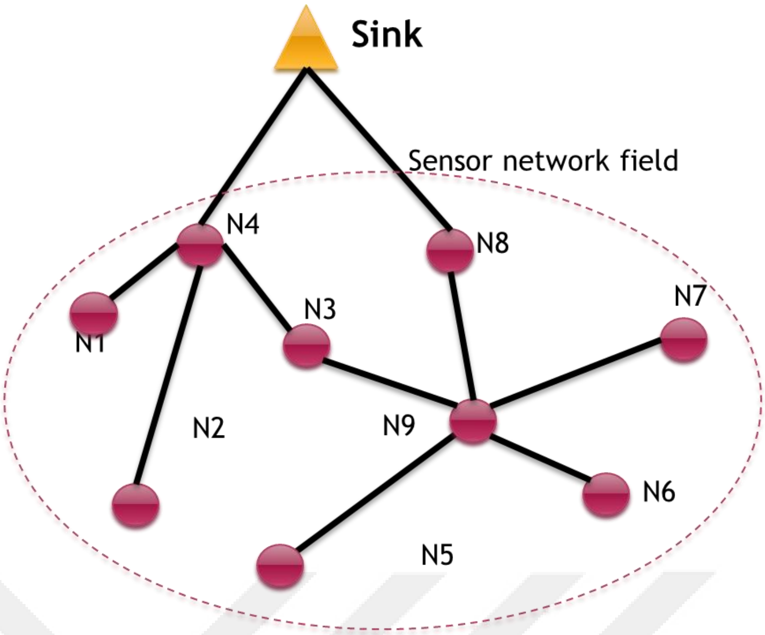


Figure 2.4 Flat network topology.

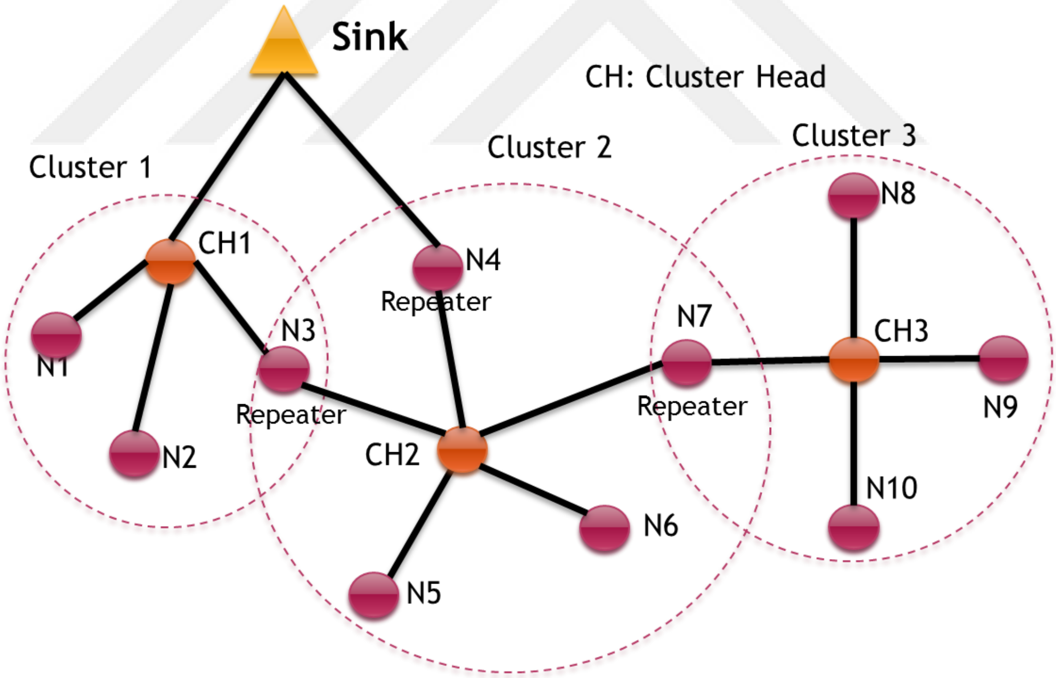


Figure 2.5 Hierarchical network topology.

- **Mobility:** WSNs can be classified by the mobility of sensor nodes or sinks. Sensor nodes or the sink can be mobile or static based on the application in the sensor networks.

- **Sink Count:** WSNs can have multiple or single sink in a network. The requirement of the sink count is related with the sensor network application. In single sink networks there is only one sink in the sensor network. If the count of the sensor nodes is too much, using multiple sink nodes will be a better solution to solve bottlenecks in the network and reduce the propagation delays.

- **Homogeneity:** The sensor nodes in the WSN would have the same structure and characteristics or not. The sensor nodes can be classified in to two sub categories in terms of homogeneity: Homogenous or heterogeneous. In homogenous sensor network, all the sensor nodes have the same hardware and software properties. In contrast, sensor nodes in a heterogeneous network may have different hardware and software properties.

- **Self-configurable or non-self-configurable network:** Self-configurable sensor networks can organize themselves to build a routing path. Sensor nodes in a non-self-configurable network a central controller is need to control and collect each sensor node.

CHAPTER THREE
WIRELESS UNDERGROUND SENSOR NETWORKS

Wireless Underground Sensor Networks (WUSNs) consist of sensor nodes which operate under the earth's surface (Akyildiz & Vuran, 2010). Wireless sensor nodes can be buried below the ground or placed inside the underground mines, tunnels or subways. Compared to the wired underground sensors, WUSNs have remarkable benefits, such as ease of deployment, coverage density, robustness and adaptivity (Akyildiz & Stuntebeck, 2006). Akyildiz and Vuran (2010), summarize the advantages of WUSN as below:

- **Ease of Deployment:** Wired underground monitoring systems need to be connected to the nearby sensors by a data cable. Collected data should be logged into a data logger device or transferred to a central station. The first development of these systems requires too much effort and cost. However, the maintenance of these systems would be also exhaustive and the scalability of these networks are limited by the socket count of the controllers. In contrast, WUSNs provide flexible deployment of sensor nodes by placing them in the desired location and the maintain of these systems is much easier than the wired systems.

- **Coverage Density:** The coverage area of the wired sensor systems is limited by the count of sensor nodes and data loggers. The hostile environment and harsh working conditions make impossible to reach everywhere with wired systems. However, WUSNs allow sensor nodes to be placed in any location. Moreover, the coverage area of the sensor network can be easily increased by adding independent sensor nodes into the sensing field without using an extra effort.

- **Robustness:** Wired systems working with data logger devices are vulnerable against the data failures. A malfunction on a data logger device cause wrong sensor readings or unexpected failure of the monitoring system. However, sensor nodes in the WUSN are independent to each other and if some of the sensor nodes fails the rest of the sensor nodes still continues to transmit their sensor readings. In addition, the reliability of the underground monitoring application can be increased by using WUSNs systems.

- **Adaptivity:** The size of the underground mine changes very quickly, so that the coverage area of the monitoring application is also modified with it. Wired monitoring systems should be redeployed to suit up with these rapid changes, however, the cost of the redeployment of these systems is much. In contrast, WUSNs have a remarkable advantage to adapt rapid topology changes by compared with the wired systems.

WUSNs are more suitable for wide variety of underground applications than the wired methods. However, the biggest challenge for implementing WUSNs is to establish reliable and efficient underground links (Akyildiz & Vuran, 2010; Akyildiz & Stuntebeck, 2006). The main difference between terrestrial and the Underground sensor networks is the propagation characteristics of the electromagnetic waves. The signal attenuation of the radio signal in soil is completely different from the air. In addition, the signal characteristics of WUSNs that deployed in underground tunnels or mines are also influenced by the underground surfaces.

3.1 Wireless Underground Sensor Network Applications

WUSNs have a wide range of application fields, for instance, smart agriculture applications (Yoo et al., 2007), structure monitoring (Li & Liu, 2009), environment monitoring (Wang et al., 2007) and border and security monitoring (Sun et al., 2011).

3.1.1 Agriculture Applications

Underground soil conditions may also be monitored by using underground sensor nodes. WUSN should monitor the soil parameters, for instance, water content, mineral content, temperature and soil moisture to maintain planted areas (Majone et al., 2013). The real-time knowledge of the planted area would be also useful when the WUSN is combined with the sprinkler system to water plants or trees (Yoo et al., 2007).

Moreover, WUSNs can be also used to monitor the growth of plants in a greenhouse system. WUSNs can be combined with the ventilation, heating and sprinkler systems to build up an entire smart agriculture system.

3.1.2 Structure Monitoring

WUSNs can be used to monitor various types of structure, for instance underground fuel storage tanks, liquid storage tanks, sewers (Akyildiz & Stuntebeck, 2006). Additionally subways, underground mines, pipes and underground cable systems are also monitored by WUSNs (Li & Liu, 2009).

Underground sensor nodes may be used to monitor structure health (Park et al., 2005). Sensor nodes may be placed under the building foundations, dams or bridges to monitor seismic shifts, durability and other parameters of these buildings.

3.1.3 Environment Monitoring

Monitoring and controlling physical parameters for underground mines and tunnels is a significant task (Wang et al., 2007). WUSNs can be used to monitor gas percentages, temperature, humidity and ventilation of underground mines, subways or tunnels (Dohare et al., 2015). Moreover, warning system may be integrated to a sensor network to inform the staff for the possible risks.

Additionally, determining a miner's position in the mining workplace is also crucial when an accident occurs (Xiuping et al., 2010). This position information will reduce the time it takes for a rescue team to reach injured or trapped workers in the underground places.

3.1.4 Border and Security Monitoring

Movement of people or vehicles can be detected by underground sensor nodes (Sun et al., 2011). In addition, the positions of the people or vehicles may also be determined when the location of the sensor nodes is also known. The sensor nodes determine the presence of a person or object by using pressure, ultrasonic or magnetic sensors. WUSNs applications are suitable for home and building security applications, where the sensor nodes are placed under the ground in order to detect intruders. The large scale of these applications can be used to provide border and patrol security.

3.2 Design Challenges of Wireless Underground Sensor Networks

WUSNs have unique challenges because of the hostile environment and wireless communication properties. The content of the soil, hostile environment, design of the network topology, design of the antenna and energy efficiency have significant effects on the communication between wireless sensor nodes in a WSN (Akyildiz & Stuntebeck, 2006).

3.2.1 Hostile Environment

The underground environment is one of the most difficult working places in the world. The lack of daylight, insufficient fresh air, high temperature and humidity makes this industrial field more challenging (Dohare et al., 2014). The dense of soil and the water content of the soil extremely weaken the wireless signal (Akyildiz & Vuran, 2010). The shell of the sensor nodes must be selected carefully. The shell should be water resistant and strong enough to the crushing or tempering. In addition, the battery of the sensor node must be chosen attentively. The environmental conditions, temperature changes, battery discharge time, physical size of the battery and the capacity should be taken into account.

3.2.2 Topology Design

The topology design of the WUSNs is crucial for network reliability, maintainability and power management (Akyildiz & Stuntebeck, 2006). The properties of the underground environment and the requirement of the monitoring application should be carefully considered during the design of the WUSNs. In order to design optimal network topology, the features given below should be balanced carefully (Akyildiz & Stuntebeck, 2006):

- Application requirements.
- Cost of the sensor nodes.
- Power management.

WUSNs can be grouped by the various requirements of the underground sensor applications. According to the underground sensor applications, Akyildiz and Stuntebeck (2006) propose two separate topologies: *underground* and *hybrid topology*.

In the underground topology, all the sensor nodes are buried under the ground only the sink node may be placed on the ground. In contrast, the hybrid topology allows sensor nodes can be deployed both under and on the ground. Hybrid topology is more suitable for shallow WUSNs such as agriculture or surface mining applications.

3.2.3 Antenna Design

The selection of a proper antenna design for underground communication a challenging problem. The propagation of the electromagnetic waves underground is precisely different from the air (Milligan, 2005). In addition, various underground applications may require distinct communication features (Akyildiz & Stuntebeck, 2006). Besides, the type and position of the antennas can be directly effects the communication distance.

Frequency band selection is another important issue. Frequencies in megahertz and lower ranges can reach longer distances (Milligan, 2005). However, it is well-known that the lower frequencies need larger antennas to properly transmit and receive radio signals. The size of the sensor nodes will be greater when the selected frequency is lower.

In antenna theory (Milligan, 2005), the wavelength of a signal can be calculated by the equation (3.1) given below:

$$\lambda = c/f \tag{3.1}$$

In equation (3.1), λ represents wavelength, c is speed of light in free space ($3x10^8$ *m/s*) and *f* is the frequency of the electromagnetic signal. For instance, a quarter-wavelength omnidirectional monopole antenna should have 75 cm length for exactly match a 100 MHz frequency (Milligan, 2005). Consequently, frequency selection is a big challenge for developing proper underground sensor nodes.

3.2.4 Power Management

Most of the underground sensor nodes are generally powered by a battery unit and the lifetime of the sensor network is related to battery power capacity of the batteries (Dohare et al., 2015). WUSN applications are expected to have a lifetime for several years in order to make their deployment efficient (Akyildiz & Stuntebeck, 2006). However, underground sensor nodes require greater transmission power than the terrestrial sensor nodes (Silva & Vuran, 2009). Consequently, power management is the primary role for designing WUSNs.

Unlike the terrestrial sensor nodes, underground sensor nodes are much difficult to recharge or replace their power units. Wireless sensor nodes on the ground may be recharged by solar cells or kinetic energy depend on the application (Voigt, Ritter & Schiller, 2003). However, the lack of daylight makes impossible to recharge underground sensor nodes. Seismic vibrations (Pan, Xue & Inoue, 2005) or thermoelectric energy (Lu & Yang, 2010) may be used to charge underground sensor nodes but most of these applications are not suitable for underground applications. Additionally, most of the underground sensor nodes placed in inaccessible locations, so replacement of their power units cannot be possible in many applications.

Although replacement of the failed sensor nodes with new nodes in terrestrial WSN applications is possible, underground deployment of new nodes to replace failed ones is quite difficult.

Power management is one of the major objective for WUSNs. In order to increase lifetime of sensor nodes, using higher capacity batteries is one of the solution. However, using higher capacity batteries would increase the cost of sensor nodes. Another solution is to implement energy-aware sensor network applications and communication protocols.

3.3 Wireless Underground Sensor Network Architectures

WUSNs applications can be grouped by the deployment of the application. According to the mentioned features in section 3.2.2, WUSNs can be categorized into two main network architectures as (Akyildiz & Vuran, 2010):

- WUSN deployed in soil.
- WUSN deployed in mines and tunnels.

These two main categories can be grouped in to subcategories as given in Figure 3.1. WUSNs deployed in the soil have two subcategories:

- Underground topology.
- Hybrid topology.

In underground topology, sensor nodes are completely buried under the land and the sink nodes may be placed above or under the ground. Underground topology is also divided into two subcategories: *single depth* and *multi-depth* topologies. Sensor nodes buried nearly at the same depth in single depth topology. However, in some WUSN applications may require sensor information from different depths that is referred to multi-depth topology.

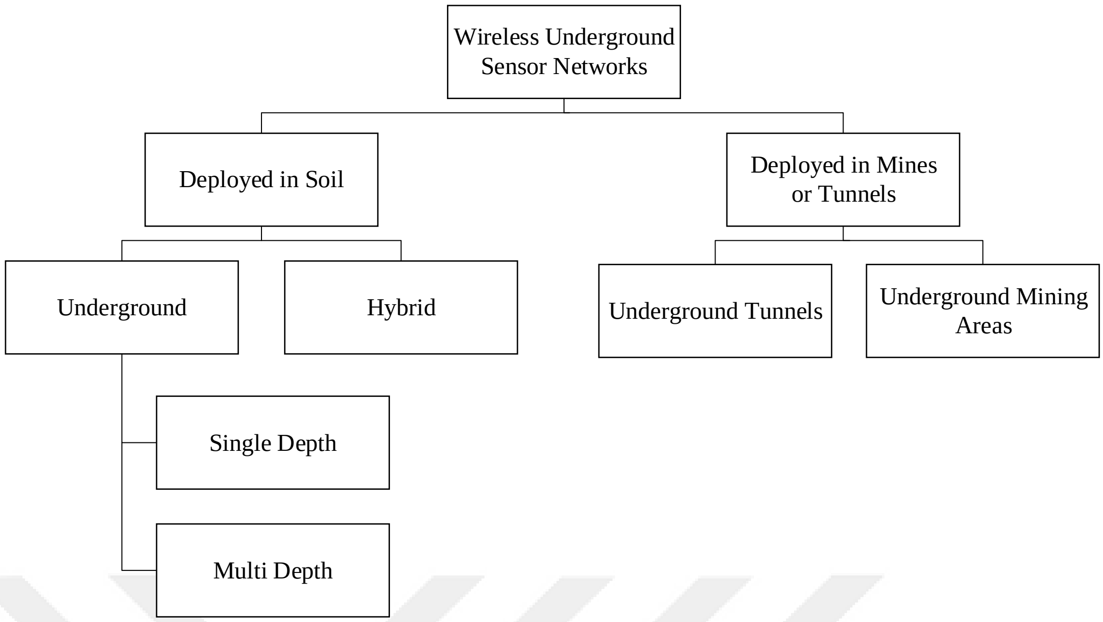


Figure 3.1 Classification of wireless underground sensor networks (Akyildiz & Vuran, 2010).

Hybrid topology is a mixture of underground and above ground sensor nodes (Akyildiz & Stuntebeck, 2006). The main difference between underground and hybrid topology is the placement of sensor nodes. Underground topology sensor nodes must be placed under the ground, however, hybrid topology sensor nodes may be placed above or under the ground. Hybrid topology is suitable for the shallower underground applications. The signal attenuation through the air is lower than in the soil, so the hybrid topology enables data to be transmitted through the air.

The second category of WUSNs is deployed in mines or tunnels. Underground mines are placed much deeper than the agricultural or under soil applications. However, radio signals propagate through the air, the shape of mining tunnels corners and obstacles cause signal reflection, diffraction, refraction, scattering and attenuation as given in Figure 3.2 (Forooshani et al., 2013). As a result, the signal may transmit over multiple paths to its destination. Because of the multiple directions of the propagation, angular dispersion of the signal is experienced.

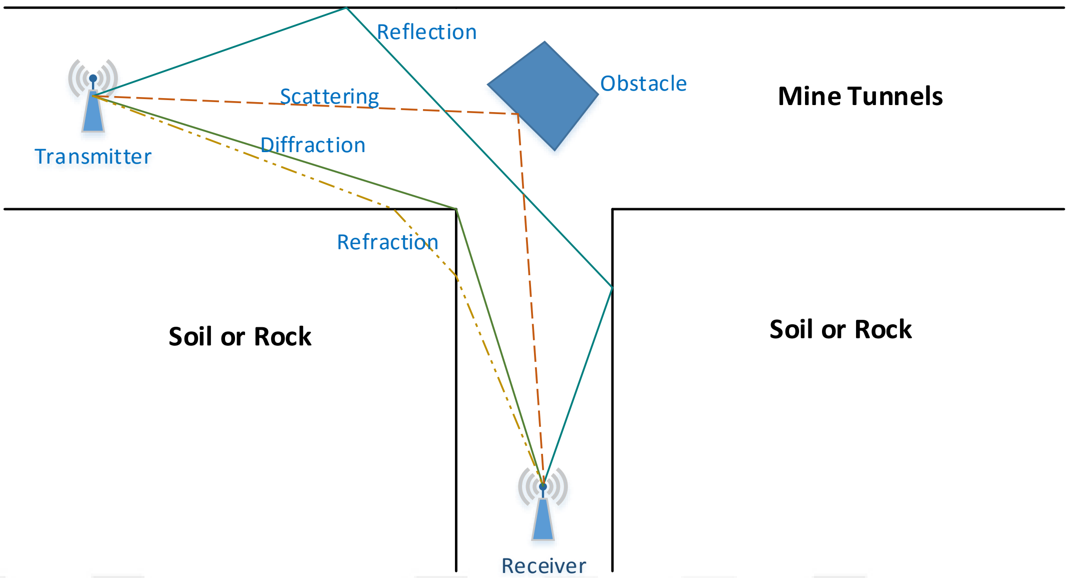


Figure 3.2 Wireless propagation model in the underground tunnels (Forooshani et al., 2013).

The structure of the underground mining filed and the underground network topology is effected by the structure of ore body (Akyildiz & Vuran, 2010). If the ore body is flat and thin longwall mining or room-and-pillar is preferred (Gertsch & Bullock, 1998). The cut-and-fill mining is much suitable for the vertical and deep ore bodies. Longwall mining example is given in Figure 3.3.

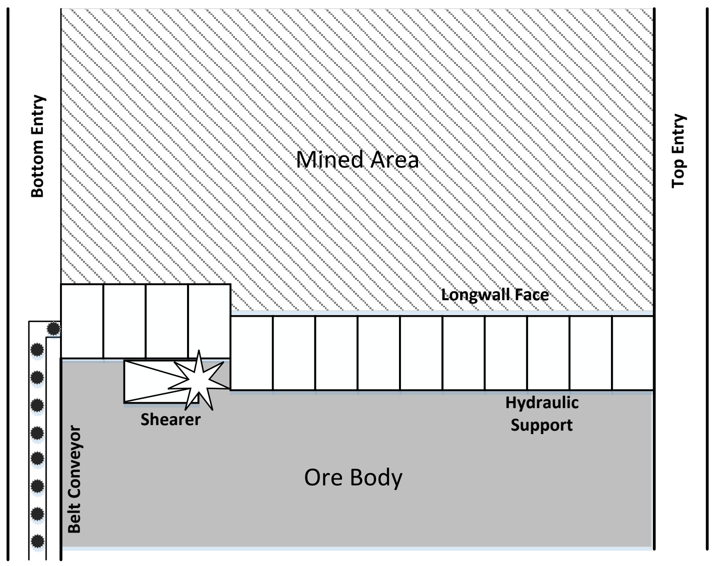


Figure 3.3 Longwall underground mining (Akyildiz & Vuran, 2010).

3.4 Sensor Networks for Underground Mining Applications

Underground mines are one of the most dangerous working places in the world. The lack of daylight, inadequate ventilation, the leakage of the toxic gases, floods and cave-in risks make these environment more challenging (Krithika & Seethalakshmi, 2014). In order to enhance production and community in mines, communication and monitoring applications should be established between the miners and the base station. However, establishing a wired communication system is very difficult because of any damage inside the vulnerable mining area. Furthermore, there is no perfect solution to resolve communications problems into the mines due to the environment properties (Forooshani et al., 2013).

WUSNs have remarkable advantages compered to wired systems for underground mining applications. The ease of deployment, coverage density and robustness makes these networks more suitable for underground applications (Akyildiz & Vuran, 2010). WUSNs are suitable for supervising the underground mines in order to prevent accidents and to provide safety production.

3.4.1 The Importance of Underground Mining Safety

Providing the underground mining safety is one of the most significant objective because of the challenging environment. Monitoring the physical parameters in underground mines is challenging due to the hostile environment and frequently changed placement of mining areas (Zhao et al., 2013). Studies about underground mining have played an important role in determining the cause of mining accidents over the years (Dohare et al., 2015). As a results of these studies, it is observed that the most important task for underground mining is to determine risks and develop a supervising system to mitigate accidents. Additionally, accurately determine the position of the miners, working at the dangerous zones, is another important issue for underground mining applications (Zhang et al., 2010).

After the underground mine disaster at Soma, which 301 miners lost their lives on 13 May 2014, the importance of underground mining safety is become more significant in Turkey. Soma disaster is one of worst mine disaster in Turkey. This accident reveals the importance of underground mine safety applications remarkably. After the accident, the Turkish Government announced three days of national mourning for the Soma disaster victims. The Ministry of Labor and Social Security investigated the reasons of this accident. As a result of these inspections a new and more detailed regulation called “Occupational Health and Safety regulations for Mining Workplaces” was prepared to prevent underground mine accidents (The Ministry of Labor and Social Security, 2013). The new regulation forces to monitor underground mines against explosive and toxic gases and determine the maximum gas percentages for safety production.

3.4.2 Source of the Accidents

Landslide and Seismic shifts are not only the major danger in underground mining, but also explosive or toxic gas leaks cause significant damages. Especially, methane gas explosion is one of the most common causes of underground mining accidents. Moreover, carbon dioxide, oxygen, carbon monoxide gas percentages and temperate should be monitored in underground mines to control air quality. In order to avoid accidents several critical parameters for underground mines should be monitored periodically. The source of accidents for underground mines are given below (Durga & Swetha, 2015):

- Methane and consecutive coal dust explosions,
- Fall of roof, side or face,
- Falling, rolling, or sliding rock or coal,
- The accumulation of methane gas,
- Methane gas leakage from a fallen coal,
- Methane gas leakage from the walls and ceilings of the mining area,
- Toxic or explosive gas leakage from the drainage area.
- Inadequate ventilation,

- Coal combustion because of the pressure,
- Inundation due to floods,
- High temperature levels in the mining workplaces.

3.4.3 The Major Parameters to Monitor in Underground Mines

The coal dust and methane gas explosions are the major risks in underground mining. Methane is a colorless, odorless and highly combustible gas that leaks out during the mining of coal seams (Durga & Swetha, 2015). The methane gas can explode with a small spark if it is left uncontrolled. The machines and the electricity should be automatically shut off when the methane level reaches 1.5%.

Additionally, toxic gases and the oxygen level should be also monitored periodically. The well-known toxic gases encountered in underground coal mines are carbon monoxide and hydrogen sulfide. Carbon monoxide is a colorless and odorless poisonous gas that exposure by a coal combustion or inadequate ventilation. Hydrogen sulfide is a colorless and very poisonous gas with a characteristic foul odor of rotten eggs. Temperate, humidity and oxygen levels are other important parameters which should be monitored in underground mines.

In order to avoid accidents in coal mines, underground mine monitoring mines should trace the changes of these important parameters:

- Methane 'CH_4' gas level,
- Carbon Monoxide 'CO' gas level,
- Hydrogen sulfur 'H_2S' gas level,
- Coal dust,
- Temperature and humidity,
- Air flow speed,
- Water floods.

3.4.4 Challenges of Wireless Communication in Underground Mines

Wireless underground communication systems are precisely different from the terrestrial systems (Akyildiz & Stuntebeck, 2006). Underground mines have a number of unique challenges in wireless communication. The wireless Communication challenges of underground mines are given below (Dohare et al., 2015):

- **Electromagnetic Interference:** Electromagnetic signals are exposed to interference because of running mining machinery and inadequate electrical ground systems.

- **Signal Attenuation:** Tunnels, corners and mining devices in underground mines cause signal attenuation.

- **Multipath Fading:** Electromagnetic waves are sometimes partially reflected or transmitted from tunnels corners or other obstacles. As a result of this, electromagnetic signal reflection, diffraction, refraction or scattering may be encountered in underground mines.

- **Noise:** Underground mining devices, conveyor belt systems, electric motors and power lines may cause noise in electromagnetic waves.

3.5 Safety and Tracking Systems in Underground Mines

The hostile environment and challenging working conditions make the underground mining one of the most difficult occupations in the world. Moreover, most of the underground mines include toxic and explosive gases such as methane, carbon monoxide and hydrogen sulfite (Donoghue, 2004). These properties make the underground mines one of the most dangerous working places.

There are several mine safety applications proposed in the literature. In their study, Yarkan, Guzelgoz, Arslan and Murphy (2009) presented a classification of underground mine communication techniques and categorized these techniques into five categories as shown in Figure 3.4. Akyildiz and Stuntebeck (2006) classified the WUSNs into four categories and asserted the underground monitoring applications. Yan, Ya-ru and Yong (2008) proposed a mine personnel positioning system with Wireless Body Sensor Networks (WBSNs). In order to classify underground safety applications, a new classification is proposed. In our study, underground mining safety systems can be categorized into two main categories: application types and communication techniques as shown in Figure 3.5. The studies concern with the application types can be categorized in to three subfields such as monitoring applications of the mining areas (Zhang et al., 2014), tracking the miner's positions, and hybrid systems (Dohare et al., 2015).

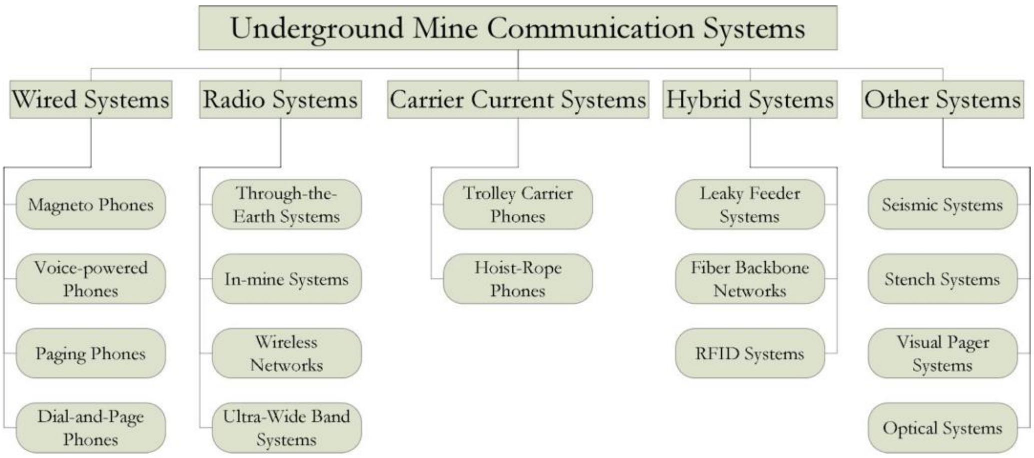


Figure 3.4 A classification of underground mine communication systems (Yarkan et al., 2009).

Although Yarkan and his friends (2009) proposed five categories for underground communication techniques in their study; the phone systems, leaky feeder systems, visual pager systems and optical systems are not directly used for underground mine monitoring or tracking applications. The rest of communication techniques may be used as a part of Underground safety systems and they can be categorized into three subcategories: wired, wireless and hybrid systems. The wired systems include fiber optic and cabled monitoring systems. Wireless communication systems for underground mining are RFID tag systems, wireless sensor networks and ultra-wide band wireless systems.

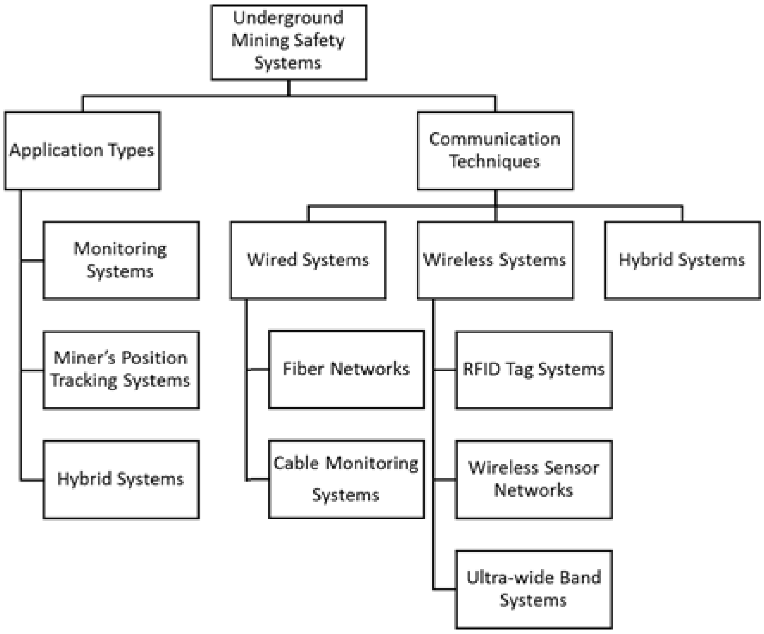


Figure 3.5 A classification of underground mining safety systems.

Both wired and wireless communication systems can be used to provide communication and data transfer for underground mine monitoring systems. One of the most significant task in underground mining is to monitor mining corridors and galleries (Donoghue, 2004). Monitoring the gas percentages in underground mines is inevitable. The aim of the underground monitoring system is to collect sensor readings from the working places and transmit the collected data to a data collector or central monitoring system. Some of the underground mining safety applications use both the wireless and wired communication techniques together.

The aim of miner's position tracking systems is to determine location of each miner in a specific area (Liu et al., 2010). The importance of these system is to determine the miner's position because the access time of a miner's location is crucial when an accident occurs.

In the recent years, considerable amount of research in the field of WSNs for underground mining applications has been done (Li & Liu, 2007; Akyildiz & Vuran, 2010; Forooshani et al., 2013; Dohare et al., 2015). The focus of these studies is to constitute a reliable and manageable monitoring application to monitor underground mining faces and tunnels. The primary design objective of these applications can be categorized into tree types: environment monitoring systems (Li & Liu, 2009), miner's position tracking systems (Yan et al., 2008) and hybrid systems (Wang et al., 2007). A detailed survey of existing studies about wireless underground applications for each category given below.

3.5.1 Wireless Underground Monitoring and Safety Systems

The harsh environment, toxic and explosive gases make the underground mines one of the most dangerous working places (Donoghue, 2004). In order to prevent disasters in underground coal mines, WSNs can be applied to mines in order to improve the coverage density of a real-time safety monitoring system at low-cost (Dohare et al., 2015). To the best of our knowledge, the most known studies about the wireless underground monitoring and safety systems are given:

- The Design and Evaluation of a Wireless Sensor Network for Mine Safety Monitoring (Niu et al., 2007). The authors proposed a distributed *heterogeneous hierarchical mine safety monitoring* (HHMSM) prototype system which monitored the methane gas concentration and location of the miners. The developed system based on an *overhearing-based adaptive data collecting* scheme, in order to reduce network traffic and control overhead for large scale WSNs. The network architecture consisted of both wired and wireless systems together. The main tunnels were equipped with wired or fiber cables. The HHMSM was located in the profile of mine and connected to wired network with cabled systems. EASINET series sensor hardware is used to build HHMSM prototype system. The developed system was experienced in indoor corridors of a building and Daylan Coal Mine several times. The results of these experiments revealed that the proposed data collecting algorithm significantly reduced the traffic volume during monitoring.

- Automatic Calibration of Methane Monitoring Based on Wireless Sensor Network (Zhang, 2008) proposed a wireless underground coal mine monitoring application with an *intelligent methane sensor* system. The methane sensors could perform calibration autonomously. The intelligent calibration system was based on a multi-hop WSN. ATMega48V based microcontroller is used in the development of sensor devices. The nRF2401A wireless module provided the network communication. The methane concentration of a specific region was obtained by sensor nodes and this information was used for *self-diagnose* and *self-maintenance* of the system. The auto-calibration system controlled the methane gas concentration of a specific field and verify the accuracy of that data by checking the information obtained from its neighbor nodes. After the auto-calibration procedure, if the sensor value was below the threshold, it was understood that there had been an error in the sensor and the data was false. If the methane gas concentration exceeded the safety limit, all sensor nodes switched to the alarm status. The *auto-calibration* based WSN was useful in keeping the reliability of the sensor nodes for long-term applications.

- Application of Wireless Sensor Network in the Monitoring and Control System of Coal Mine Safety (Qiao, Zhang & Yang, 2009) proposed a system monitored the methane, carbon monoxide, humidity, temperature and light parameters and transferred the collected data to the main station. A hierarchical mixed network topology was used in this study. A cluster based architecture was established to reduce network power consumption. ZigBee modules were used as sensor nodes. The developed system was tested the workstation of Yongcheng Coal & Electricity Group Co., Ltd. In China.

- Application of the Wireless Sensor Network Based on ZigBee Technology in Monitoring System for Coal Mine Safety (Bian, 2010) proposed a WSN based on ZigBee technology. The developed system was used for collecting and transmitting various types of sensor readings in the underground coal mine. ZigBee wireless technology based on IEEE802.15.4 standard was used for establishing sensor devices. A multi-hop wireless network topology was selected for network architecture. ATMega128L microcontroller and ZigBee wireless module was used in sensor devices. The developed monitoring system collected the humidity temperature and combustible gas information from the environment and transferred to the base station. If one of the monitoring parameters exceeded the predefined threshold value, an alarm system was activated in the central monitoring system.

- Coal Mine Environment Monitoring with WSNs (Zhao et al., 2013) proposed a security monitoring system to reduce human and material losses. In underground coal mining some parameters such as coal dust density, temperature, wind speed, gas density and carbonic oxide density effected on safe coal production. This study proposed an *information fusion model* based on Self-Organizing Map (SOM) Algorithm. The developed model was applied to a sample data retrieved from a coal mine. As a result, this model divided the coal mine into four clusters: *safe, general safe, abnormal, and dangerous*.

- Integrated Mine Safety Monitoring and Alerting System Using Zigbee & Can Bus (Kumar & Rao, 2013) proposed a *coal mine safety monitoring* system using WSNs. The developed system consisted of ZigBee modules and Controller Area Network (CAN) bus architecture. Sensor nodes were able to monitor temperature humidity and mixed gas concentrations. Single hop network architecture was used for communication between sensor nodes and the coordinator node. The hardware and software implementation of the sensor network was explained briefly in this study.

- An Integrated Environment Monitoring System for Underground Coal Mines-Wireless Sensor Network Subsystem with Multi-Parameter Monitoring (Zhang et al., 2014) presented an environment monitoring system for underground coal mines. The developed system combined the existing Cable Monitoring System (CBS) with a multi-parameter WSN. ZigBee modules were used in the design of sensor nodes. A mesh like hierarchical network architecture was used for data transfer. In order to manage and optimize the sensor network, sensor nodes were deployed manually in the environment,

- The developed WSN had two working modes: *periodic inspection* and *interrupt service*. The periodic inspection mode was using a scheduling cycle and sensor nodes transmits their data to the sink node at the end of each cycle. The interrupt service mode was only activated if an incident occurred or one of the parameters exceeded the threshold values. In this study, a collision avoidance mechanism in combination of Carrier Sense Multiple Access with Collusion Avoidance (CSMA/CA) and Time Division Multiple Access (TDMA) was used for medium access control and data aggregation strategy was implemented. The performance of developed system was tested both in the laboratory and in an underground coal mine.

3.5.2 Wireless Miner's Position Tracking Systems

In order to confirm miner's positions in underground tunnels and working areas, WSN based applications can be used in underground mining (Dohare et al., 2015). To the best of our knowledge, a few well-known miner's position tracking applications in the literature is summarized:

- Study on the Coal Mine Personnel Position System Based on Wireless Body Sensor Networks (Yan et al., 2008) proposed a personnel positioning system based on wireless body sensor networks (WBSNs). The developed system not only determined the positions of the miners, but also traced their pulse rate and body temperature of the miners. Sensor devices consisted of a PIC16F877 microcontroller with RFM TR1000 wireless module. Star topology was used in the design of wireless underground network architecture. The mobile nodes were attached to the miners in order to track them.

- Research of Wireless Sensor Networks based on ZigBee for Miner Position (Zhang et al., 2010) presented a WSN based on ZigBee technology in order to determine the position of miners in the mining workplaces for coalmine industry. Additionally, the developed monitoring system was used to determine the miners working timeline from looking the time intervals they found the mine. In order to determine position of the miners in the working places, a combination of wired and wireless network topology was chosen for this aim. ATMega128 microcontroller with CC2420 wireless module was used in the development of sensor devices. The ZigBee sensor nodes in the underground mining workplaces worked like a *Reduced Function Device* (RFD) in a star network topology. The wireless substations collected the information from sensor nodes and forwarded the information to a base station over a wired network. The substations worked as *Full Function Devices* (FFD) in the sensor network.

- A Wireless Sensor Network Based Personnel Positioning Scheme in Coal Mines with Blind Areas (Liu et al., 2010) proposed a new miners positioning scheme for a tunnel network with blind areas. The proposed system was divided into four steps:

1. In the first step, the real time personnel location in the working places was calculated by a location engine, and sent them to the gateway.
2. In the second step, the localization errors caused by the underground mining tunnels were corrected.
3. In the third step, the global three-dimensional position of each personnel was determined by coordinate transformation.
4. Finally, the developed system estimated the personnel locations in the blind areas.

A prototype of this system was constructed to verify the positioning performance in an underground coal mine for three months. The results showed that the proposed personnel location system had good reliability, scalability, and positioning performance.

- A Novel Real-Time Coal Miner Localization and Tracking System Based on Self-Organized Sensor Networks (Wang, Huang & Yang, 2010) proposed a real-time coal miner localization and tracking system by using on self-organized sensor nodes. The hardware and software implementation was summarized in the study. Three key localization technologies were used in the scope of this work. Firstly, the *received signal strength indication* (RSSI) based algorithm was used to reduce the influence of the hostile environment. Secondly, a robust fault-tolerant localization mechanism was used to improve the inherent defect of instability of RSSI localization. Finally, an accurate localization algorithm based on Monte Carlo Localization (MCL) was implemented to increase adaptation of the underground tunnel structure. The system network architecture consisted of mobile nodes, fixed nodes and a base station with optical port. The system was deployed in an underground mine and the simulation results showed that the accuracy of that system is acceptable.

- Real Time Location Tracking System for Metal Miners (Wadhwa et al., 2014) proposed a new miner's position tracking method in an underground metal mine. The real-time positioning system was based on wireless sensor nodes that employs ARM processor LPC2148 as the microcontroller and ZigBee as wireless communication module. An RSSI based localization algorithm was developed for this aim. WSN topology consisted of mobile and fixed nodes in order to determine the position of the miners. The developed algorithm estimated the location of the miners from the intersection of the three circular coverage zone of fixed nodes. However, the randomness of RSS patterns reduced the performance of the system during the indoor experiments.

3.5.3 Hybrid Systems

Underground mine environment monitoring and miner's position tracking systems are the two significant applications to provide underground mining safety (Dohare et al., 2015). Hybrid systems can combine the both underground monitoring and miner’s position tracking systems together. To the best of our knowledge, the well-known studies which can be categorized as hybrid systems are given:

- Deploying a Wireless Sensor Network on the Coal Mines (Wang et al., 2007) presented a wireless sensor network for monitoring of coal mine conditions and localization of miners. The sensor network application was designed on TinyOS and Motes platform. The sensor node was based on TMote Sky Mote with a sensor board. A wired mesh network topology was proposed for the network architecture. Sensor nodes were divided into two types. The first type was worked as a *beacon* node and fixed into the walls or ceilings. The second type was a mobile node and had to be carried by the miners. The software of the sensor network was developed on TinyOS platform and TinyDB database. The mobile sensor nodes measured the various gas parameters from the environment, and the position of the miners was estimated by the triangulation method of the static beacon nodes. Finally, the WSN was implemented in a coal mine.

- Automatic Monitoring System for Coal Mine Safety Based on Wireless Sensor Network (Song, Zhu & Dong, 2011) proposed a coal mine monitoring and safety system was presented in this study. Sensor devices were constructed by MSP430F microcontroller and nRF2401 wireless module. The system monitored humidity, temperature and other parameters in mine. The coal mine safety monitoring system consisted of four parts: Sink node, sensor nodes transmission networks and a central monitoring system. Sensor nodes could be grouped in to two types: mobile and fixed nodes. The mobile nodes were responsible from sensing parameters. The fixed nodes collected the incoming data and transmit this data to the central monitoring system. Fixed nodes had both wireless and wired communication interface to support data acquisition. The developed WSN was using star topology and supported one-hop communication. Each mobile sensor node had a unique sensor ID and the placement of the miners were able to be extracted from the mobile sensor nodes.

- Safety Scheme for Mining Industry using ZigBee Module (Krithika & Seethalakshmi, 2014) proposed an underground mining safety scheme using LPC2148 based underground sensors and wireless ZigBee modules. Moreover, the personal protective equipment wore by the miners also helped to identify their location. In addition, an alarm unit attached to the sensor module gave an emergency signal based on the analysis of monitored parameters. Temperature, humidity and gas concentrations were monitored by the underground sensor nodes. LPC2148 ARM processor with ZigBee modules were used in the design of sensor devices. This system was able to help to find miner's location, which were working inside of the underground galleries and monitors the presence of combustible gas in the working places.

CHAPTER FOUR

DESIGN AND IMPLEMENTATION OF THE SENSOR MOTE

Recent improvements in the microcontroller technology allow semiconductor producers to develop various kinds of low-power consumption microcontrollers, suitable for WSNs (Wang et al., 2006). Wireless sensor mote developers such as; SOWNet, Libelium and Memsic Companies (2016) , produce several types of wireless sensor motes (sensor node hardware) for WSN applications. However, most of these sensor motes are designed for terrestrial sensor network applications and commercially sold with high prices (Rawat et al., 2014). In addition, these sensor motes are not suitable for underground mine monitoring applications due to the power and signal propagation constraints.

In the marketplace, several sensor motes, which are commercially available, can be found. Some examples of sensor motes are given in Table 4.1. Because of the power, signal and cost limitations of these sensor motes, a low-cost and low-power sensor mote design and implementation is required for wireless underground mine monitoring applications.

Table 4.1 Examples of some commercially sold sensor motes in the marketplace.

Name	Manufacturer	Price	Release	Device
G-Node G301	SOWNet Technologies	68 euros	2010	TI MSP430F2418
MTM-CM3000-MSP	AdvanticSys	80 euros	2011	TI MSP430F1611
TMote Sky/TelosB	MEMSIC	N/A	2005	TI MSP430F1611
Waspmote (starter kit)	Libelium	199 euros	2011	Atmel ATmega1281
MICA	Memsic	N/A	2003	Atmel ATMega 128L

One of the aims of this study is to create a low-cost and low-power WSN network to monitor ongoing or abandoned areas in the underground mines. The component selection and hardware implementation of the sensor mote for our study is explained in this chapter.

4.1 Hardware Implementation of the Sensor Node

Sensor nodes are the basis units of a WSN. The stable and robust running sensor motes ensure the reliability of the entire sensor network. Sensor nodes are responsible from the data acquisition from the sensors, data processing and wireless communication between the other nodes. Therefore, the sensor node hardware design and implementation is a significant part of developing a senor network.

Component selection is the first part of developing a wireless sensor mote for underground mine monitoring application. In order to monitor underground mining workplaces four parameters are selected: temperature, humidity, methane and carbon monoxide. These are the most preferred parameters by the previous underground coal mine monitoring applications (Bian, 2010; Kumar & Rao, 2013).

4.1.1 Development Platform Selection

In the first step of developing a sensor mote, a hardware platform should be selected. For this purpose, the Arduino platform was analyzed. Arduino is an open source embedded system development platform which allows easy to use hardware and software together (Arduino, n.d.). Arduino platform supports various types of embedded development boards and hundreds of suitable devices. Arduino provides an open-source software (IDE) for programming the hardware. All Arduino boards and software are completely open-source and supports multi-platform support. As a result of these properties, Arduino is selected as our development and testing platform.

Since, Arduino Uno R3 boards were the most used and documented board of the Arduino family, these boards were selected as the first development kits for sensor motes (Arduino Uno, n.d.). Arduino Uno board is also called Genuino Uno outside the United States of America.

Arduino Uno R3 board is using ATmega328P microcontroller with 16MHz clock speed (Arduino Uno, n.d.). ATmega328P microcontrollers have 32KB code memory

2KB SRAM and 1KB EEPROM (Atmel, 2014). This board also supports 14 I/O pins, 6 of the I/O pins provides Pulse with Modulation (PWM) out, and 6 analog input pins. The board has a power jack, a USB connection, an ICSP header and a RESET button. The board can be easily connected to a computer with a USB cable. Arduino Uno can be programmed with Arduino IDE over a USB port. These properties make this board suitable for any embedded prototyping applications. Technical details about Arduino Uno R3 development board is given in Table 4.2.

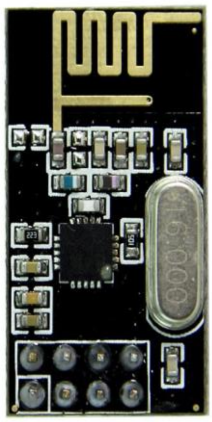
Table 4.2 Properties of Arduino Uno R3 development kit (Arduino Uno, n.d.)

	**Microcontroller**	ATmega328P
	Operating Voltage	5V
	Input Voltage	6-20V
	Digital I/O Pins	14 I/O 6 of provide PWM out
	Analog Input Pins	6
	DC Current per I/O Pin	40 mA
	DC Current for 3.3V Pin	50 mA
	Flash Memory	32 KB
	SRAM	2 KB
	EEPROM	1 KB
	Clock Speed	16 MHz
	Weight	25 g

4.1.2 Wireless Module Selection

After selecting the development platform and the embedded board, in order to support wireless communication, 2.4 GHz nRF24L01++ wireless modules were selected (Nordic Semiconductor, 2008). The nRF24L01+ wireless modules were used to provide 2.4 GHz wireless communication with ultra-low power consumptions which is a significant property for battery powered sensor motes. These modules provide nice wireless access with low-power consumption properties. The technical details of the nRF24L01+ wireless module is given in Table 4.3.

Table 4.3 Properties of the 2.4 GHz NRF24L01+ wireless module (Nordic Semiconductor, 2008)

	**Power supply :**	1.9V~3.6V
	Working current :	13.5mA at 2Mbps / 11.3mA at 0dBm output power
	Sensitivity :	-85dBm at 1Mbps
	Emission distance :	70~100 meter at 256kbps
	Data rate :	256kbps / 1Mb
	Communication mode :	Enhanced ShockBurst TM / ShockBurst TM
	Working mode :	Power Down Mode / Standby Mode / RX Mode / TX Mode
	Temperatures :	Operating:-40°C ~ 85°C / Storage:-40°C ~ 125°C

The nRF24L01+ is a single chip 2.4Ghz wireless module using an embedded baseband protocol engine called "*Enhanced ShockBurst*" for ultra-low power wireless applications. The nRF24L01+ works between 2.400 and 2.525 GHz ISM frequency bands (Nordic Semiconductor, 2008).

The nRF24L01+ wireless module can be controlled over Serial Peripheral Interface (SPI) bus. SPI devices can communicate in full duplex mode using a master-slave architecture with a single master (Miesterfeld et al., 1988). The master device organizes the communication between slave devices. The nRF24L01+ module supports various data rates of 250Kbps, 1Mbps and 2Mbps (Nordic Semiconductor, 2008). The lowest data rate has the highest communication range about 100 meters.

The nRF24L01+ wireless module uses Gaussian Frequency Shift Keying (GFSK) modulation technique. A GFSK modulator smooths the transmitting signal by using a Gaussian Filter. The GFSK modulator allows the wireless module to communicate with lower signal powers than the Wi-Fi modules.

The nRF24L01+ module can be powered between 1.9 to 3.6 V supply voltage, but it is robust at 3.3 V (Nordic Semiconductor, 2008). This module supports 125 different channels between 2.4 GHz and 2.525 GHz frequencies and each channel has 6 data pipes for data communication. This module requires 11.3 mA at 0 dBm output power at transmitter mode and 12.3mA output current in receiver mode. Receiver module can read data at -94 dBm power sensitivity.

The *Enhanced ShockBurst* is a packet based data link layer protocol which allows automatic packet assembly, acknowledgement and retransmissions of packets with supporting ultra-low power and high performance communication (Nordic Semiconductor, 2008). The *Enhanced ShockBurst* is responsible from the packet handling and time synchronization. The protocol assembles the data packets during the transmission. The *Enhanced ShockBurst* protocol constantly searches for a valid address in the demodulated signal during the reception. When a valid address is found, the rest of the packet is validated by the CRC bits. If the received data is valid, the payload is moved to the receiver's buffer. The data transaction is completed when the transmitter has received an acknowledgement (ACK) packet from the receiver. Packet format of Enhanced ShockBurst protocol using in the nRF24L01+ wireless module is given in Figure 4.1.

Preamble 1 byte	Address 3-5 byte	Packet Control Field 9 bit	Payload 0-32 byte	CRC 1-2 byte

Figure 4.1 Enhanced ShockBurst protocol packet (Nordic Semiconductor, 2008).

The preamble field as shown in the packet format is used to synchronize sender and receiver modules (Nordic Semiconductor, 2008). The nRF24L01+ module has a 3 or 5-byte address field which should be unique for each wireless module. The 9-bit packet control field is used to send payload length, packet identity and acknowledgement. Payload field has a various size up to 32-bytes. Cyclic Redundancy Check (CRC) field is used for error detecting and packet validation.

4.2 Sensor Selection for Underground Monitoring Applications.

Sensor selection is another important task of building a wireless sensor mote for monitoring underground mines. For this purpose, four different parameters are chosen to monitor carbon monoxide, methane, humidity and temperature in underground mines. The regulation titled “Occupational Health and Safety Regulations for Mining Workplaces” published by The Ministry of Labor and Social Security has been effective during the parameters selection process. This regulation specifies the maximum allowable gas percentages and proper working conditions for a safety mine production.

According to this regulation, the maximum permissible gas levels for underground mines should be under 50 ppm for carbon monoxide (CO), 2000 ppm for methane (CH_4), 5000 ppm for carbon dioxide (CO_2) and 20 ppm for hydrogen sulfide (H_2S). Moreover, the oxygen (O_2) percentage should not be under 19% of the air (The Ministry of Labor and Social Security, 2013).

After determining the parameters for underground mine monitoring application, Arduino suitable temperature, humidity and gas sensors are selected and supplied from the manufacturers. The selected sensors are;

- Temperature and Humidity Monitoring: DHT11 (Figure 4.2a).
- Methane gas Monitoring: MQ-4 (Figure 4.2b).
- Carbon monoxide gas monitoring: MQ-7 (Figure 4.2c).

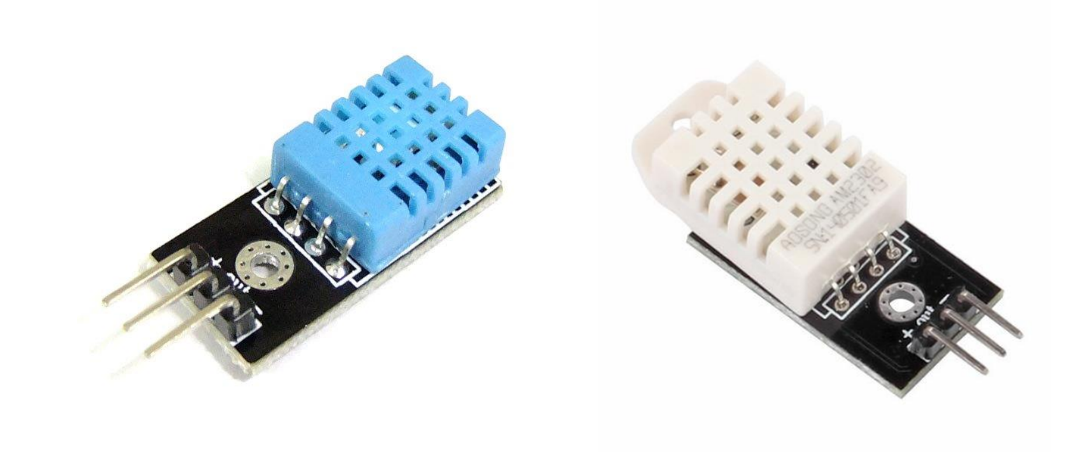
a) b) c)

Figure 4.2 Arduino suitable sensors: a) DHT11: Temperature and Humidity Sensor, b) MQ-4: Methane Sensor, c) MQ-7: Carbon Monoxide Sensor.

4.2.1 DHT Temperature and Humidity Sensor

The DHT is a digital, low-cost and low-power digital temperature and humidity sensor (DHT Datasheet, 2015). It uses a capacitive humidity sensor and a thermistor for temperature measurement. The DHT sensors include an ADC inside and converts analog readings to digital and represent the sensor values from its digital output.

DHT sensor has two versions named by DHT11 and DHT22 (Figure 4.3). Although, both sensors have same power consumptions, DHT22 is more accurate, and has a large sensing range than DHT11. At the beginning of this study, DHT11 version is chosen because of its price. The DHT11 sensor can detect the temperature between 0 to +50 °C and humidity between 20% to 80% RH with low-power consumption (DHT Datasheet, 2015). DHT11 sensor can be powered between 3 to 5.5 V supply voltages and it requires maximum 2.5 mA during measurement and 60 µA current in standby current (DHT Datasheet, 2015).



a) b)

Figure 4.3 Two versions of DHT sensor: a) DTH11, b) DHT22.

In order to improve accuracy of temperature and humidity readings, DHT11 was replaced by the enhanced version called DHT22 sensor. The DHT22 sensor supports 0 to 100% RH humidity reading with 2% accuracy and -40 to +125 °C temperature measurement range with ±0.5 °C accuracy. DHT22 sensor also has nearly the same power consumption parameters with DHT11 sensor.

4.2.2 MQ Series Gas Sensors

In order to measure gas levels in the environment, a low-cost Arduino suitable MQ series gas sensors were selected for this purpose. In addition, the regulations governing the underground mining safety working conditions forces to monitor underground tunnels and galleries continuously. Monitoring methane and carbon monoxide gas levels in underground mine is very crucial because carbon monoxide is a very poisonous gas and it may also indicate a fire or inadequate ventilation of the working place. Although methane is not a poisonous gas, it is very explosive in some concentrations and must be periodically monitored all time in the underground mines. If the methane concentration reaches the critical levels, the production should be immediately stopped and the explosive gas must be drained from the working place. The methane gas is lighter than the air so the gas is piled up to the ceilings. The pilled methane gas is removed from the working place by gas drainage pipes or ventilation systems.

MQ series gas sensors are analog sensors and working by a heating cathode covered with a sensitive material to a specific hazardous or explosive gas (Hanwei Electronics, n.d.-a). Before taking a gas measurement from the environment, the MQ gas sensors should be heated for at least 30 seconds with 5 V DC or AC voltage from their cathode, but 90 seconds preheating is recommended. Moreover, these sensors should require a preheating time about 48 hours before using. The MQ gas sensors consume maximum 150 mA current from their cathode during the measurement. All MQ series gas sensors have the base electrical circuit design as shown in Figure 4.4.

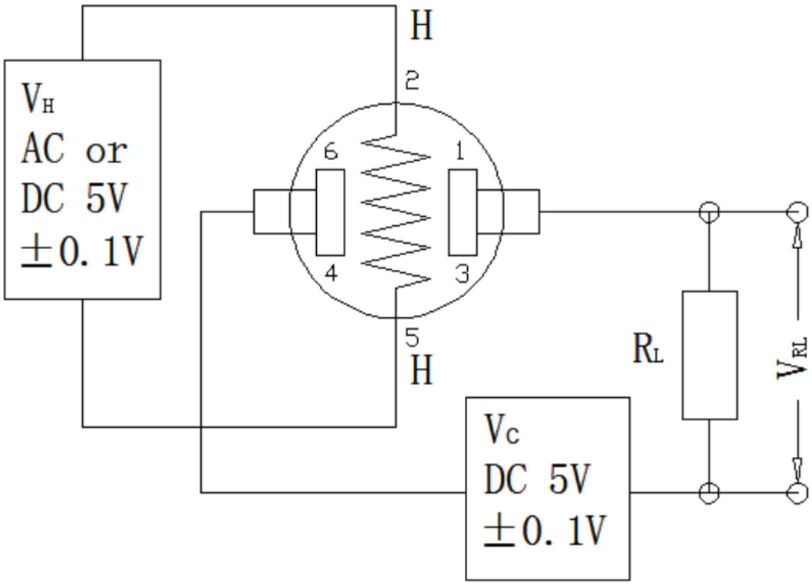


Figure 4.4 MQ series gas sensor electrical circuit (Hanwei Electronics, n.d.-a).

In order to measure methane gas levels from the environment MQ-4 module was selected (Hanwei Electronics, n.d.-a). This sensor also detects the LPG gas levels; however, this type of gas never exists in underground mines. The structure of the sensor is composed by a micro AL_2O_3 ceramic tube, Tin Dioxide (SnO_2) sensitive layer, heater, measuring electrode, and stainless steel net. Inside of a MQ-4 methane sensor is given in Figure 4.5, and technical drawing of the MQ series gas sensors is given in Figure 4.6.

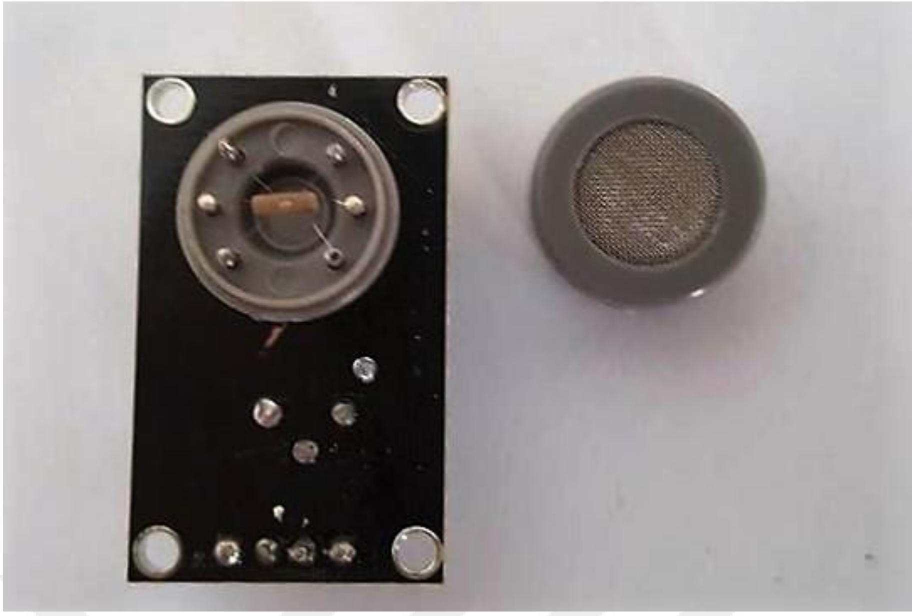


Figure 4.5 Inside a MQ-4 methane sensor.

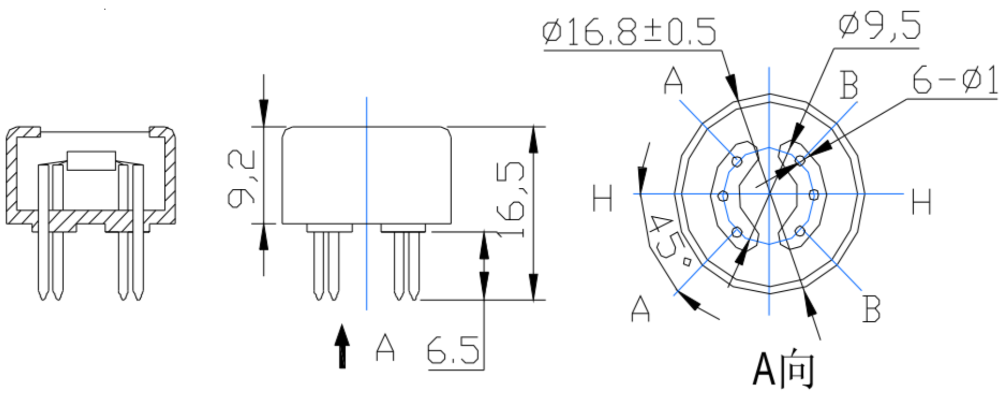


Figure 4.6 Technical drawing of a MQ series gas sensor.

MQ-4 sensor is configured to detect methane gas concentration in the air for home or industrial applications. The sensitivity characteristics of the MQ-4 sensor is given in Figure 4.7. The MQ-4 sensor has a methane sensitivity between 200 to 10000 ppm.

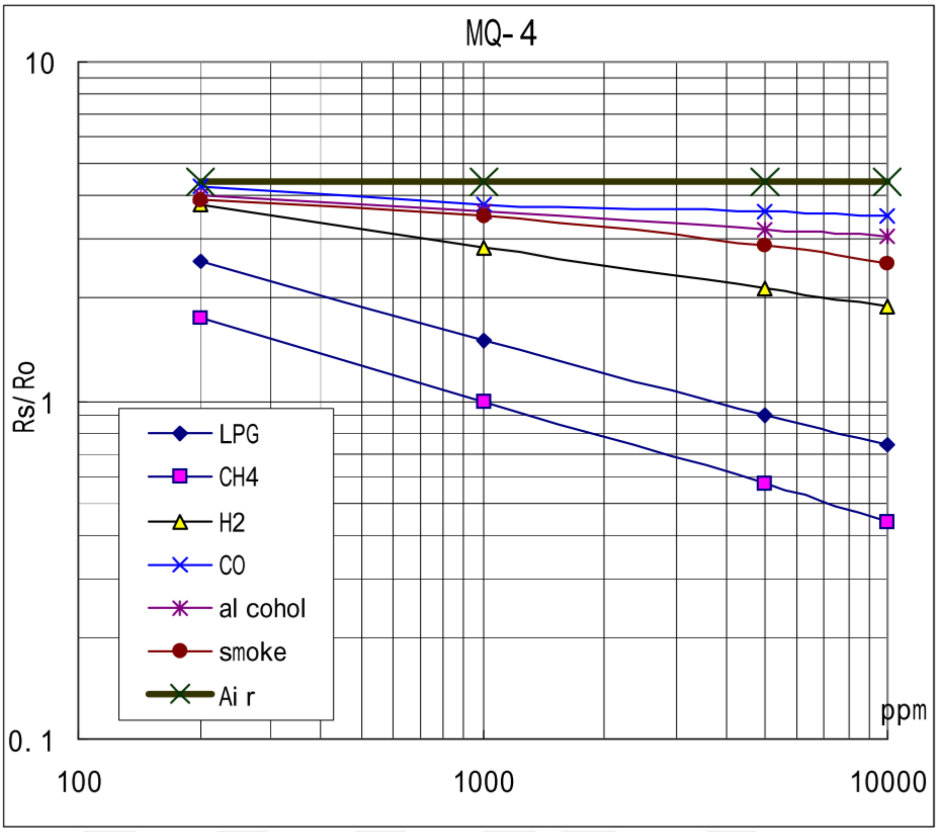


Figure 4.7 Sensitivity characteristics of MQ-4 gas sensor (Hanwei Electronics, n.d.-a)

MQ-7 sensor module is used to measure carbon monoxide gas levels. The structure of the sensor is same with the MQ-4 sensor. Carbon monoxide gas sensitivity characteristics of the MQ-7 sensor is given in Figure 4.8 (Hanwei Electronics, n.d.-b). This sensor has a carbon monoxide sensitivity between 20 to 2000 ppm. The sensitive layer of the sensor is made of SnO_2 sensitive layer and it can work about five years depending on the using conditions.

MQ gas sensor requires 125 mA current at 5 V for proper working. The sensor motes using MQ-4 and MQ-7 gas sensors together consumes 250 mA current for sensing, which is very high for battery powered sensor nodes. The MQ-9 sensor is preferred instead of MQ-4 and MQ-7 in order to reduce power consumption of these sensors by half. However, MQ-9 gas sensor still have a 125 mA current consumption which is relatively high for battery powered sensor modules. Therefore, power management methods should be implemented to reduce power consumption of sensor motes. The power consumption of the sensors and the other modules will be exhaustively discussed in the power management chapter.

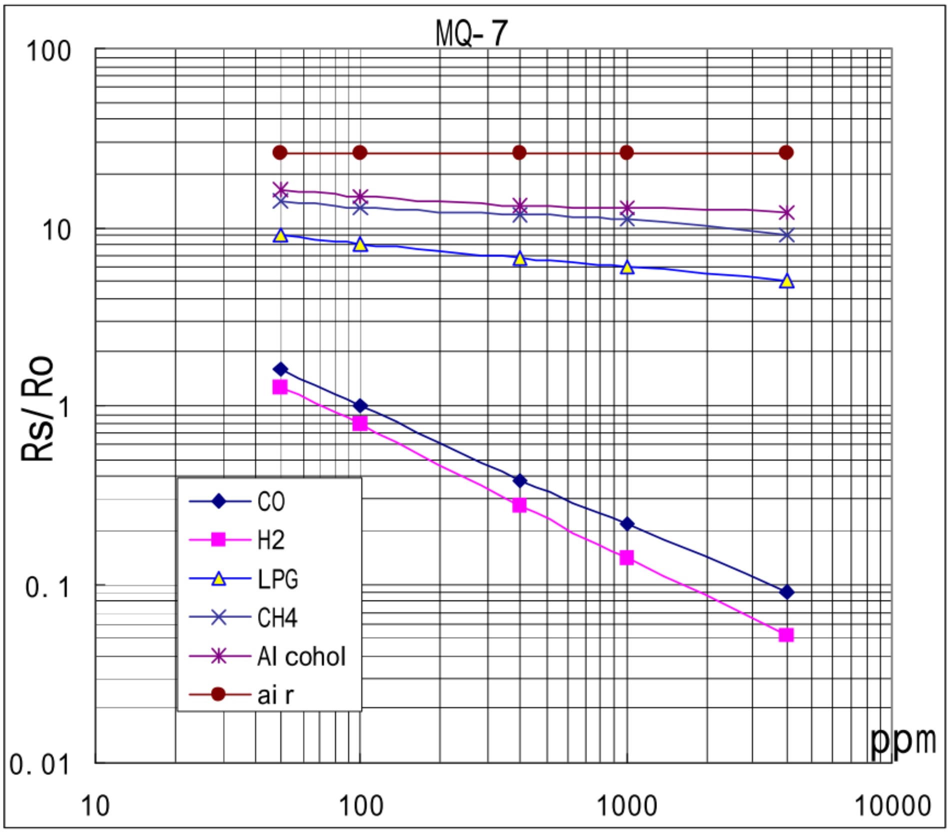


Figure 4.8 Sensitivity characteristics of MQ-7 carbon monoxide sensor (Hanwei Electronics, n.d.-b)

The MQ-9 gas sensor module is developed to measure carbon monoxide and flammable gas levels from the environment (Hanwei Electronics, n.d.-c). This gas sensor combines the properties of both of the MQ-4 and MQ-7 sensors in one sensor module with a high sensitivity. The sensitivity characteristics of the MQ-9 sensor is given in Figure 4.9. The MQ-9 sensor has a carbon monoxide sensitivity between 20 to 2000 ppm, methane sensitivity between 500 to 10000 ppm, and LPG sensitivity between 500 to 10000 ppm.

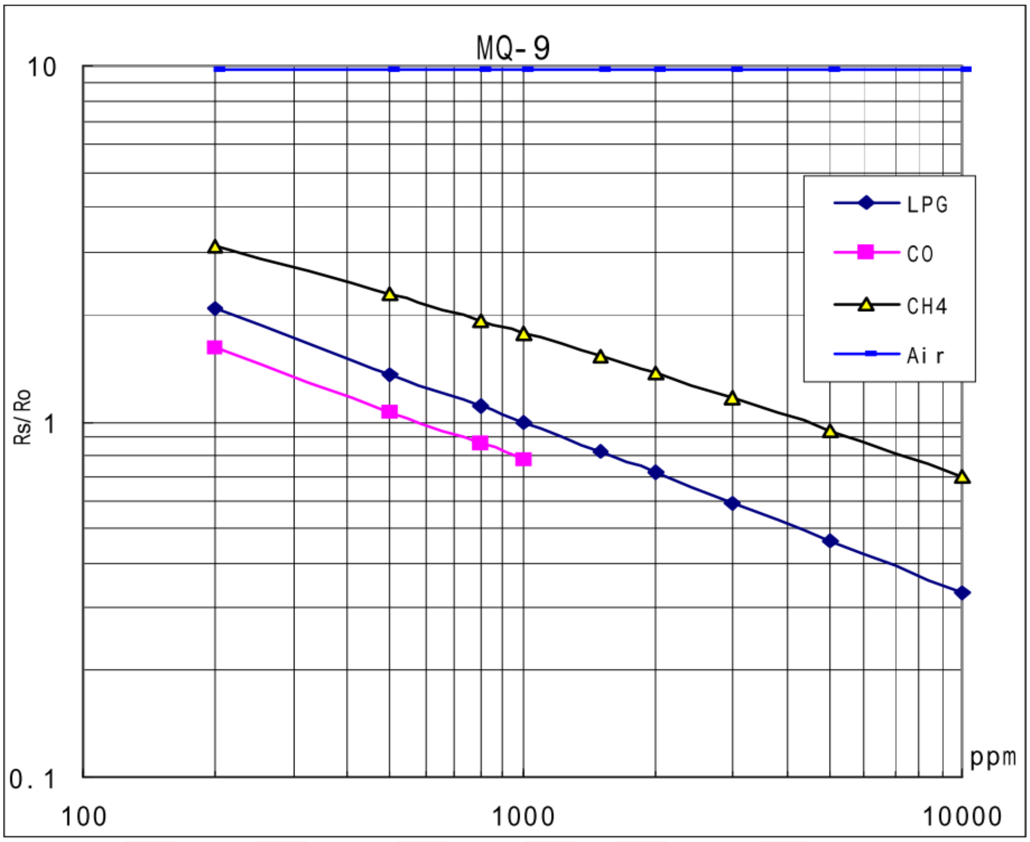


Figure 4.9 Sensitivity characteristics of MQ-9 carbon monoxide and flammable gas sensor (Hanwei Electronics, n.d.-c)

4.2.3 Improvements on the MQ Gas Sensors

In the first development of the sensor motes, the presence of methane and carbon monoxide gases in the environment is detected by MQ-4 and MQ-7 gas sensors. The developed sensor motes could detect the methane and carbon monoxide gases, but they did not calculate the percentage of gas concentrations. The Arduino Uno boards have 10 bits ADC for converting the analog sensor output to digital format which means our measurement scale is between 0 to 1023 range. However, the amount of the gas particles in the air is represented by percentages in particles per million (ppm) format. For this reason, the digital readings from the sensors need to be transformed to the ppm format. In order to calculate gas concentrations in ppm format, a series of mathematical transformations should be done. In order to understand the operating principle of the sensor, electrical circuit of the MQ gas sensor is given in Figure 4.10 (Hanwei Electronics, n.d.-c).

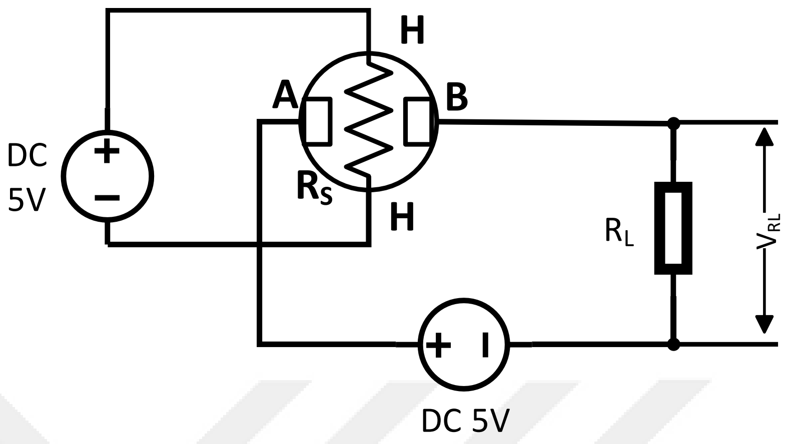


Figure 4.10 The electrical circuit of MQ gas sensor (Hanwei Electronics, n.d.-c)

The relationship between sensor resistance and the output voltage of the load resistance is given in the equation (4.1) from MQ-9 datasheet.

$$\frac{R_s}{R_L} = \frac{V_{CC} - V_{RL}}{V_{RL}} \tag{4.1}$$

The sensor resistance is changed by the various gas concentrations. The R_s value can be calculated from the equation (4.2).

$$R_s = \frac{V_{CC} - V_{RL}}{V_{RL}} * R_L \tag{4.2}$$

In order to calculate gas percentage from MQ gas sensors the equation (4.3) was constructed from the formulas and the sensitivity characteristics of MQ-9 given in datasheets.

$$GasPersentage\ (ppm) = 10^{\left(\frac{log\left(\frac{R_s}{R_0}\right) - P_1}{P_2} + P_3\right)} \tag{4.3}$$

In equation (4.3), MQ sensor gas percentage is calculated by the ratio between R_s, resistance value of the sensor, and R_0, clean air resistance. R_0 value is calculated by using a calibration program in clean air when the sensor node first power up. P_1, P_2 and P_3 are the gas percentage calculation parameters calculated from the MQ sensor datasheets. These parameters are separately calculated for each kind of gas sensor module.

4.3 Development of the Sensor Mote

The development process and the hardware implementation of the sensor mote for underground monitoring applications is summarized in this section. In the first part, the first prototype development of the sensor node with MQ-4 and MQ-7 gas sensors is discussed. In the second part, hardware improvements of the sensor mote, after realizing the disadvantages of the first prototype of the sensor node is explained.

4.3.1 Prototype with MQ-4 and MQ-7 Sensors

In order to test the selected components, Arduino Uno board, wireless module, DHT11, MQ-4 and MQ-7 sensors were combined together and the first prototype of the sensor mote was developed (Figure 4.11). The sensor mote is powered by a 9 V battery. The nRF24L01+ wireless module works with 3.3V DC voltage and provides 250Kbps data rate at 2.4 GHz ISM band (Nordic Semiconductor, 2008).

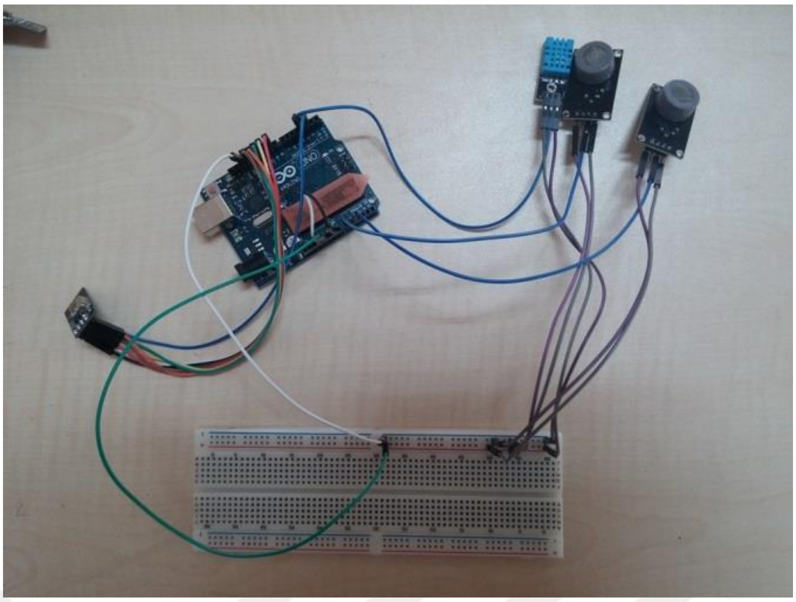


Figure 4.11 First prototype of the sensor mote.

The first prototype of the sensor mote can detect methane gas, carbon monoxide gas, temperature and humidity values from the environment. However, this sensor mote has some disadvantages such as size, power consumption, handling two different gas sensors and antenna range. Therefore, after realizing initial experiments with this prototype, improvements were done by changing some of the hardware components.

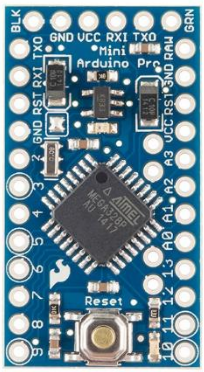
4.3.2 Enhancements of the Sensor Mote

Arduino Uno board was replaced with Arduino Pro Mini 8 MHz 3.3 V microcontroller board in the enhanced design of the sensor mote because this board is small in size and the power consumption is lower than the Arduino Uno boards. The nRF24L01+ wireless module is also replaced with a nRF24L01+ PA (Power Amplifier) and LNA (Low Noise Amplifier) radio module. The new module has longer transmission range than the chip antenna version of nRF24L01+ module. The MQ-4 methane and MQ-7 carbon monoxide gas sensors are replaced with the MQ-9 carbon monoxide and flammable gas sensor due to reduce power consumption of sensor motes. In addition, DHT11 temperature and humidity sensor is also replaced with an upper version, DHT22, as it is explained in the DHT temperature and humidity sensor section.

4.3.2.1 Arduino Pro Mini Board

The Arduino Pro Mini is a microcontroller board based on ATmega328P microcontroller as same as the microcontroller at Arduino Uno board. The properties of Arduino Pro Mini board are given in Table 4.4 (Arduino Pro Mini, n.d.). The board has 14 digital pins, 6 analog inputs, reset button and a six pin headers. The Arduino Pro Mini board does not include a USB interface for programming instead of this it can be programmed and powered with a Future Technology Devices International (FTDI) breakout board connected to its six pin header. The Arduino Pro Mini boards have two versions. The first version runs at 3.3 V and 8 MHz, and the other one runs at 5 V and 16 MHz. The main differences between these versions are the power supply voltage and the clock frequency of the microcontroller.

Table 4.4 Properties of Arduino Pro Mini Board (Arduino Pro Mini, n.d.).

	**Microcontroller**	ATmega328P
	Operating Voltage	3.3V
	Input Voltage	3.35 -12 V
	Digital I/O Pins	14 I/O 6 of provide PWM
	Analog Input Pins	6
	DC Current per I/O Pin	40 mA
	DC Current for 3.3V Pin	50 mA
	Flash Memory	32 KB
	SRAM	2 KB
	EEPROM	1 KB
	Clock Speed	8 MHz

4.3.2.2 FTDI Breakout board

The FTDI breakout board is used to convert RS-232 or serial transmissions to USB signals (Figure 4.12) (SparkFun, n.d.). The FTDI breakout board is connected to the Arduino Pro Mini board with six pin programming header, besides, the FTDI board is connected with a PC over USB port for programming. There is a voltage regulator on the FTDI breakout board so it can be powered with an unregulated voltage source.

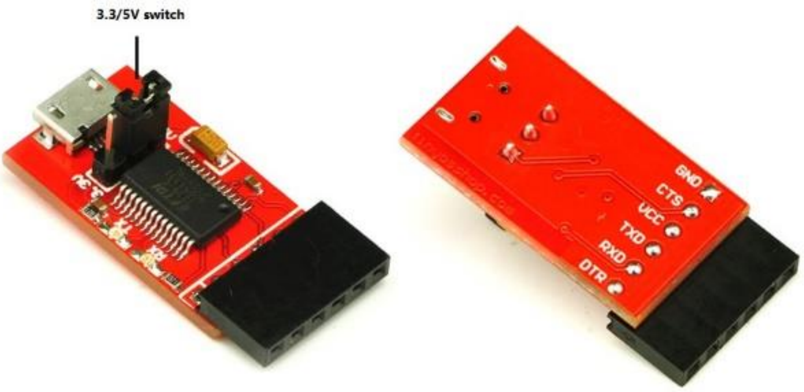


Figure 4.12 The FTDI breakout board.

4.3.2.3 nRF24L01+ PA & LNA Wireless Module

The nRF24L01+ PA & LNA with external monopole antenna module was preferred for underground sensor mote development as shown in Figure 4.13. This module has nearly 10 times longer range than classic nRF24L01+ chip antenna modules (Nordic Semiconductor, 2008). The nRF24L01+ PA & LNA wireless module transmission range can reach the maximum level of 1000 meters at 250 Kbps data rate in open area.

Figure 4.13 The nRF24L01+ PA & LNA wireless module with monopole antenna.

4.3.2.4 Selection of the Battery and Voltage Regulator

The final version of the sensor mote was powered with a 3.6 V primary lithium battery. In order to power Arduino Pro Mini module and sensors accurately, a 5 V switching step-up voltage regulator (Pololu U1V11F5) was used to generate 5 V from input voltage (Pololu, n.d.). The step-up voltage regulator is given in Figure 4.14. This step-up voltage regulator generates higher output voltages between 0.5 V to 5.5 V. In addition, this regulator has automatically linear down-regulation property when the input voltage is greater than the output voltage. The maximum quiescent current is 1 mA for very low input voltages, but typical quiescent current is lower than 100 μA. The regulator has an integrated over temperature thermal shutdown property at 140 °C.

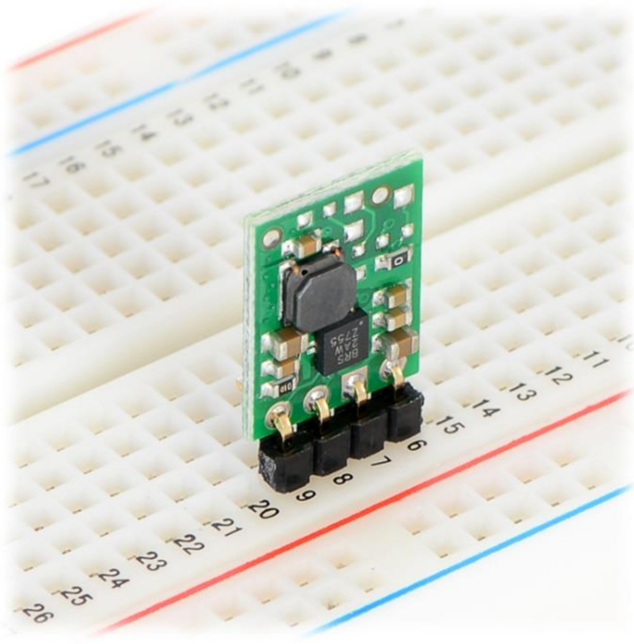


Figure 4.14 Pololu 5 V switching step-up voltage regulator.

A Lithium-thionyl Chloride ($Li\text{-}SOCl_2$) Spiral battery was selected as the primary power unit for the battery powered sensor motes as shown in Figure 4.15. The lithium-thionyl chloride battery has a constant voltage output at 3.6 V, and provides 13 mAh nominal capacity for a long time (ER34615M Datasheet, 2010). The operation temperature range is between -60 °C to +85 °C, however, the temperature changes may lead to reduce nominal capacity.

Figure 4.15 3.6 V Lithium-thionyl Chloride battery.

4.3.2.5 Assembling the Enhanced Sensor Mote

Sensor mote was assembled into a IP65 waterproof box in order to protect the sensor mote from dust, water and hazardous gases. The sensors were placed at one side of the box and isolated from outside with silicon insulating material. The enhanced version of the developed sensor mote is given in Figure 4.16.

The sensor node is powered on with an external IP67 waterproof switch. There is a waring led placed inside the switch. This led is used to warn workers for possible temperature or gas concentration changes. If any of the monitoring parameters is above the predefined threshold values, sensor motes immediately turn on the warring led on to protect miners near in that place.

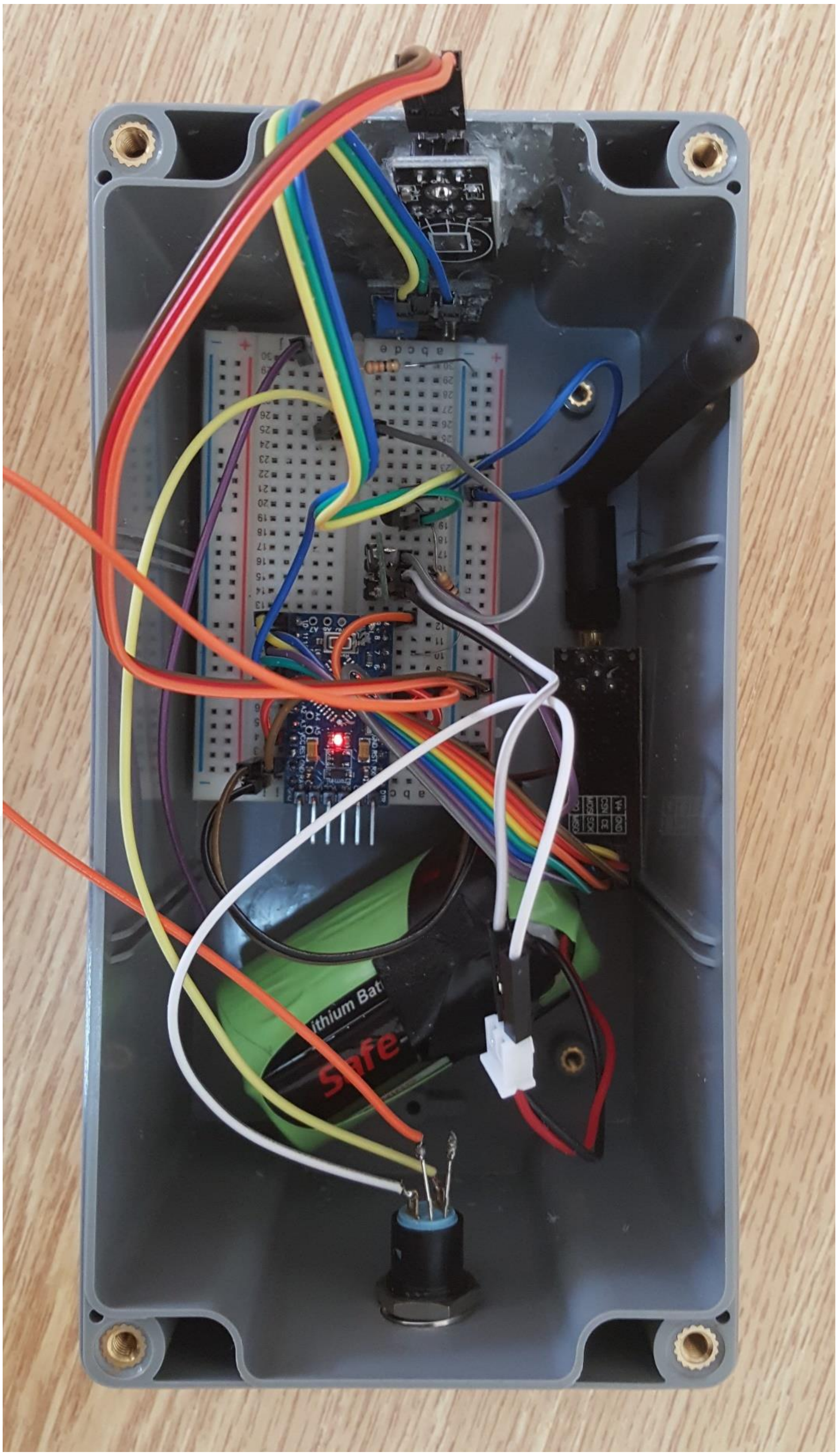


Figure 4.16 The final version of the developed sensor mote

4.3.3 PCB Design and Implementation

A printed circuit board (PCB) card design and implementation is done on EAGLE 7.2.0 software in order to combine all parts of the sensor device. Easily Applicable Graphical Layout Editor (EAGLE) is a flexible electronic design and schematic capture editor. Moreover, EAGLE editor allow users to design and implement PCB card for engineering applications. A two layered PCB card is designed to combine all parts together. The designed PCB board for the final sensor mote is given in Figure 4.17. The assembled PCB version of the sensor mote is given in Figure 4.18.

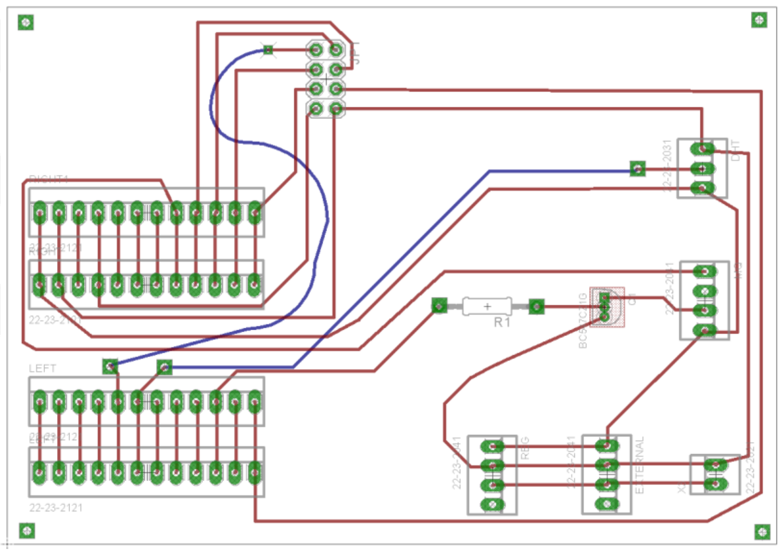


Figure 4.17 The PCB design of the sensor mote.

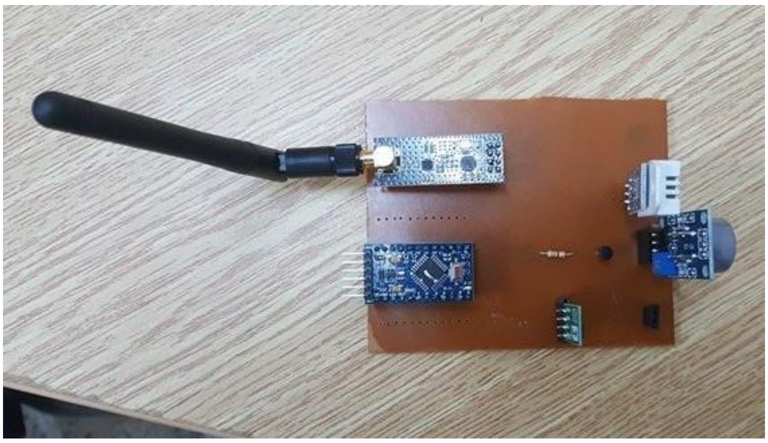


Figure 4.18 The PCB implementation of the sensor mote.

CHAPTER FIVE
POWER MANAGEMENT OF THE SENSOR NODES

Power management has been always a significant research area in WSNs. Wireless sensor nodes, which have low computational capacity and limited power, are usually powered by battery power (Akyildiz & Kasimoglu, 2004). In order to increase the lifetime of WSNs, the power consumption of the sensor nodes should be reduced (Sandal & Verma, 2012). The lifetime of a sensor node could be affected by the battery power, network topology and the networking protocols. The power management applications can be grouped into two distinct categories: networking protocols and power management techniques (Silva, Liu & Moghaddam, 2012). There are several power management approaches in the literature in order to extent lifetime of sensor nodes:

- **Dynamic Power Management (DPM):** The DPM technique reduces the power consumption by employing a dynamic sleep and wake up schedule (Sinha & Chandrakasan, 2001). The microcontrollers and radio modules sleep and awake modes are switched by the DPM algorithm to reduce power consumption of sensor nodes.

- **Environmental Energy Harvesting:** The sensor network applications which are expected to operate for long durations, the power consumption becomes a bottleneck and more effort is required to extent battery life (Raghunathan, Ganeriwal & Srivastava, 2006). An alternative solution is harvesting energy from the environment instead of replacement of the batteries. The solar panels (Voigt et al., 2003) and vibration- based energy generation (Pan et al., 2005) can be used to recharge sensor nodes.

- **Dynamic Sensing:** The main focus of the energy efficiency issues was on the energy spent for wireless communication. Although, the digital sensors have low power consumption and saving modes, analog sensors, for instance: gas, acoustic and seismic sensors, have relatively high energy consumptions

(Raghunathan et al., 2006). In order to reduce energy consumption of the sensors adaptive sensing algorithms can be developed.

Buried nodes especially used in underground mines or placed under the buildings cannot use rechargeable batteries or solar cells (Silva et al., 2012). Therefore, power management is one of the most important issue for battery powered sensor modules in WUSNs. Additionally, environmental energy harvesting methods, for instance solar cells, cannot be applied to the underground sensor nodes. In this chapter, the importance of the power management is emphasized and proposed solutions to reduce power consumption of the sensor nodes will be described respectively.

5.1 Power Consumption of Sensor Nodes

In order to understand the lifecycle of a battery powered sensor node, current consumptions of the sensor node should be examined first. Most of the sensor nodes generally consume the highest energy at data processing and transmission phases (Wang et al., 2011). An example current consumption graphic of a sensor node is given in Figure 5.1.

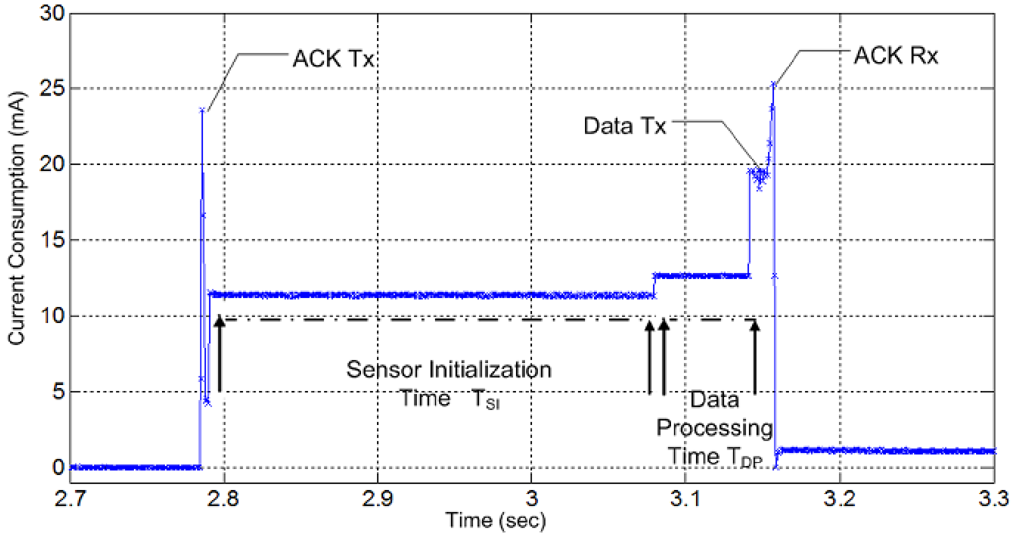


Figure 5.1 Current consumption of a sensor node (Wang et al., 2011).

As shown in Figure 5.1, the sensor node reaches the highest current consumption at data transmit (Tx) and data receive (Rx) modes. However, the energy consumption is nearly reduced to microampere levels during the sleep mode.

Raymond and his friends (2009) gives the energy consumption, memory and other information for the Crossbow Mica2 and Tmote Sky sensor motes as shown in Table 5.1.

Table 5.1 Energy consumption of sensor motes (Raymond et al., 2009)

		Mica2	Tmote Sky
Power Draw	**Receive (mW)**	36.81	64.68
	Transmit (mW)	87.90	55.20
	Sleep (mW)	0.090	0.114
RF Transiver		CC1000	CC2420
RAM		4 KB	10 KB
Program Memory		128 KB	48 KB
Sleep Transition Time (ms)		2.60	6.81
Data Rate (kbps)		78.8	250

The sleep ratio of a sensor node can be calculated from the equation (5.1). Formally, the life time of a battery powered sensor node is calculated from the equation (5.2) (Raymond et al., 2009).

$$R_{sleep} = \frac{T_{sleep}}{T_{active} + T_{sleep}} \tag{5.1}$$

$$T_{sensorlife} = \frac{C_{battery}}{(R_{sleep})(I_{sleep}) + (1 - R_{sleep})(I_{active})} \tag{5.2}$$

In equation (5.1), the sleep ratio of a sensor node R_{sleep} is calculated by the relation between T_{active} active and T_{sleep} sleep times. In equation (5.2), sensor nodes lifetime is calculated by using the sleep ratio R_{sleep} from equation (5.1), $C_{battery}$ refers to total amount of sensor node's battery power (mAh), I_{sleep}, represents the sleep mode current requirement (mAh), and I_{active} represents the active mode current requirement (mAh).

The battery of a sensor node would be drained only in few days if the sensor node and the radio module stay in active mode. (Raymond et al., 2009). However, the lifetime of the sensor node can be expanded to the years by using a dynamic sleep and wake up schedule.

5.2 Optimizing the Power Consumption of Sensor Nodes

The lifetime of a WSN is depended to the battery capacity of the sensor nodes. In order to prolong lifetime of a battery powered sensor node, power management methods and energy-aware networking protocols should be applied (Silva et al., 2012). In this study, several power management methods are applied to the sensor nodes (Ünsal, Akkan, Akkan & Çebi, 2016). These methods are:

- Voltage regulator selection.
- Determining the operation voltage and frequency.
- Removing the unnecessary parts.
- Using power saving modes.
- Optimizing the power consumption of the sensors.

5.2.1 Voltage Regulator Selection

Voltage regulators are generally used for providing a constant voltage level (Boylestad & Nashelsky, 1998). They may be used to regulate one or more DC or AC voltages. Electronic voltage regulators become one of the permanent parts of embedded boards. These regulators consume a quiescent current when they are working. The quiescent current is the current drawn by the voltage regulator when it is not amplifying a signal or driving a circuit. Generally, linear voltage regulators such as: NCP1117 (ON Semiconductor, 2014) or LM7805 (Texsas Instruments, 2004), which are used in Arduino boards, consumes about 5 mA quiescent current for proper working. This power consumption reduces the battery life of the sensor node. Most of the linear voltage regulators provides power efficiency about %86. In order to save battery power of sensor nodes, low-energy consumption dropout positive voltage regulator such as MCP1702 should be chosen instead of linear voltage regulators (Microchip, 2005). For instance, MCP1702 regulator has 2.0 µA quiescent current instead of 5mA for LM7805 which makes MCP1702 regulator more efficient.

Another solution is to remove voltage regulator from circuit and use 5 V or 3.3 V raw battery power to supply embedded board. In order to avoid voltage peaks and noise, two capacitors can be added between voltage and ground pins to protect microcontroller from momentary voltage peaks. However, if the current consumption of the embedded board is frequently changed by the sensors or other devices, raw battery power cannot be used.

5.2.2 Determining the Operation Voltage and Frequency

Generally, microcontrollers are able to work with various voltage power with different clock frequencies. In order to optimize power consumption of an MCU, the power supply voltage clock frequency of MCU should be decreased. For instance, the power consumption of ATmega328P microcontroller in terms of I_{CC} is given in Table 5.2 (Atmel, 2014).

Table 5.2 ATmega328P microcontroller power consumptions (Atmel, 2014).

Parameter	Condition	Typical	Units
Power Supply Current	Active 1MHz,VCC=2V	0.3	mA
	Active 4MHz,VCC=3V	1.7	
	Active 8MHz,VCC=5V	5.2	
	Idle 1MHz,VCC=2V	0.04	
	Idle 4MHz,VCC=3V	0.3	
	Idle 8MHz,VCC=5V	1.2	
Power-down Mode	WDT enabled, VCC=3V	4.2	µA
	WDT disabled VCC=3V	0.1	

As it can be seen from the Table 5.2, the power consumption of a ATmega328P MCU is reducing when the supply voltage and frequency is decreasing. The key point is to find the optimal voltage and frequency levels for proper operation. The requirements of the application determine the optimum power and clock speed values.

One of the most important part of reducing power supply current is to determine the optimum voltage level for the application.

Wireless sensor nodes, wireless modules usually require 5 or 3.3 V supply voltage. These modules determine the minimum supply voltage. The voltage and frequency relation graphic for ATmega328P MCU is given in Figure 5.2.

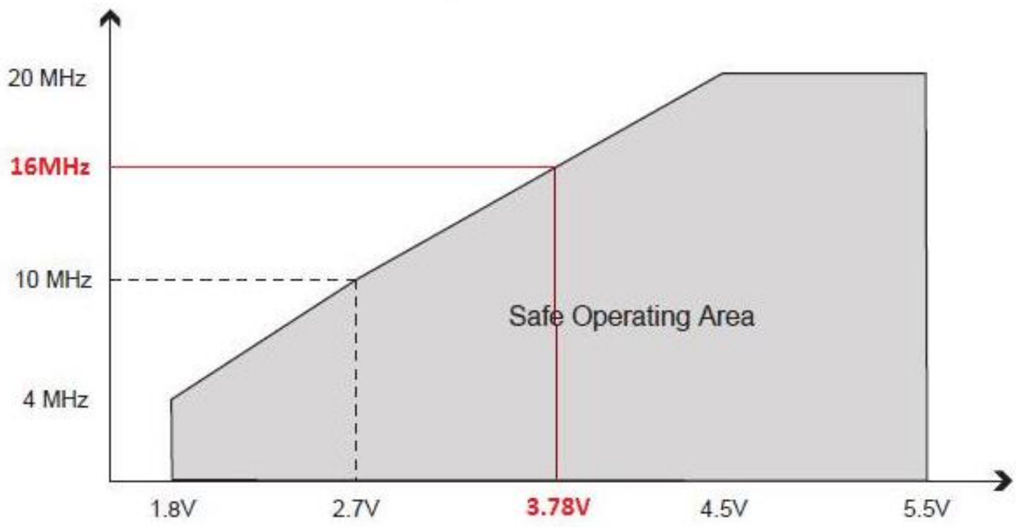


Figure 5.2 ATmega328P V_{CC} to frequency graphic (Atmel, 2014).

5.2.3 Removing the Unnecessary Parts

Embedded prototyping boards, such as Arduino Uno, include power or notification LEDs in order to inform users. Some of the sensor nodes may include LCD panels to display system information. LCD displays and notification LEDs consume big amount of power when they are working. Removing these unnecessary parts will increase the lifetime of sensor nodes.

5.2.4 Using Power Saving Mode

In the low density WSNs, sensor nodes stay on a wait or idle mode and consume a lot of power without doing anything most of the time. This situation causes a huge waste of energy for battery powered sensor nodes. Some of the microcontrollers, which support low power consumption modes, has power saving properties such as ATmega328P. The ATmega328P provides six different power saving modes, which can be ordered from minimal to excellent (Atmel, 2014). The power consumption will be highly reduced by using the microcontrollers power saving modes.

The power consumption properties of the ATmega328P is given in Figure 5.2. The power consumption of ATmega328P micro controller is reduced from milliampere to microampere values when the power mode is changed from active to power-down mode. As a result, the lifetime of a sensor node can be extended from days to months by using low power modes of the microcontrollers.

5.2.5 Optimizing the Power Consumption of the Sensors

Wireless sensor nodes are using a wide variety of sensor types to monitor environmental parameters. Although the digital sensors have power saving properties, the analog sensors consume too much power for proper working (Raghunathan et al., 2006). Moreover, the sampling frequency has also a significant impact on power consumption. The sensor network applications working with long intervals have to be optimized to prolong the lifetime of sensor nodes.

In this study, temperature, humidity, carbon monoxide and methane gas levels are monitored. In chapter four, technical information about the DHT22 Temperature and Humidity and MQ-9 carbon monoxide and flammable gas sensors, which are used in this study, has been explained. The DHT22 is a digital sensor with low power consumption. The DHT22 requires max 2.5 mA during measurement and 60 µA maximum current in standby mode (DHT Datasheet, 2015). However, MQ series gas sensors are analog sensors and need to be heated about 60 seconds before sensing which cost dramatically high power consumption for battery powered sensor nodes. The MQ-9 sensor consumes 150 mA maximum current for proper working (Hanwei Electronics, n.d.-c).

5.3 Battery Selection for the Wireless Underground Sensor Nodes

Battery selection is one of the most important parts for developing WUSNs because most of the sensor nodes cannot be powered by a constant power line and should only work with a battery power for months. The properties of the well-known portable battery types are summarized in this section. After that, battery types suitable for underground applications are compared to each other at the end of this section.

In terms of their reusability property, batteries can be grouped in to two categories; primary and secondary batteries as shown in Figure 5.3 (Linden & Reddy, 2002). Primary batteries are designed to be used for once and cannot be recharged again. The cost of the primary batteries is generally cheaper than secondary batteries. In contrast, secondary batteries can be recharged and used for many times. However, the cost of the secondary batteries is higher.

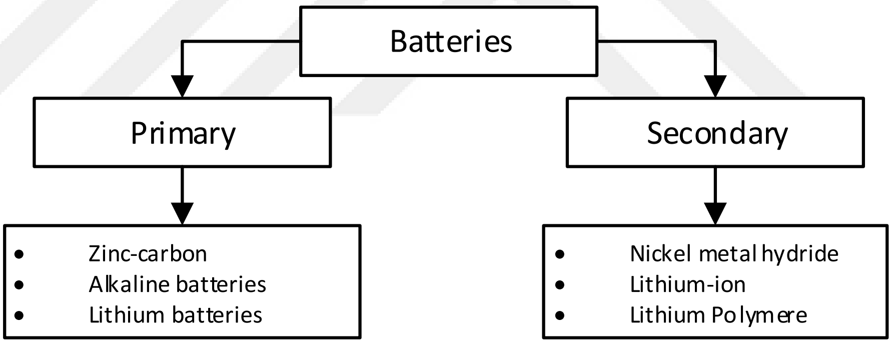


Figure 5.3 Types of portable chemical batteries.

The power units used for underground mining applications should obey the ATEX (ATmosphères EXplosibles, an abbreviation from French) Directives which are forced to isolate power supply units to contact with the unsafe environment (ATEX Directive, n.d.). In addition, the electronic devices should also be protected from exposing with the air. The only exception is the sensors and wireless communication units.

The battery selection is considered only a constant power source by developers. However, battery is a little chemical factory with limited energy resources (Barsukov, 2006). Batteries are used in both mobile and stationary equipment in the underground applications. The performance and safety requirements of these equipment have a significant impact on battery selection. Therefore, the selected batteries for underground mining applications should provide the following properties (Beck, Nieto & Lvov, 2015):

- Give a fixed voltage level until to fully discharged.
- Resistant against to momentary voltage and current surges.
- Durability against leakage, rupture and punctures.
- Durability against thermal changes.
- Have a large energy storage capacity.

5.3.1 Primary Batteries

Zinc carbon (ZnC) batteries were the first commercial dry batteries which are used less frequently nowadays. The zinc carbon batteries have an average energy storage capacity when compared with the other types of primary batteries.

Alkaline batteries (AlMn) is another kind of well-known kind of primary battery type. Alkaline batteries have a high energy capacity and an average lifetime. The lifetime of these batteries is changed by the application types. Shelf-life of these batteries can be reached up to five years. However, these batteries are not very durable against leaks and ruptures. The most common type of these battery is Alkaline Manganese (Zn/MnO_2) cells (Linden & Reddy, 2002).

Another high capacity primary battery type is the Lithium batteries which have lithium metal or lithium compounds as an anode and includes various types of metal oxide compounds as a cathode. The most well-known variation of Lithium cell is lithium manganese dioxide ($LiMnO_2$) cells (Linden & Reddy, 2002).

Primary lithium batteries can keep large amount of chemical energy. Another high capacity lithium battery is lithium thionyl chloride ($Li\text{-}SOCl_2$) which has three times high capacity of an equivalent alkaline battery (Schweitzer, Sherwin & Emmerich, n.d.). However, lithium batteries are very sensitive against water and moisture because Lithium metal is very sensitive against water.

5.3.2 Secondary Batteries

The nickel-cadmium battery (NiCd) is the first type of rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes (Beck et al., 2015). The nickel-cadmium batteries very durable against fast charging options and can be used in very low temperatures (Linden & Reddy, 2002). These batteries can be qualified as one of the most reliable batteries for wireless applications. However, the capacity of these batteries are slightly low when compared with the primary lithium and alkaline batteries.,

A nickel-metal hydride battery, abbreviated as (NiMH), is a kind of rechargeable battery (Linden & Reddy, 2002). Nickel-metal hydride batteries are very similar to nickel-cadmium (NiCd) batteries except they use metal hydride instead of cadmium in their cathode (Beck et al., 2015). The capacity of these batteries are three times more than an equivalent size nickel-cadmium battery. However, nickel-metal hydride and nickel-cadmium batteries have memory effect due to several charge and discharge periods.

Another well-known rechargeable battery type is Lithium-ion battery (Li-ion). Similar to primary lithium batteries lithium-ion batteries have high energy capacity with rechargeable capability (Linden & Reddy, 2002). Lithium-ion batteries can hold very high amount of energy.

A lithium polymer battery, or more correctly lithium-ion polymer battery (LiPo or Li-poly) is another type of rechargeable lithium battery (Beck et al., 2015). Lithium polymer batteries are using a polymer electrolyte instead of the more liquid electrolyte, so these batteries can be thin and light. However, Lithium Polymer (LiPo) batteries can support quite sufficient lifetime, they are very weak against puncture, crash, heat and high pressure (Linden & Reddy, 2002). A comparison of chemical batteries discussed above is given in Table 5.3.

The advantages and disadvantages of the portable chemical batteries which are suitable for mobile and WSN applications are given in Table 5.3.

Table 5.3 A comparison of portable chemical batteries.

Battery Name	Battery Type	Working temperature (°C)	Advantages	Disadvantages
Zinc-Carbon	Primary	-10 to +50	*cheap	* a significant loss of voltage during discharge * low power capacity * risk of leaking
Alkaline (Alkaline Manganese)	Primary	-20 to +50	* high performance * long life * the self-discharge speed is low	* risk of leaking (less than zinc-carbon batteries)
Lithium (lithium manganese dioxide)	Primary	-50 to +60	* long life * constant voltage * high power density	* very affected by water and moisture
Nickel metal hydride	Secondary	-20 to +60	* recharge ability * high elasticity * high power capacity (2-3 times capacity to NiCd)	* memory effect
Lithium-ion	Secondary	-20 to +60	* higher power capacity * recharge ability * high elasticity * produce higher voltages	* more expensive * need to be carefully recharged.
Lithium polymer	Secondary	Not more than +60	* Higher power capacity * lighter than other batteries * longer life time * can be producing as any shape and size	* requires special charge devices * requires special attention while using and charging

5.3.3 The Selected Battery Type for Wireless Underground Applications

Underground mines are hostile environments and the lack of sunlight causes unavailable to use solar cells for energy harvesting. Replacing or recharging the batteries of the sensor nodes placed in the underground workplaces may not be possible in most scenarios. Therefore, the primary batteries are more suitable for underground mining applications due to their cost and capacity. As a result, the lithium-thionyl Chloride (Li-$SOCl_2$) battery was selected as the primary power unit for the battery powered sensor motes. These batteries provide about 3.6 V voltage level with very high capacities with 25 year operating life under the most challenging conditions. The energy capacity of these batteries can reach up to 35,000 mAh.

5.4 Optimizing the Power Consumption of Sensor Motes

The importance of the power management and battery selection for battery powered sensor motes is summarized during this chapter. In this part, the experimental results of these methods applied to the sensor nodes used in this study will be explained.

The Arduino Uno R3 board, used in the first prototyping of sensor nodes, is not designed for energy-aware applications. The Arduino Uno board consumes 24 mA operating current without any load. MC33269 voltage regulator (Motorola, 1997) used in Arduino Uno boards requires 5 mA quiescent current. The unnecessary power LED consumes about 1 mA on process. When the mentioned parts are removed or bypassed from the board, the power consumption of the Arduino Uno board is reduced about 6 mA. However, after removing these parts from the board, the current consumption of this board was still about 18 mA.

When the ATmega328P microcontroller operating individually at 16 MHz frequency and 5 V voltage power, the current consumption of this board was reduced to 14.6 mA. If the operating frequency was reduced to 8 MHz, the operating current was decreased to 10.3 mA levels. In addition, when the microcontroller was switched to the power-down mode during the waiting period, the operating current was reduced to 0.0058 mA.

In order to prolong lifetime and reduce the size of the sensor motes, the Arduino Uno R3 board was replaced with Arduino Pro Mini 8 MHz 3.3 V microcontroller board. This board consumed 4.74 mA current at active mode and 1.5 mA current at power-down (sleep) mode. After removing the power LED from the circuit the power consumption of this board was reduced to 3.8 mA at active mode 0.054 mA at power-down mode. If the voltage regulator is removed from the circuit, the current consumption would be reduced to 4.5 μA levels. However, the nRF24L01 wireless module was not worked properly and reset the sensor node when the voltage regulator was bypassed from the sensor mote. Therefore, the voltage regulator was not removed from the sensor mote.

The nRF24L01 PA and LNA module consumed 24 mA current during the data transmission. However, the data transmission was taken one second and rest of the time the wireless module waits in the sleep mode. This module consumed 26 μA at standby and 0.9 μA at sleep mode.

The DHT11 and DHT22 sensors have the same power consumption properties. The DHT22 temperature and humidity sensor has a relatively low power consumption. It draws about 1.5 mA current for two seconds during the measurement and just 9.8 μA in the standby mode.

The MQ gas sensors are analog sensors and do not support any power-saving options. In order to reduce power consumption of the sensor motes, the MQ-9 carbon monoxide and combustible gas sensor was used instead of both MQ-4 methane and MQ-7 carbon monoxide sensors in the enhanced version of the sensor motes explained in chapter four.

The MQ-9 gas sensor requires high current values about 132 mA for measurement. However, 132 mA is still a very high value for battery powered sensor nodes. Therefore, in order to extend battery life of sensor nodes an efficient sampling period should be selected. In this study, the sampling period of the sensor nodes was selected as 8 hours interval (three times in a day). Although, Sensor nodes stays in power down mode most of the time, analog gas sensor drains the battery power during the sleep time. The best solution is to control MQ gas sensor with a switching circuit. For this aim, a switching circuit is prepared by using BC547 transistor to power on and off the gas sensor as shown in Figure 5.4. The transistor is controlled with a digital pin from Arduino board.

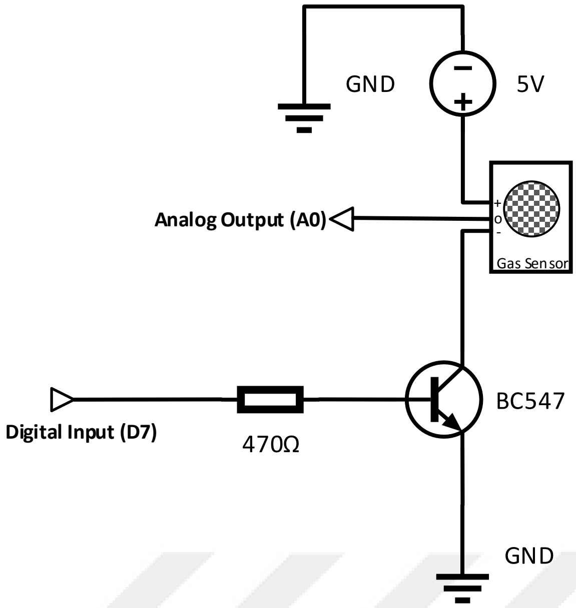


Figure 5.4 MQ-9 gas sensor switching circuit.

When the sensor node switches to active mode, the microcontroller power up the MQ gas sensor with setting the Arduino's digital pin 7 high and the MQ gas sensor is heated for 60 seconds for a proper sensor reading. After measuring the gas percentage from environment the microcontroller closes the switching circuit and MQ gas sensor is closed. The Average current consumption of the gas sensor is reduced to 2.2 mA for hourly sampling period.

In order to calculate the lifetime of a sensor node, equation (5.2) was used. The total operating current (I_{active}) of a sensor node is calculated about 162 mA, and standby current is about 0.164 mA. If the sensor node operated continuously without using the power management techniques, a 3000 mAh capacity battery will run out completely in about 18.49 hours. However, by using the power management techniques mentioned in this chapter, the battery life of a sensor node can be extended to 1046.53 hours for hourly sampling periods. This means providing approximately 59 times better longer battery life. In order to prolong lifetime of the sensor nodes the sensing period should be reduced. The best sampling period is determined three times in this study. The lifetime of sensor node graphics for three different sampling periods is given in Figure 5.5.

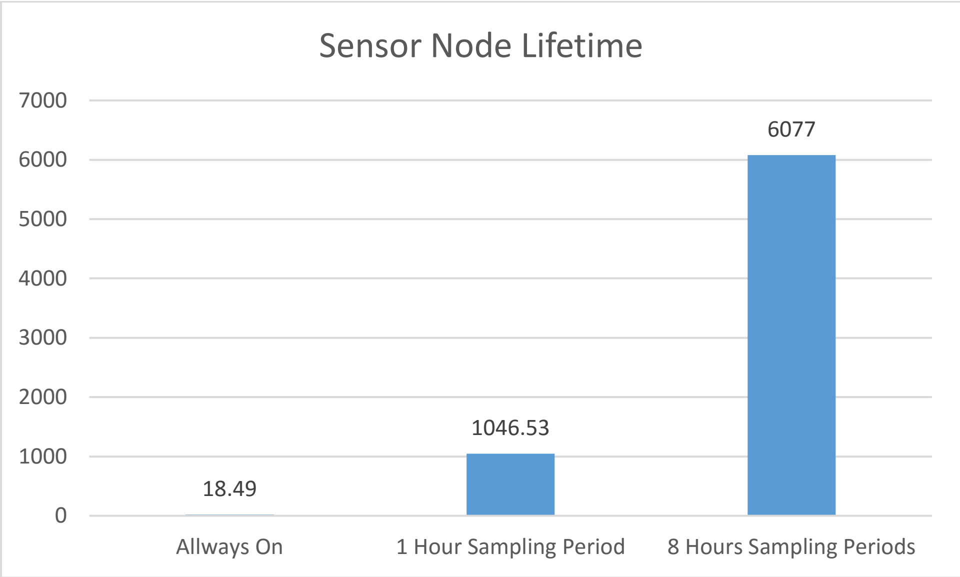


Figure 5.5 The lifetime of the sensor node for three different sampling periods.

CHAPTER SIX
RADIO SIGNAL AND WIRELESS NETWORK STUDIES

In this chapter, the experimental studies about radio signal propagation in underground mines and the implementation of a WSN for underground mine monitoring were explained. In the first part, signal attenuation properties of the various materials frequently encountered in underground mines were tested during the radio signal and frequency experiments. In the second part, radio signal ranges of the wireless modules were measured for indoor and outdoor experiments. In the third part, a wireless sensor network for monitoring underground workplaces was implemented and tested with different scenarios. Finally, the wireless connectivity of the developed wireless nodes was tested under the ground.

6.1 Radio Signal and Frequency Experiments

Establishing a reliable and effective communication system is always a desirable objective for providing safety and efficient mining operations (Moridi et al., 2014). However, providing a reliable communication system for underground mining is difficult due to the harsh environment and the changing topology of the underground mining workplaces. The signal propagation through the tunnels, mining galleries or obstacles encountered in mines are different from the terrestrial applications. The radio signals may be weakened or reflected from the mining faces, walls, corners or obstacles of the mining workplaces (Forooshani et al., 2013). In this chapter, the radio signal delivery through different materials, which are often encountered in underground coal mines, has been investigated. The most frequently encountered materials in underground coal mines are:

- Marl rock.
- Lump of marl.
- Lump of coal.
- Coal dust.

For the analyses, samples of these materials from Soma Eynez Underground Coal Mine were supplied by the professors of Dokuz Eylul University, Engineering Faculty Department of Mining Engineering.

The marl rock is shown in Figure 6.1a and lump of marl is shown in Figure 6.1b. The lump of coal is shown Figure 6.2a and coal dust is shown in Figure 6.2b. In order to make a proper radio signal tests over these materials a 5 cm diameter hole is opened into the marl rock samples.

a) b)

Figure 6.1 Marl material samples: a) Marl rock, b) Lump of marl.

a) b)

Figure 6.2 Coal material samples: a) Lump of coal, b) Coal dust.

Radio frequency and signal strength test were performed in Signal Laboratory of Dokuz Eylul University, Engineering Faculty Department of Electrical and Electronics Engineering. In the Signal Laboratory, an anechoic chamber is located (Figure 6.3).

Figure 6.3 Anechoic chamber at Signal Laboratory of Electrical and Electronics Engineering.

The anechoic chamber is a specially designed cabinet in order to completely absorb the reflections of either sound or electromagnetic waves. The inside of the chamber is covered with a signal damping material. This cabinet is specially designed to measure any kind of radio or audio signals without any noise and reflection.

A spectrum analyzer and two omnidirectional antennas were used to measure radio signal frequency and signal strength tests (Figure 6.4). Anritsu Spectrum Analyzer (MS2711D) is a handheld spectrum analyzer for installing, provisioning, maintaining and troubleshooting wireless systems and radio frequency spectrum interference issues.

Anritsu Spectrum Analyzer covers from 100 kHz to 3.0 GHz frequency range, with a build in standard pre-amplifier (Anritsu, 2007). The display of the spectrum analyzer represents the signal frequency on the horizontal axis and the amplitude on the vertical axis.

Figure 6.4 Anritsu spectrum analyzer and two omnidirectional antennas

In order to test various frequencies in the experiments, two OmniLOG 70600 omnidirectional antennas were used. The OmniLOG 70600 Antenna is a specially developed small and compact device for signal experiments. These antennas cover the frequency ranges from 680 MHz to 6 GHz (Aaronia AG, 2014).

6.1.1 Radio Signal Experiment with CC2541 SensorTag

In order to measure the signal attenuation through various materials, radio signal tests were performed by using TI CC2541 SensorTag kits in the Signal Laboratory. The properties of TI CC2541 SensorTag is given in Table 6.1.

Table 6.1 Properties of TI CC2541 SensorTag kit.

<table>
<tr>
<td></td>
<td>Properties:
• 2.4 GHz Bluetooth low energy Compliant
• Supports 250 kbps to 2 Mbps Data Rates
• Programmable Flash, 128Kb or 256Kb
• 8 KB RAM
• Software support.
• Compatible with Android or iPhone smart phones.</td>
</tr>
</table>

The results of the experiment revealed that the substance of the material had a significant effect on the radio signal propagation. It was observed that, the materials having higher densities weakened the signal strength more than the materials having low densities. For example, signal strength was weakening about 13 dB while passing through a 10 cm thick marl rock. The results of the experiments are given in Table 6.2.

Table 6.2 TI CC2541 SensorTag experiment with various materials

Measurement Medium	**Values (dBm)**
Reference	-52
Marl Rock	-64
Lump of Marl	-65
Lump of Coal	-57
Coal Dust	-53.7

Two different solutions are available in order to overcome signal attenuation. The first solution is to increase the radio signal strength to enlarge the range of signal coverage. However, the cost of increasing signal strength causes higher energy consumption for battery powered sensor nodes. The second solution is to change the frequency bands of the radio signal. Although the lower frequency bands have longer coverage ranges, the data transmission rates will be reduced accordingly. In next experiment, radio signal propagation properties of the various frequency bands were examined.

6.1.2 Radio Signal Propagation in Various Frequencies

During the experiments carried out, the radio signal propagation of different frequency bands through test materials encountered in coal mines were examined. For this purpose, conductivity of the test materials was tested in anechoic chamber by using Anritsu Spectrum Analyzer and two OmniLOG 70600 omnidirectional antennas. The frequency bands between 700 MHz to 2.5 GHz were investigated and the signal strength values of each frequency band was collected.

The Anritsu Spectrum Analyzer was used for both signal source and receiver. One of the omnidirectional antennas was placed top of the anechoic chamber and the other one was placed under the test material. The tests were performed with four different materials individually. The measurement results of four different materials are given in Figures 6.5, 6.6, 6.7, 6.8 and 6.9.

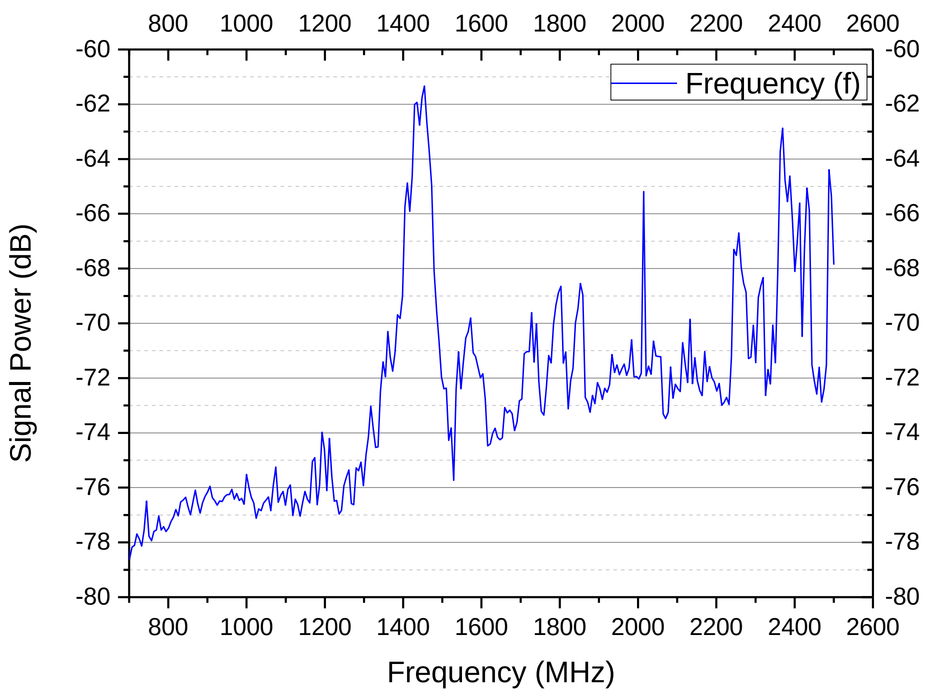


Figure 6.5 The reference measurement.

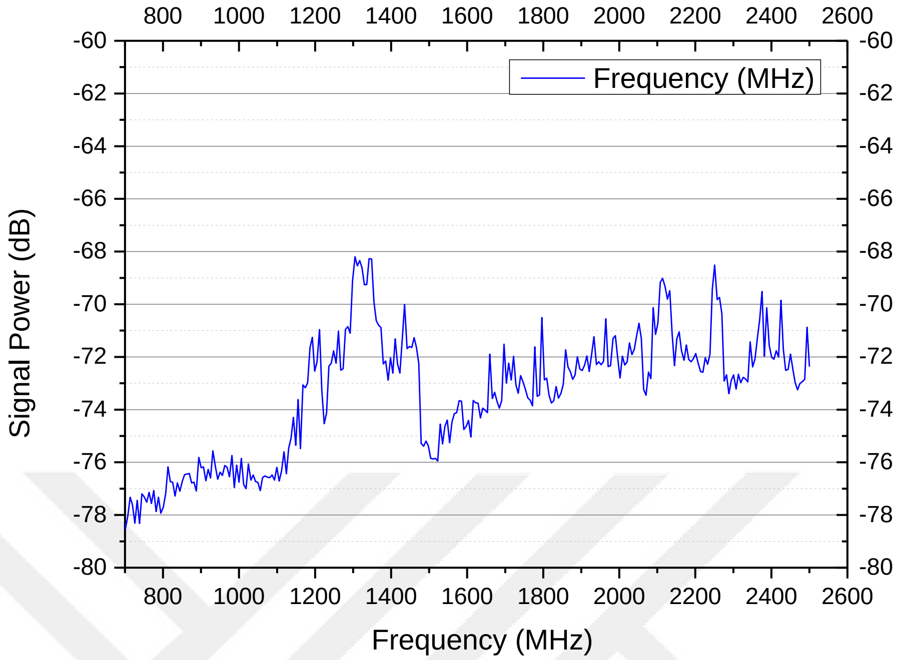


Figure 6.6 The measurement results of coal dust

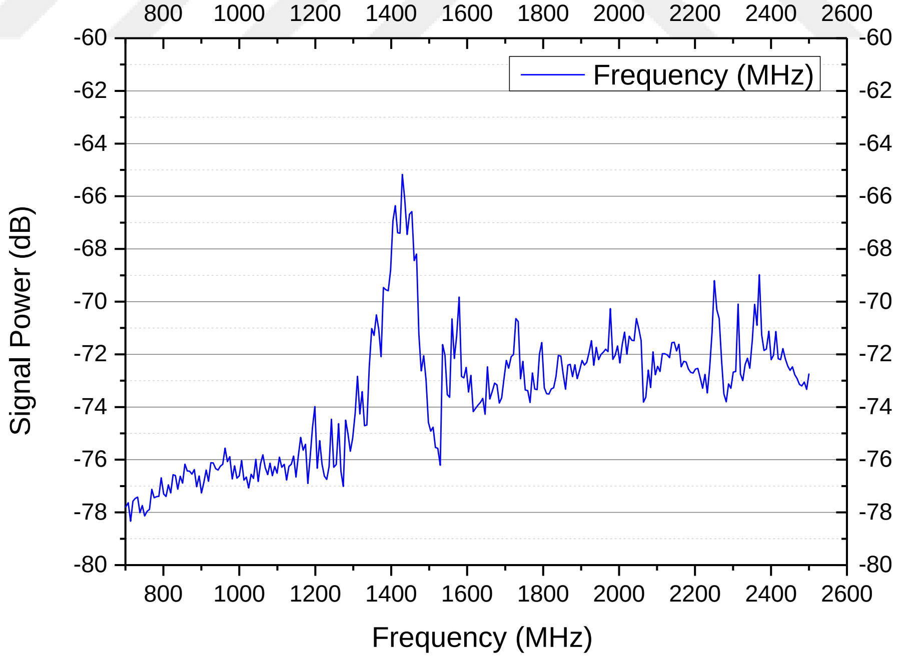


Figure 6.7 The measurement results of lump of coal

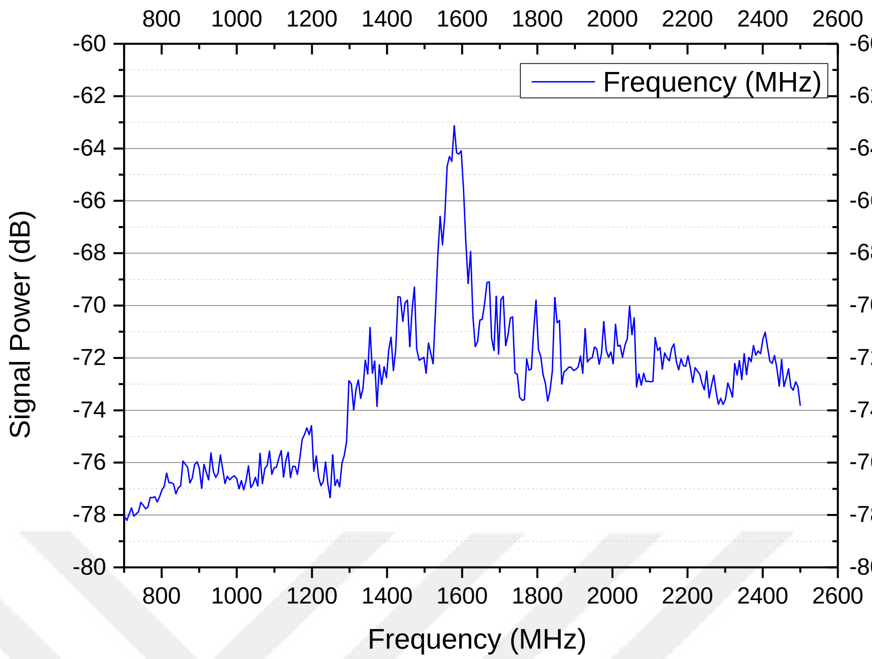


Figure 6.8 The measurement results of lump of marl

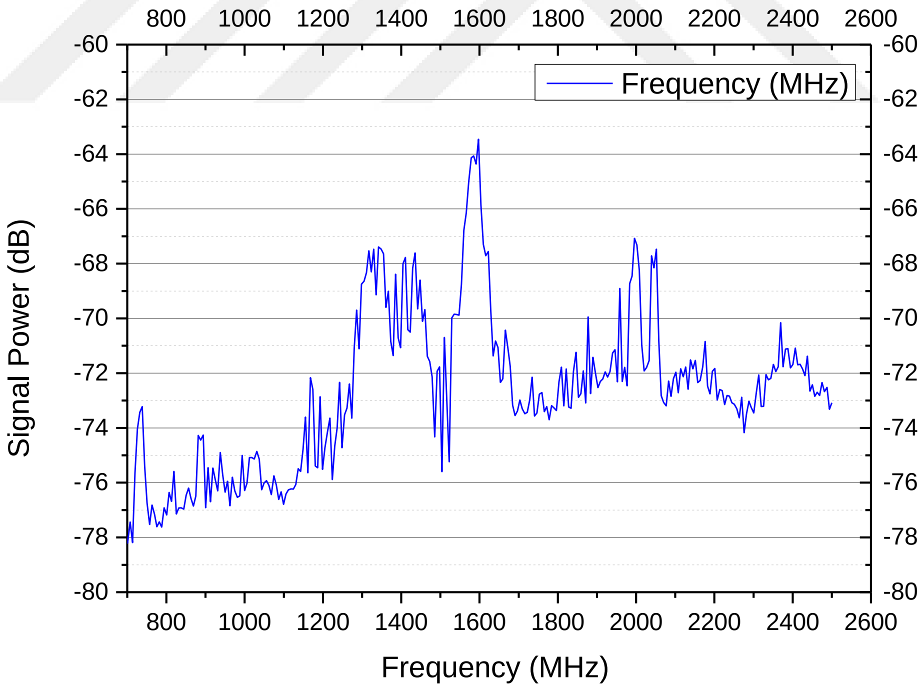


Figure 6.9 The measurement results of marl rock

According to the experiment results, the highest signal power of the coal dust, lump of coal, lump of marl and marl rock samples were recorded -68 dB at 1.304 GHz, -65 dB at 1.425 GHz, -63 dB at 1.578 GHz and -63 dB at 1.597 GHz frequencies respectively. The coal material reached the highest signal power between 1.3 GHz and 1.4 GHz frequency bands as shown in the Figures 6.6 and 6.7. However, marl material reached the highest signal power about 1.6 GHz frequency band (Figures 6.8 and 6.9).

The average signal strength values of the test materials used in this experiment is given in Table 6.3. The results of this experiment reveals that the signal power is reduced nearly all of the frequency bands between 700 MHz and 3 GHz. Moreover, the average radio signal power was nearly reduced about 5 dB between the 2.4 GHz and 2.5 GHz frequency bands when comparing the reference measurement with marl rock results. Although the marl rock and lump of marl have higher signal power at 1.6 GHz frequency bands, the coal dust and lump of coal have higher signal power between 1.3 and 1.4 GHz bands. After these experiments, it was seen that, the different kind of materials encountered in mines have different signal permeability.

Table 6.3 Average signal strength values of test materials

Measurement Medium	**Average Signal Strength Values (dB)**
Reference	-72.162
Coal Dust	-73.393
Lump of Coal	-73.559
Lump of Marl	-73.389
Marl Rock	-74.163

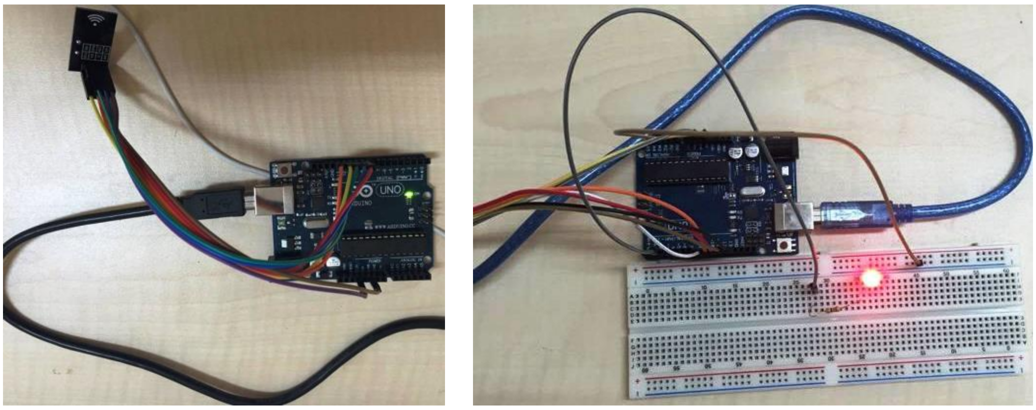
6.2 Signal Range Experiments of the Wireless Modules

The nRF24L01 radio modules used in this study have commercially available two versions; chip antenna and external antenna. Both of these versions were tested during the experiments. Both of the nRF24L01 modules supports 3 different data rates: 250 kbps, 1 Mbps or 2 Mbps. These modules can reach up to the highest radio signal range at 250 kbps data rate.

The signal range experiments could be categorized into two groups; indoor and outdoor experiments. The outdoor experiments were done in Tınaztepe Campus of Dokuz Eylul University, and the indoor experiments were done in the Embedded Laboratory of Computer Engineering Department. In order to determine the signal ranges of nRF24L01+ wireless modules, two sensor motes were developed for proper data transmission. One of these modules worked in sender and the other one worked in receiver mode.

6.2.1 Signal Range Experiments of the Chip Antenna Module

Radio signal test of the nRF24L01+ with chip antenna module was carried out for two different scenarios. In the first scenario, the highest signal range of the wireless module was measured in an empty straight corridor without any obstacles. Two sensor nodes were used for this issue. One of the sensor nodes worked as a sender (Figure 6.10a) and the other one worked in receiver node (Figure 6.10b). Both of the sensor nodes were worked on 250 Kbps data transfer rate with maximum signal power. According to our measurements, the nRF24L01+ modules were able to transmit data up to 70 meters in open filed experiments.



a) b)

Figure 6.10 Sensor nodes with chip antennas: a) Sender Node, b) Receiver Node.

In the second scenario, the radio modules were placed into a closed indoor room. According to the measurement results, the range of wireless module was excessively reduced and the radio signal could not be transmitted far than 20 meters behind a 50 cm concrete wall.

6.2.2 Signal Range Experiments of the External Antenna Module

The nRF24L01+ PA & LNA module uses an external monopole antenna for providing longer data transmission ranges (Nordic Semiconductor, 2008). The sensor motes by using Arduino Pro mini with nRF24L01 PA and LNA module was used for the radio signal range tests is shown in Figure 6.11.

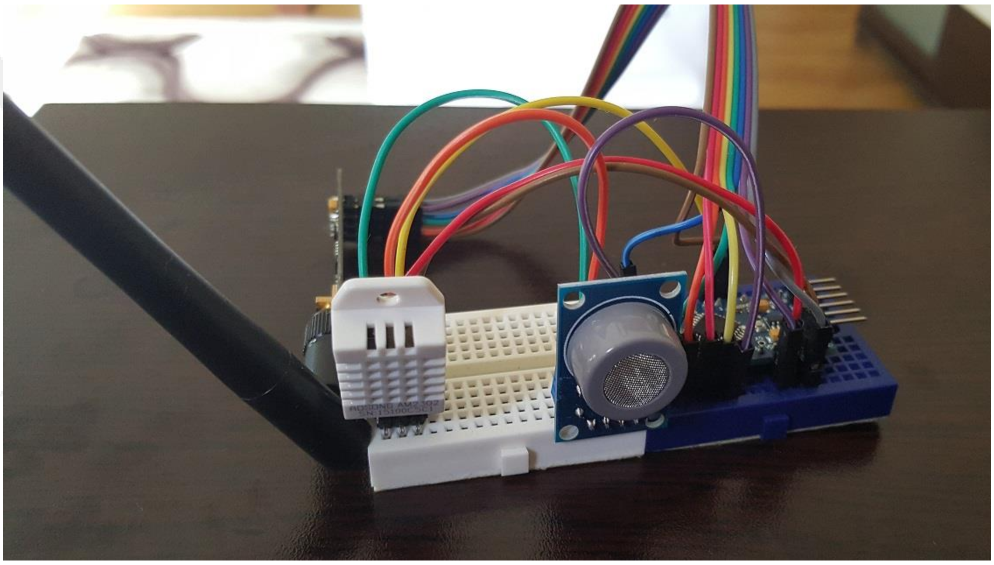


Figure 6.11 Sensor mote with monopole antenna.

In the first scenario, the highest signal range of the wireless module was measured in open field without any obstacles (Figure 6.12a). Both of the nRF24L01+ wireless modules were worked on 250 Kbps data transfer rate with maximum signal power. One of the sensor nodes works as a sender and the other one works in receiver node. According to our measurements, the nRF24L01with external antenna modules could transmit data up to 1000 meters in open field experiments.

a) b)

Figure 6.12 Pictures of the signal range experiments: a) Outdoor test area, b) Indoor test area.

In the second scenario, the sensor nodes were placed into an indoor area. The signal range of wireless module was tested behind the rooms inside the Computer Engineering Department (Figure 6.12b). The sensor nodes were tested for three different data transmission rates: 250 Kbps, 1 Mbps and 2Mbps. Two sensor nodes were used in the experiments. The sender node was placed into a closed room and the receiver node was moved inside the building in order to determine the maximum signal ranges behind the walls. The results of the radio signal range experiments for various data transmission rates was given in Table 6.4.

Table 6.4 Radio signal range experiments for various data transmission ranges.

Radio Signal Range	**Data Transmission Rates**		
	250 Kbps	**1 Mbps**	**2 Mbps**
12 m, no wall	OK	OK	OK
17 m, 2 walls	OK	OK	OK
50 m, 3 walls	OK	X	X
70 m, 3 walls	OK	X	X
28 m, 5 walls	OK	X	X
70 m, 4 walls	X	X	X

The sensor nodes with external antennas were tested for six different scenarios. The distance between sensor nodes was increased until the data transmission had failed. The sensor node could transmit data signals up to 28 meters behind four walls. There are 5 rooms between the sender and receiver nodes and each room was separated with a 20 cm thick wall. The signal attenuation was excessively high; therefore, the sensor nodes could not be placed far than 25 meters between them.

The results of the indoor experiments show that the maximum range of a sensor node should not be more than 25 meters for indoor implementations. For this reason, the maximum coverage range of two sensor nodes cannot exceed 50 m diameter circular area in theory. This range is not enough for wide underground mine monitoring applications. In order to widen coverage area of sensor nodes two solutions can be implemented. The first solution is to increase radio module signal strength. Radio module signal strength broadened the wireless access area, however, the power consumption of the sensor network is also increased. The second solution is to implement a multi-hop wireless sensor network by adding extra nodes for providing data transmission resulting a cost increase.

6.3 Designing a Wireless Sensor Network Topology for Underground Mining

The structure of the underground network topology is effected by the structure of underground mining filed, tunnels and the ore body (Akyildiz & Vuran, 2010). The terrestrial WSN architectures cannot be used for WUSN without making any changes due to the propagation characteristics of the electromagnetic signals. In addition, the original radio signal is distorted because of the signal reflection, diffraction, refraction and scattering from the surfaces of underground mines (Forooshani et al., 2013).

In order to implement a reliable wireless sensor network topology for underground coal mine monitoring application, several investigations about Arduino platform suitable libraries (Ekblad et al., n.d.; “Mirf library,” n.d., “RF24Network Library,” n.d.) were carried out by different researchers. Among of these studies, MySensors library developed by Henrik Ekblad and his team mates was selected to use in this study (Ekblad et al., n.d.). MySensors library allows users to build up wireless networks with Arduino modules. This library also supports Arduino suitable embedded boards, nRF24L01 wireless modules and RFM69 wireless modules.

MySensors library is using a tree like network topology as given in Figure 6.13. The sensor network can include three types of nodes which are sensor nodes, repeater nodes and the gateway node. Sensor nodes continuously check the attached sensors and send the sensorial data through the wireless network. These nodes can be slept if it is preferred to run them with battery. Repeater nodes are used to transfer data packets forward to the gate way node. These nodes are used to enlarge the coverage area of the sensor network. The gateway node is working as a base station and collects the all data coming from the sensor nodes. The gateway node is also responsible from the communication between the controller and the sensor network.

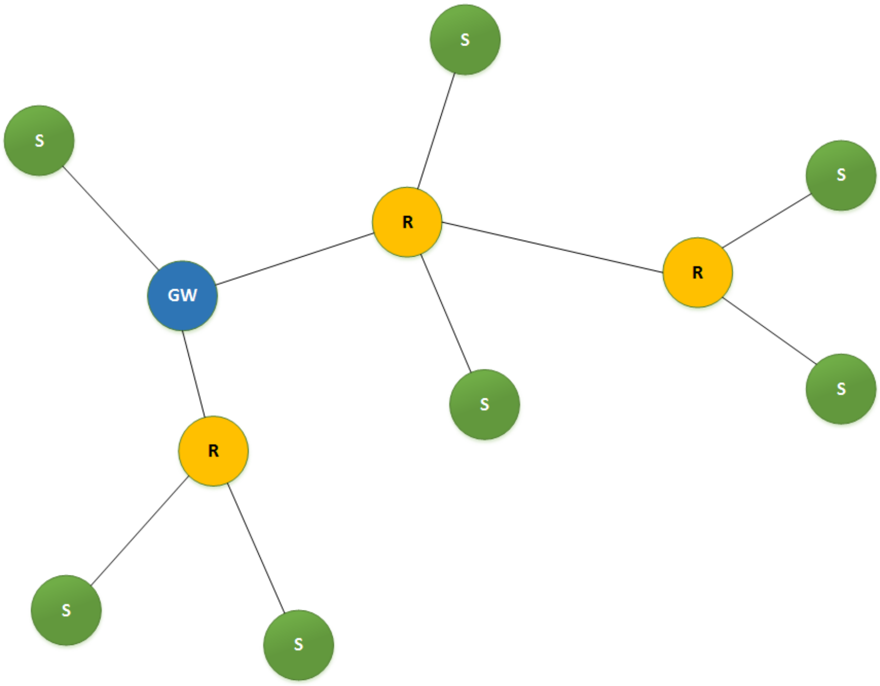


Figure 6.13 MySensors tree like wireless network topology.

Each sensor node in the network has a unique sensor identification number called "sensor id (SID)" that is used for sending or receiving messages. In this study, the SID numbers are assigned to each sensor node statically because the positions of the sensor nodes will be defined by SID numbers. MySensors library can support 254 different wireless nodes and each node can report data from 254 attached sensors. If more sensors are needed, it is possible to build up a parallel network on a different radio channel and there are 126 available channels (Ekblad et al., n.d.). The protocol format of MySensors library is given in Figure 6.14. The nRF24L01+ has a maximum of 32-bytes payload size (Nordic Semiconductor, 2008). However, the MySensors library (version 1.5) uses seven bytes for the message header.

The message header includes the last SID of the last message passed repeater node, SID of the sender and destination nodes, protocol version, payload length, acknowledgement message (ACK) request and ACK indicator field in the network header. Type of the sensor, SID and data type fields are added to the network header for determining each sensor attached to the sensor node.

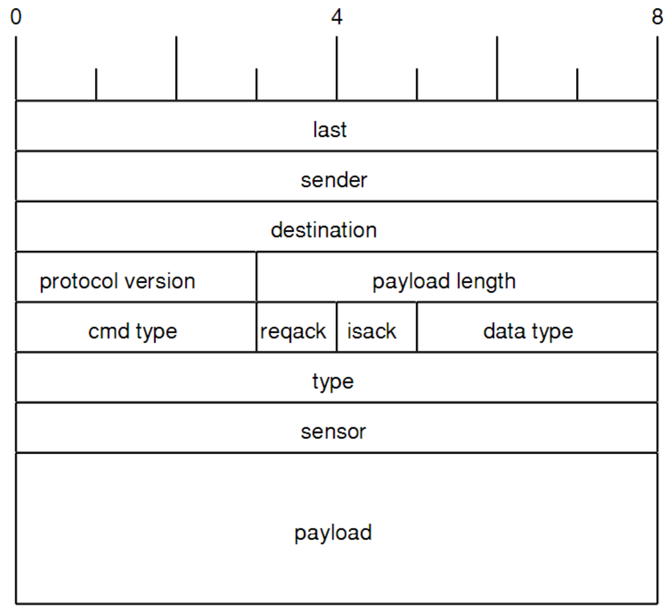


Figure 6.14 MySensors Library Protocol Stack (Ekblad et al., n.d.)

Sensor motes were developed by using Arduino Uno boards, nRF24L01+ chip antenna modules, DHT11, MQ-4 and MQ-7 sensors. The sensor motes were used to implement a multi-hop WSN for underground mine monitoring applications and the developed system was tested at the Dokuz Eylul University, Computer Engineering Department.

6.3.1 Wireless Sensor Network Implementation Experiments

In order to implement a WSN for underground monitoring, six new sensor nodes were deployed into the WSN (Ünsal, Milli & Çebi, 2016). The sensor nodes were placed nearly two meters to each other in the Embedded Laboratory of Computer Engineering Department. The deployed WSN architecture is given in the Figure 6.15.

The numbers given in Figure 6.15 represented the SID. Each sensor node in the network had a unique SID number. SID numbers were static and given to each sensor node before adding them into the network. Moreover, each sensor node was aware of SID of its destination sensor node for data transmission.

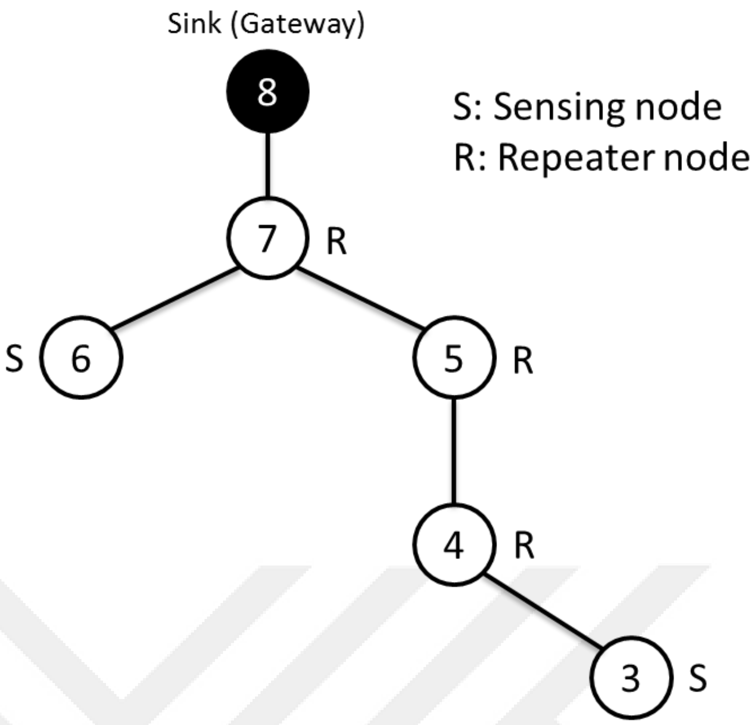
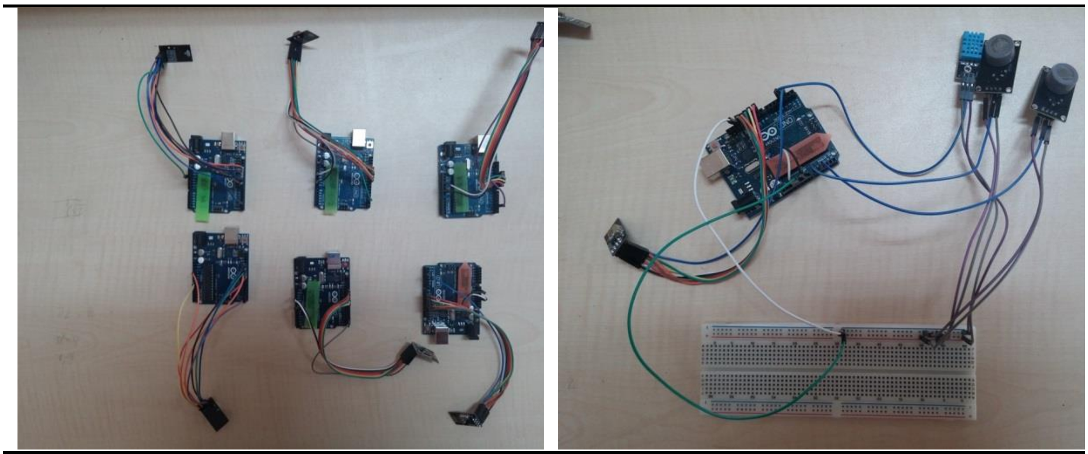


Figure 6.15 The multi-hop WSN architecture for environment monitoring.

The nodes with SIDs 3 and 6 were working as sensing nodes which collected data from environment and transmitted to its destination node. The node with SID 8 was working as a gateway node and all the incoming data from the sensor nodes were collected from gateway node. Moreover, gateway node was also connected by a computer via universal serial bus (USB) port to collect and store the incoming data from the WSN. The nodes with SIDs 4, 5 and 7 were used as repeater nodes which were used for routing the data from low order sensor nodes to the gateway. Repeater nodes could allow multiple sensor nodes to transmit their data.

The sensor motes used in this experiment were developed by using Arduino Uno boards, nRF24L01+ chip antenna modules, DHT11, MQ-4 and MQ-7 sensors. The gateway and repeater nodes were given in Figure 6.16a and the developed sensor nodes with DHT11, MQ-4 and MQ-7 sensors were given in Figure 6.16b.



a) b)

Figure 6.16 The wireless sensor motes: a) Repeater and gateway motes, b) The sensor node

6.3.2 Expanded Wireless Sensor Network Experiments

The wireless coverage area of the WSN was expanded and the sensor nodes were placed in different laboratories in this experiment. The test area was carried from the Embedded Laboratory to the Computer Laboratory Block of the Computer Engineering Department, which includes 7 separate computer laboratories and a free study space for students. The physical placement of the computer laboratory blocks and the dimensions of the laboratories are given in Figure 6.17.

Each sensor node was placed in the corner of a different computer laboratory and the repeater nodes were placed at the center of the corridor. The gateway node was placed in the free study space for students. All the placement of the sensor nodes was given in Figure 6.17 The doors of the computer laboratories were closed during the experiments.

The WSN consisted of 10 nodes and each node had a unique and static SID. This SID was given to each node before adding them into the sensor network. In this way, the physical placement of each sensor could be determined from the predefined sensor SID. Moreover, the physical placement of a sensor nodes was very important for the real world underground WSN implementations.

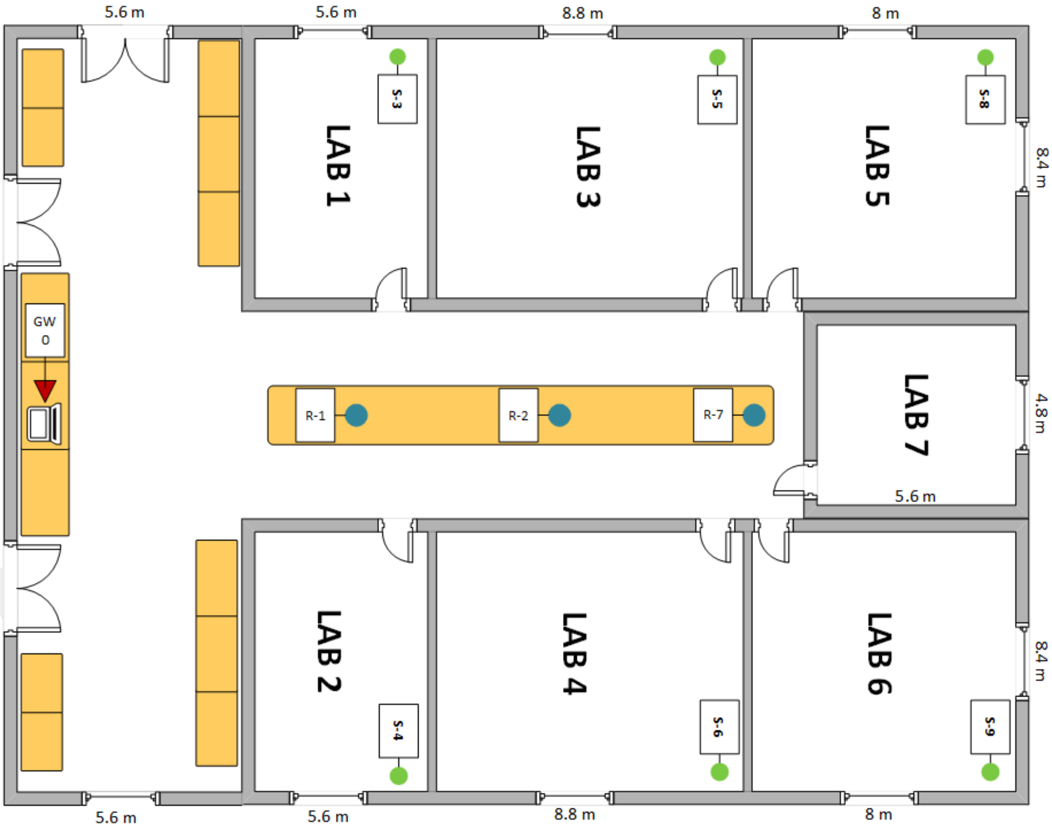


Figure 6.17 The placement of the sensor nodes and physical placement of the computer laboratory block of Computer Engineering Department.

Sensor nodes with SIDs 3, 4, 5, 6, 8 and 9 were working as sensing nodes which were responsible from monitoring the environment. The nodes with SIDs 1, 2 and 7 were repeater nodes and node with SID 0 was the gateway node. The WSN architecture was represented in the Figure 6.18. The deployed WSN had a tree based grid architecture. The distance between sensor nodes and the repeater was nearly equal and about 8 meters. A sample of received data to the gateway node was given in Figure 6.19.

The physical properties of the sensor motes used in this experiment were the same as the motes used in the previous experiment explained in section 6.3.1.

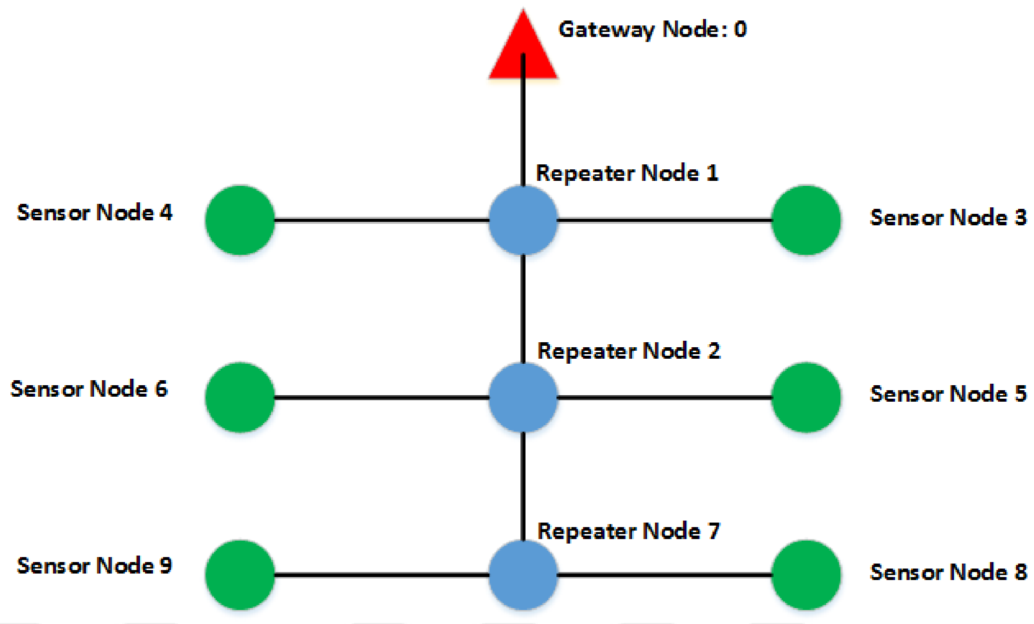
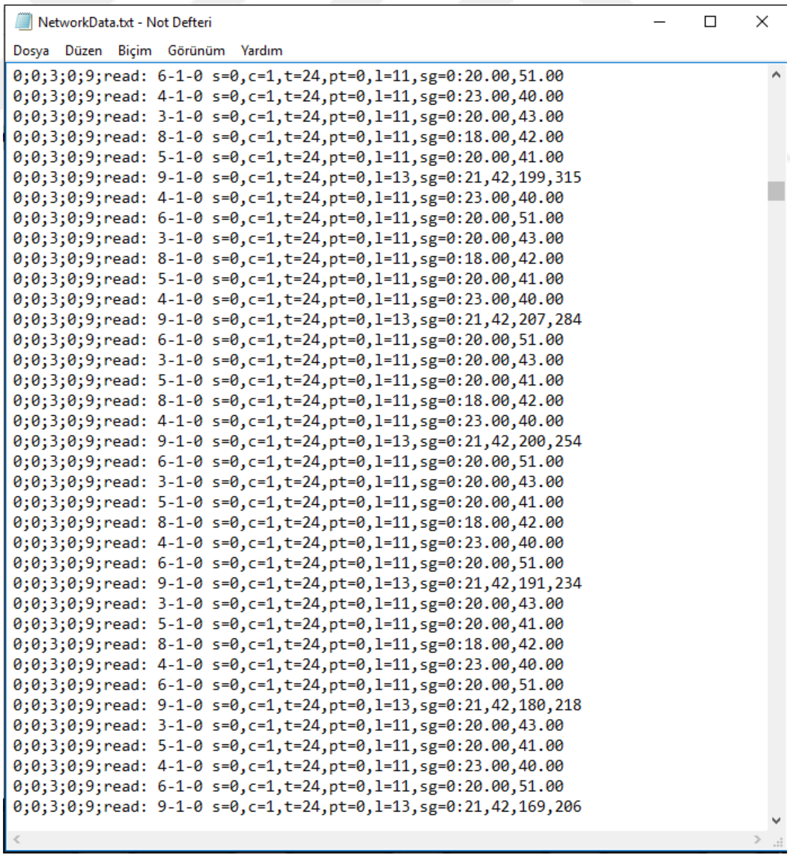


Figure 6.18 The WSN architecture of the expended wireless sensor network experiment.



NetworkData.txt - Not Defteri

Dosya Düzen Biçim Görünüm Yardım

```
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 8-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:18.00,42.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,199,315
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 8-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:18.00,42.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,207,284
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 8-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:18.00,42.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,200,254
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 8-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:18.00,42.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,191,234
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 8-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:18.00,42.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,180,218
0;0;3;0;9;read: 3-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,43.00
0;0;3;0;9;read: 5-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,41.00
0;0;3;0;9;read: 4-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:23.00,40.00
0;0;3;0;9;read: 6-1-0 s=0,c=1,t=24,pt=0,l=11,sg=0:20.00,51.00
0;0;3;0;9;read: 9-1-0 s=0,c=1,t=24,pt=0,l=13,sg=0:21,42,169,206
```

Figure 6.19 Sample of sensor network data received to gateway node.

In the second experiment, in order to test the signal range of the sensor motes with chip antenna modules, two sensor nodes were placed in computer laboratory 1 and laboratory 2. A repeater node was placed outside the computer laboratory 1 and the gateway node was placed outside the computer laboratory 2 as shown in Figure 6.20. The signal ranges of sensor nodes behind the walls was tested. Both of the sensors were able to transmit their data without any loss.

Figure 6.20 The placements of the sensor nodes in the second experiment.

In the third experiment, in order to block data communication between sensor nodes and the gateway node, the gateway node was moved from Computer Laboratories Block to Academic Stuff block which was 29 meters far from the repeater node as shown in Figure 6.21. As expected, the data transmission was lost because the gateway was placed into a distant room. In order to establish the data transmission again a new repeater node is added between the gateway and the previous repeater node.

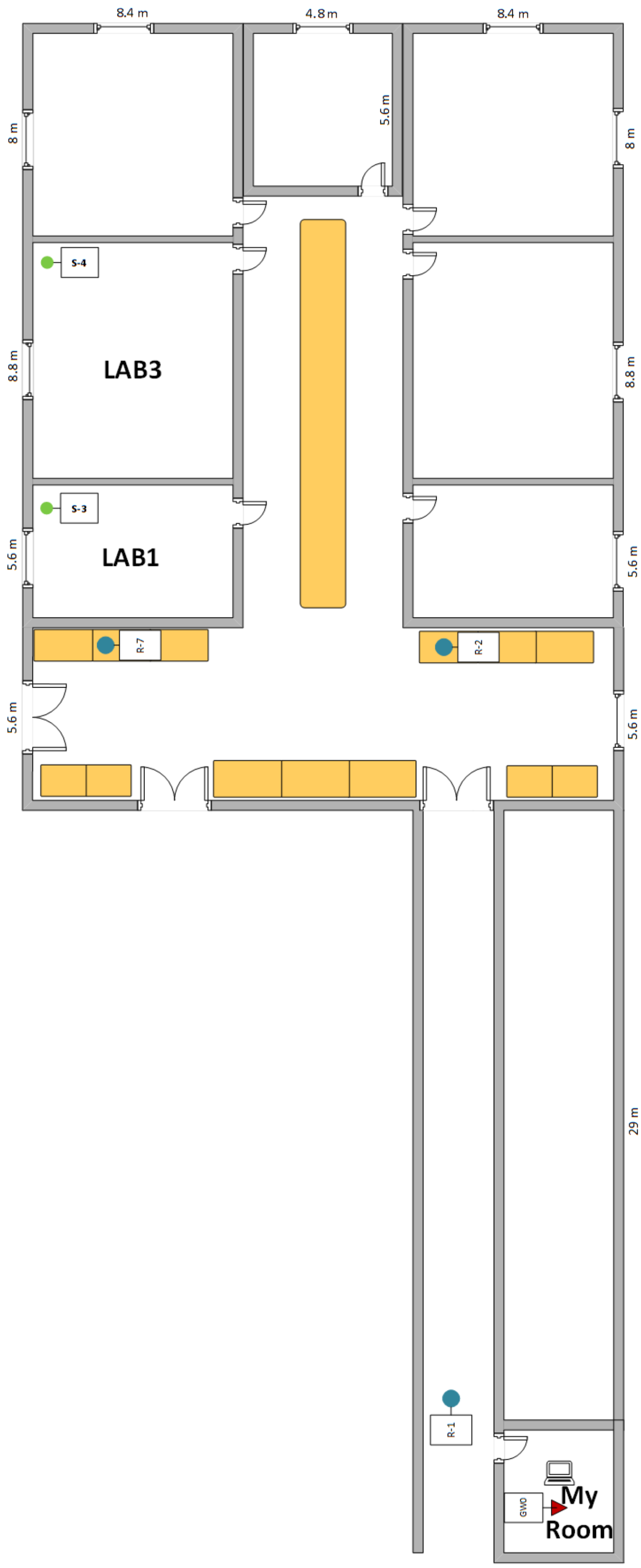


Figure 6.21 Move the gateway node to a distant room from the Computer Laboratory Block.

6.4 Underground Wireless Sensor Network Experiments

In the last step of the experiments, the final developed sensor motes after combining the nRF24L01 wireless module with external antenna, Arduino Pro Mini 3.3 V embedded board, DHT22 and MQ-9 sensors together, were tested under the ground. The wireless sensor mote was placed into a IP65 standard waterproof box and powered with a 3.6 V lithium thionyl chloride battery as shown in Figure 6.22.

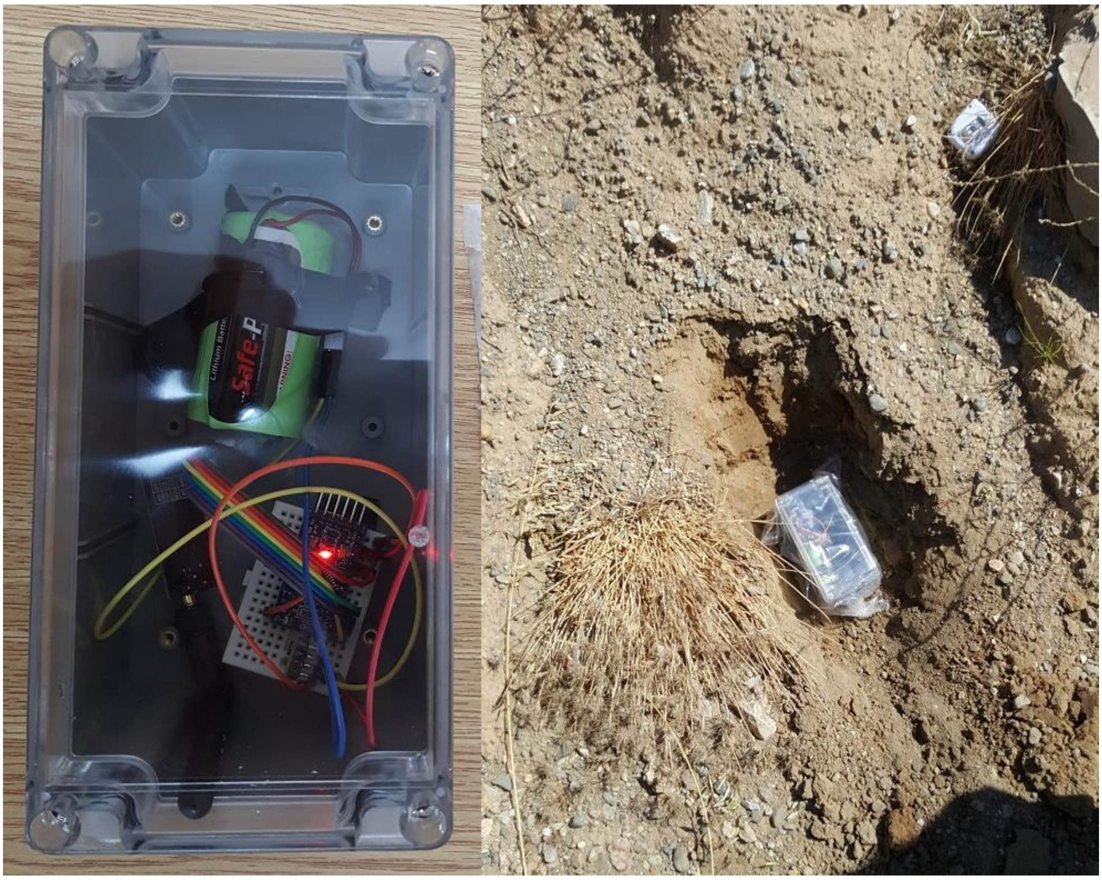


Figure 6.22 Sensor node into a IP65 box and buried under a soil hill.

In this experiment, the sensor node was buried under the soil and the range of the radio signal was tested. The wireless module worked at 250 Kbps data transmission rate with the highest power. Two sensor nodes were used during the experiments. One of them worked as a sender and the other one was worked as a receiver. The boxed sensor node (sender) was buried under the soil about 40 cm deep and the digged pit was filled by soil and rocks as shown in Figure 6.23. The data signal of the sender node signal could be taken from 15 meters from the receiver node.

Figure 6.23 The sensor node was buried under the soil and the range of radio signal is tested.

CHAPTER SEVEN
SOFTWARE IMPLEMENTATION

In order to understand developed applications to ensure safety of the underground mining workplaces, it is better to follow a top-down approach to examine its structural design. Initially, an entire and simple sketch of the developed applications will be displayed (Figure 7.1), and explanations of each part will be explained.

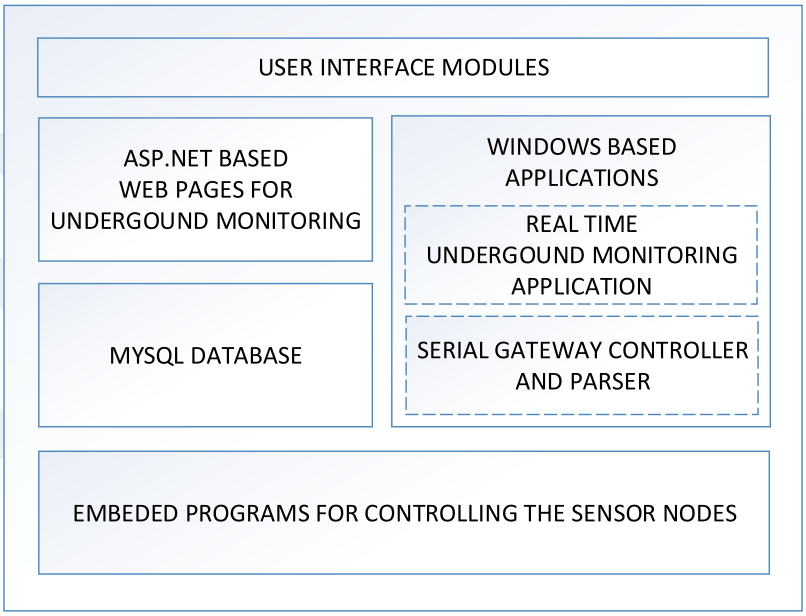


Figure 7.1 Block diagram of the developed applications for underground monitoring system.

The developed applications can be categorized into three groups. First, embedded wireless node applications and an adaptive underground monitoring algorithm were developed to control and manage the sensor nodes. Second, a windows based underground monitoring application was developed to monitor and visualize the collected data from the WSN. Moreover, the developed windows application could visualize the statistics of the stored sensor values of any selected sensor node. A MySQL database system was used to store parsed sensor values by the serial controller and parser program. Third, an ASP.NET based web application was developed to display the sensor network statistics of each parameter graphically from a webpage.

7.1 Developed Embedded Applications for the Sensor Nodes

In order to control the sensor nodes in the WSN, embedded wireless sensor node applications were developed at Arduino IDE. The proposed WSN for underground mine monitoring included three types of nodes; a gateway node, repeater nodes and sensor nodes.

The gateway application was responsible from the management of the gateway node. The gateway node collected all incoming messages from the sensor nodes and transferred the incoming data to a controller program over the serial interface. The repeater program was responsible from to manage repeater nodes and forwarded the incoming sensor node packets to its destination node. The sensor node application control and manage the sensor nodes by using an adaptive underground monitoring application.

7.1.1 Adaptive Underground Monitoring Algorithm

In order to control sensor nodes and reduce the power consumption of this nodes, an adaptive underground monitoring algorithm was developed for this purpose. The flow chart of the developed Adaptive Underground Monitoring Algorithm is given in Figure 7.2.

At the time of boot up, each sensor node calibrated its gas sensor and calculated Clean Air Resistance Value (R_0) of the gas sensor. After the calibration process, the sensor node started to monitor environment with a default wake up and sleep period. If the sensor readings were above any of the predefined threshold values, the sensor node immediately reduced the wake up and sleep period 10 times shorter than default to check the risky areas more often. Moreover, when the sensor readings did not exceed the threshold values; however, the differences between the last two sensor readings getting raised more than an expected value then the wake up and sleep period were reduced by the half of the default wake up and sleep period. The developed adaptive underground monitoring algorithm provides sensor nodes to adapt quickly to the changes in the underground workplaces with low power consumption properties.

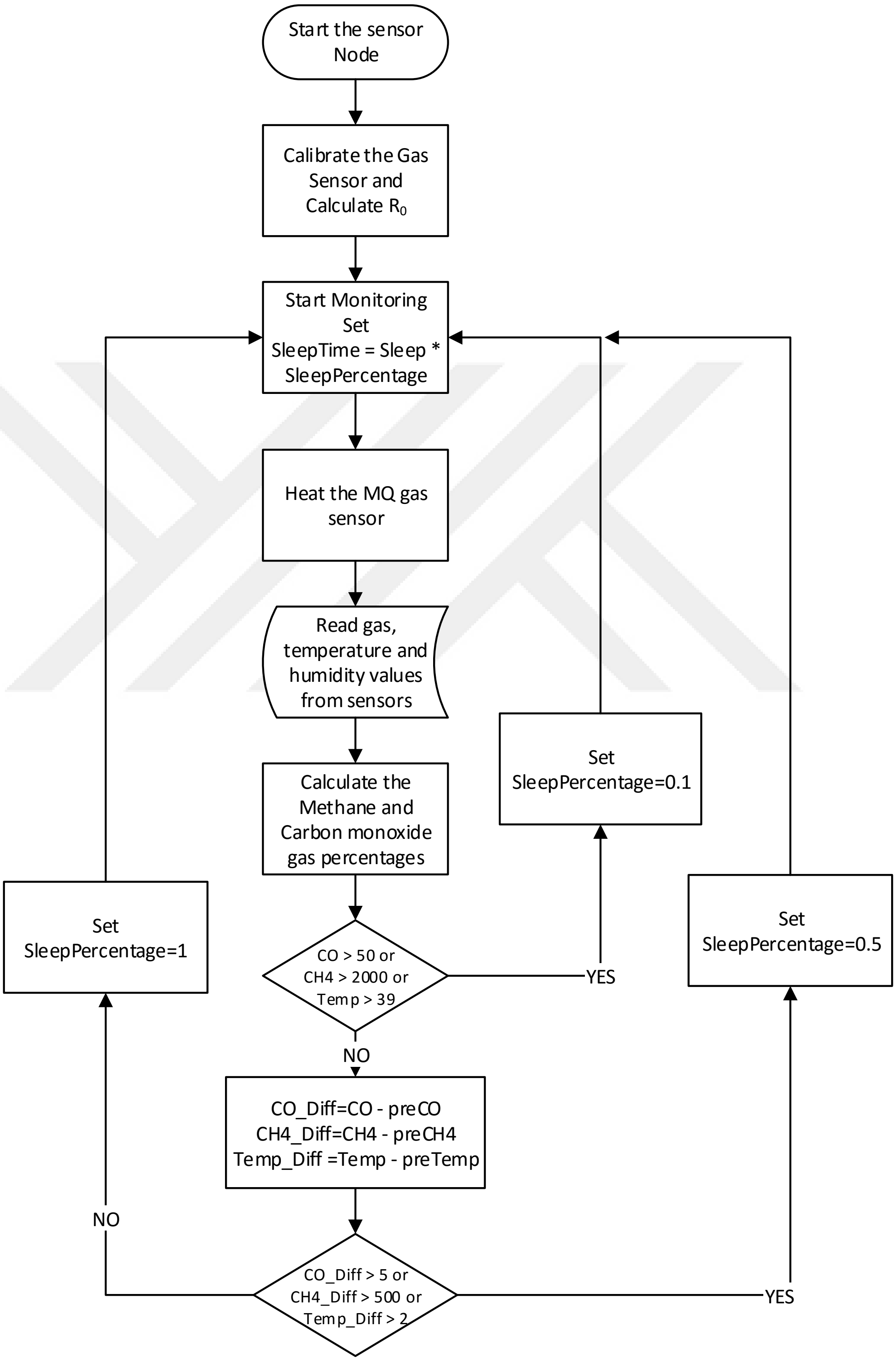


Figure 7.2 Flowchart of the Adaptive Underground Monitoring Algorithm

7.2 Windows Application to Monitor Sensor Network

In order to store and display the incoming data from the sensor network a windows based underground monitoring application was developed (Figure 7.3). This application was programmed in C# programing language at Visual Studio.NET 2015 platform (Microsoft, 2015b). The incoming sensor values from the sensor nodes were stored into a MySQL database. The incoming message was parsed by a parser program before saving the sensor readings of each sensor node into the database. The parser program split the incoming message into pieces to extract the SID of sensor node, temperature, humidity, methane and carbon monoxide sensor values. After the parsing process, the sensor values of each sensor was saved into the database with adding a received date and time value.

The developed windows application could display the incoming sensor values of each sensor node into a gird view titled “Last Sensor Data”. Therefore, the security operator was able to trace each sensor node located into the underground working places momentarily. Moreover, this application allowed users to preview individual statistics for each sensor node.

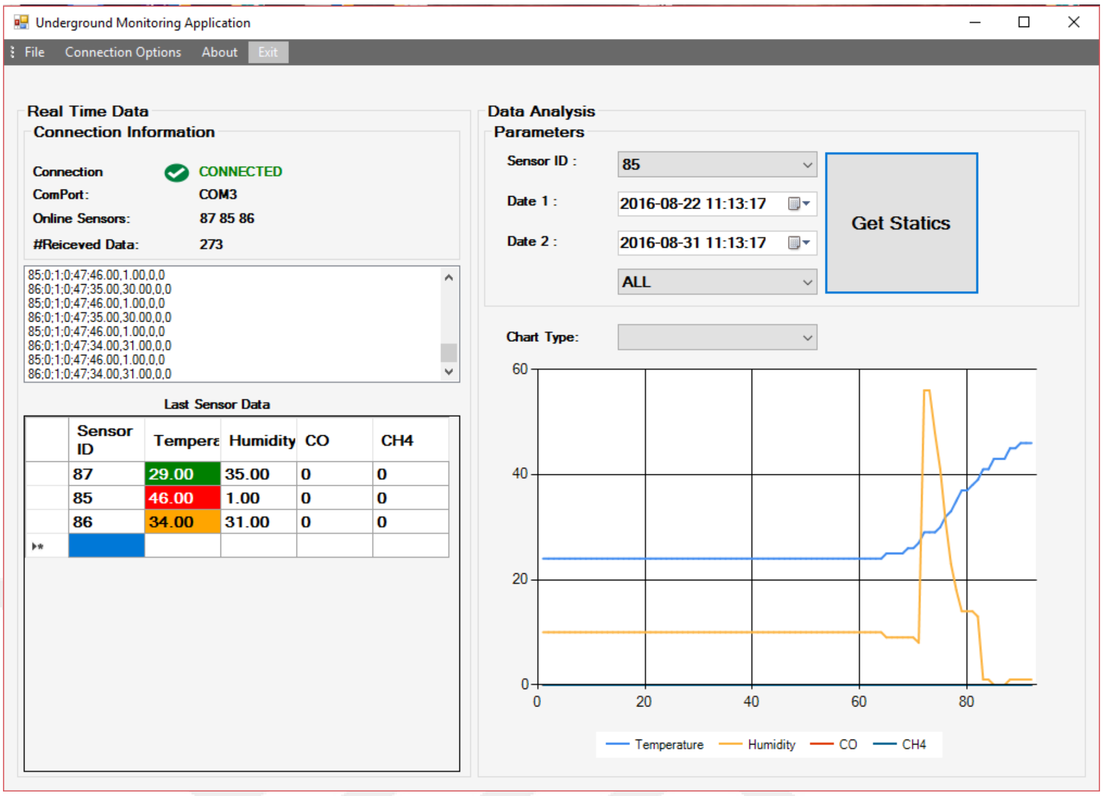


Figure 7.3 Underground mines monitoring application.

The underground monitoring application could display all the stored data of sensor nodes. This application includes a statistics section called "Data Analysis" to display sensor node statistics. The Data Analysis section takes five parameters from the uses to display a graphic. The first parameter was SID, second and third parameters determined the start and stop dates of the statistic. The fourth parameter was the type of sensor and the last parameter was chart type. The program could draw three types of charts as line, bar or points. For instance, the sensor node with SID 3 methane gas sensor values were displayed into a line graph on Figure 7.4.

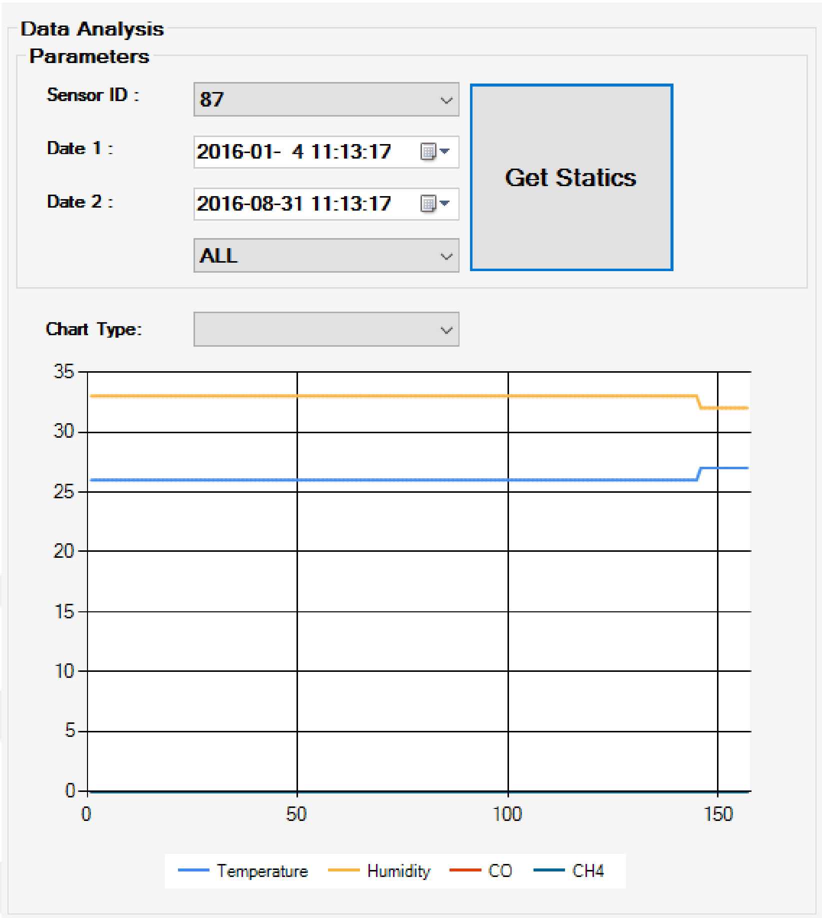


Figure 7.4 Data Analysis section of the underground monitoring program.

7.3 Web Application to Monitor Sensor Network

In order to monitor the developed WSN for underground mining workplaces from Internet, a web based monitoring application was developed. The web application is developed on ASP.NET on Visual Studio.net 2015 platform (Microsoft, 2015a). This application displays the temperature, humidity, methane and carbon monoxide gas sensor values of the selected sensor nodes from a web-based user interface (Figure 7.4). The developed web application takes a date range and SID from the user and represent the statistics of the sensor values into a line chart. The charts used in the web applications were prepared by using a JavaScript library called Highcharts.

Highcharts library is developed by Highsoft Company (Highsoft, n.d.). Highcharts supports a noncommercial license for personal or non-profit projects under the Creative Commons Attribution-NonCommercial 3.0 License.

In order to improve the visual representation of the graphics, temperature and humidity values represented together into the same chart (Figure 7.5). Additionally, the methane and carbon monoxide values were also represented together into another chart (Figure 7.6).

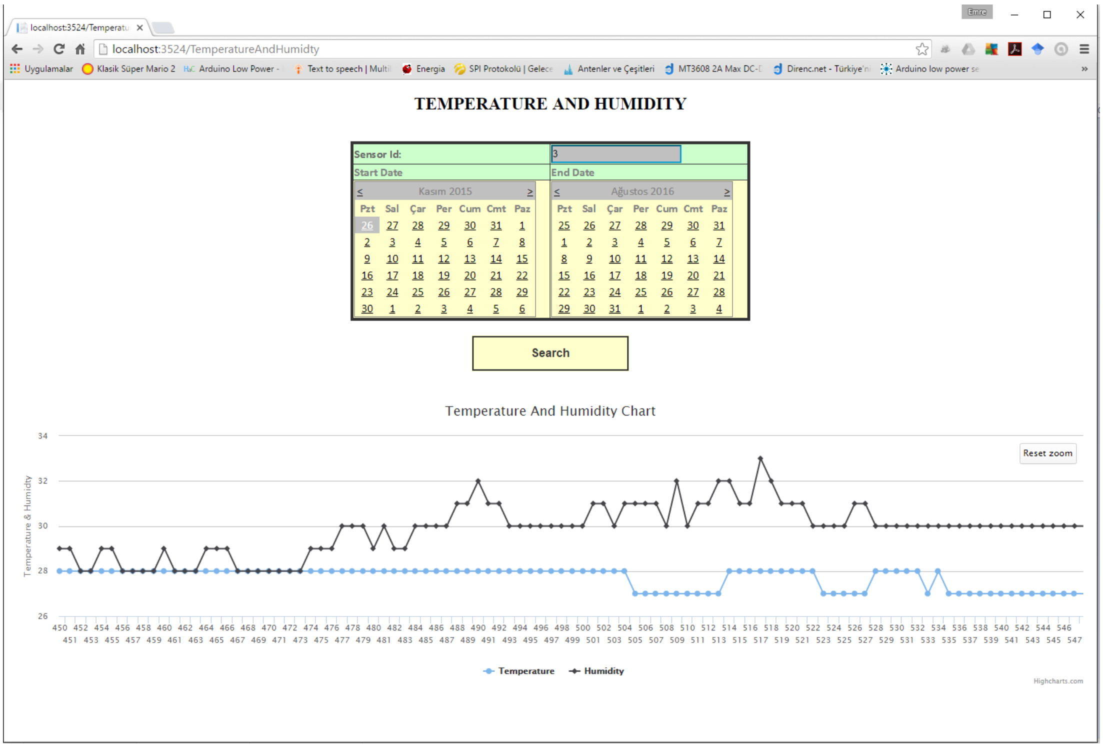


Figure 7.5 Temperature and humidity values over web interface

Highcharts supports the Visual Studio.Net platform and it can be integrated with the ASP.NET web applications. The library allows user to auto zoom over the graphics or focus one of the parameters on the graphic as shown in Figure 7.7.

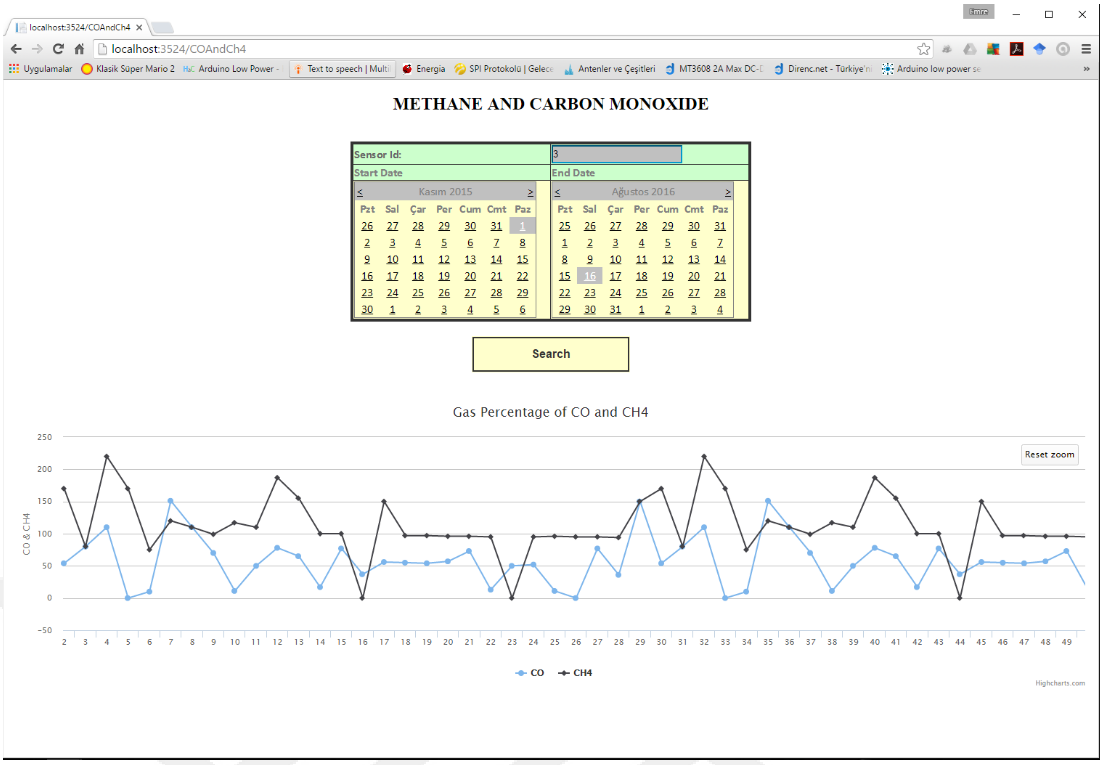


Figure 7.6 Methane and Carbon monoxide values over web interface

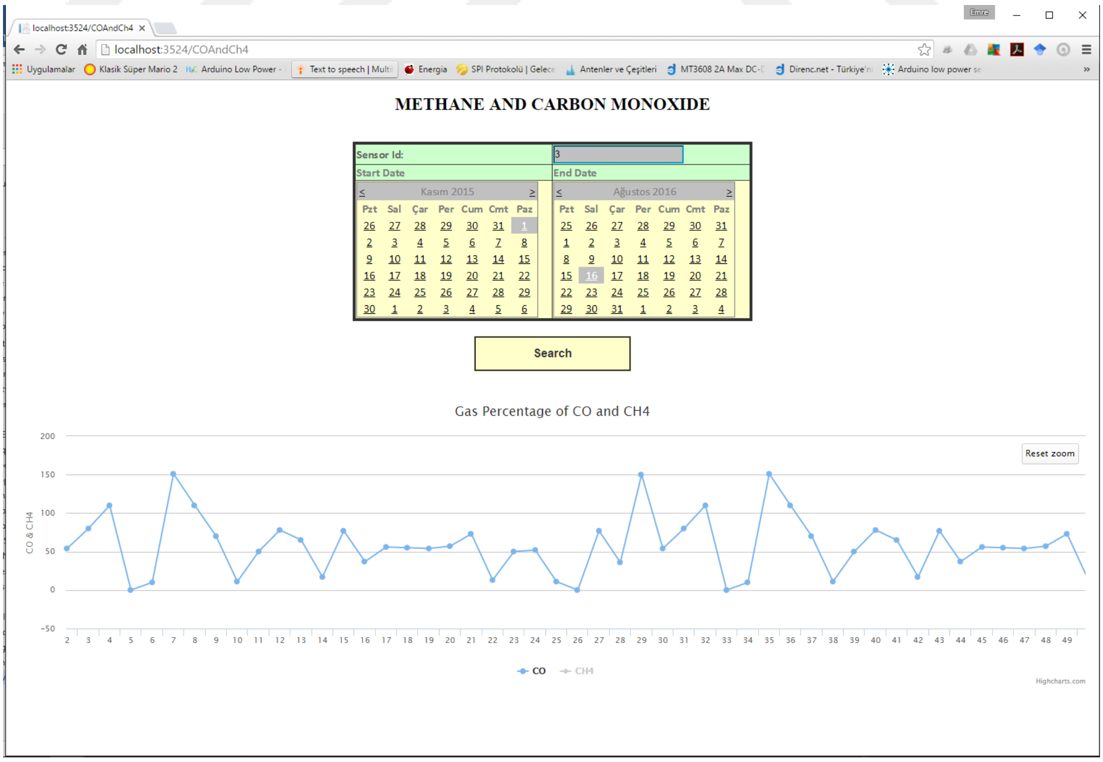


Figure 7.7 Web Application for underground mine monitoring

CHAPTER EIGHT
CONCLUSION

Underground mines are one of the most difficult working places in the world. The, lack of light, fresh air, electrical energy and the harsh environment makes this industrial filed more challenging. In order to avoid underground coal mining accidents generally caused by methane and consecutive coal dust explosions or toxic gas leakages such as carbon monoxide, several critical parameters for underground mines should be monitored periodically. However, the lack of electricity behind or under the mining faces and abandoned areas, deploying a wired underground mine monitoring system is getting more challenging. Rapid topology changes and unexpected accidents such as cave-in or landslides causes to redeploy the wired monitoring system which requires high costs.

In order to reduce the cost of underground mine monitoring systems and to extend its coverage area, deploying a monitoring system based on a WSN is a good solution. Although, there were similar studies to monitor underground mining workplaces in the literature, most of these studies are using commercially sold sensor motes which are designed for terrestrial sensor network applications and sold with high prices.

In this study, a low-cost, low-power WSN architecture is proposed to monitor active and abandoned underground mining workplaces. The proposed sensor network will monitor the presence of temperature, humidity, methane and carbon monoxide gas percentages from underground mining workplaces for preventing accidents or disasters.

In order to monitor underground mining workplaces, a low-cost and low-power wireless sensor mote and network architecture is developed by using Arduino platform. The cost of the sensor mote is suitable for small budgets. The network topology of the developed WSN is based on a tree like multi-hop grid network architecture to enlarge coverage area of the wireless network.

One of the main objectives of this study is optimizing the energy efficiency of the sensor nodes which is the most important tasks for battery powered underground WSNs. The power management methods are discussed and the implementation of these methods to the sensor nodes is explained in this study. After the experiments carried out it was seen that, by reducing the sampling period to one hour, the lifetime of a sensor node can be extended to 59 times longer than standard. The lifetime of the sensor nodes can be extended to 328 times at 8 hours sampling period.

Radio signal propagation and the coverage are of the developed sensor network are tested under the indoor and outdoor experiments. The maximum ranges of the used wireless modules are determined for underground and over ground experiments. In addition, the propagation of the electromagnetic waves through to various kind of materials which are frequently encountered in coal mines is examined. The results reveals that the different materials have different signal permeability. Although, the coal material reached the highest signal power between 1.3 GHz and 1.4 GHz frequency bands, marl material reached the highest signal power about 1.6 GHz frequency band. Additionally, signal attenuation reaches about 2 dB for marl rock.

Static and unique SID is given to each sensor node in order to determine their placement in the mining workplaces. The sensor nodes sense the environment and send the collected data through to wireless network. Therefore, an adaptive underground monitoring algorithm was developed to control and reduce the power consumption of sensor nodes. The gateway node collects all the incoming data and forward to the controller and parser application. The controller application parses each of the incoming data and store them into a MySQL database system. Moreover, the developed environment monitoring application is used to display the collected data from the WSN.

In the future work, the developed sensor nodes can be improved to monitor more parameters by adding new sensors. Another improvement will be the determination of the positons of the miners in the mining work places. A new antenna design and implementation will be required for extending the coverage area of underground communication. In addition, data aggregation and mining techniques may be tested over the collected real sensor network data. Eventually, a new clustering algorithm will be added to improve the developed sensor network reliability.

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