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Routing of emergency data in a wireless sensor network for mining applications

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ROUTING OF EMERGENCY DATA IN A WIRELESS SENSOR NETWORK FOR MINING APPLICATIONS

By

Mandana Jafarian

**B.Sc. in Computer Hardware Engineering
University of Tehran, Iran, 1999**

A thesis
Presented to Ryerson University
In partial fulfillment of the
Requirements of the degree of
Master of Applied Science
In the program of
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Abstract
Mandana Jafarian,
Routing of Emergency data in a Wireless Sensor Network for Mining Applications
M.A.Sc, Electrical and Computer Engineering, Ryerson University, 2007

Emergency situations in mines result in loss of precious human lives. In this thesis we discussed architecture of a Wireless Sensor Network (WSN) that can be deployed in mines, which takes care of severe geographical and environmental constraints found inside mines. The proposed architecture is a two-level hierarchy of small sized WSNs that employs a wireless Mesh network as the backbone connecting small sized WSNs scattered inside mines. We proposed a routing protocol for that WSN that is optimized for both emergency and non-emergency data routing. Since our main goal is to provide safety in the mining environment, the main consideration of the routing protocol is to provide reliability and reduce the end-to-end delay for vital emergency traffic while optimizing for network longevity for non-emergency traffic. We present a new cost-based routing protocol called MDML, which provides Minimum Delay and Maximum Lifetime routing for such networks. The proposed MDML routing defines separate cost metrics for emergency and non-emergency traffic. It finds the least-cost path for the reliable delay-constrained emergency traffic with regards to link error rate but also gives secondary consideration to nodes' residual energy. It is an energy efficient routing scheme for non-emergency or regular data traffic routing that maximizes the network lifetime. However, for emergency traffic energy efficiency is compromised to achieving minimal delay. Regular traffic is generated through periodic monitoring and is delay-insensitive. For regular traffic delivery, a shortest path routing algorithm is employed which uses link costs that reflect both the communication energy consumption rates and the residual energy levels at the two end nodes. Simulation results show that using the proposed emergency routes reduces the end-to-end delay for emergency traffic. The effect of protocol update cycle on increasing the network lifetime is verified true simulation. MDML is also compared with a simulated non-MDML approach to compare the lifetime and delay performance. Simulation results have demonstrated the effectiveness of our approach.

Keywords: Delay-constrained traffic, end-to-end delay, energy-constrained network, network lifetime maximization, power-aware routing, wireless sensor networks.

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To Kambiz, Azin, Matin, Babak, and my parents

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List of Abbreviations

[illegible]

1 Introduction

Wireless Sensor Networks (WSN) consist of small nodes with sensing, computation, and wireless communications capabilities. The infrastructure-less network design of sensor devices and their ease of deployment, makes WSN an attractive solution to problems in various domains. Sensor networks are typically proposed to deliver in situ observations at low cost over long periods of time, in far, gigantic, or inhospitable terrains. Some of WSN applications are indoor and outdoor environmental monitoring, military surveillance, disaster relief operation, and human-centric applications. However, sensor nodes have various energy and communication constraints because of their inexpensive nature and ad-hoc method of deployment. Considerable research has been focused at overcoming these deficiencies through more energy-efficient routing techniques and specific system design. However, no single protocol works for all possible sensor networking scenarios. Each sensor network may have certain specific design requirements in order to satisfy certain design goals.

Many critical applications of WSN, such as forest fire detection, target tracking application, and disaster relief operation, generate traffic that have a strict reliability and delay requirements. Special types of data traffic, such as real-time video and voice, are also delay constrained [18, 19]. The losses or delayed delivery of such information can affect the quality of resulting decisions and actions undertaken. Monitoring underground mining environments in order to provide safety and prevent disastrous events, which is the subject of interest in this thesis, is one of these reliable and time critical applications. For example, miners can be informed of the danger of a probable explosion with periodic updates of gas level measurements in specific mine tunnels. The miners can also be notified of the nearest escape route through actuators. The loss or delayed delivery of such vital information may endanger the lives of miners and ruin the objective of the entire networking system. While it is important to provide reliable and timely delivery of data for the abovementioned applications, an efficient use of the network's non-renewable energy resource must also be considered. Sensor nodes operate on batteries and have limited energy supplies, but in many applications the network is expected to

have a long operation lifetime [19]. When nodes exhaust their initial energy, replacing their batteries or redeployment of new sensor nodes is inconvenient or highly expensive in most applications. Especially in applications such as mining, where ad-hoc sensor nodes are spread over a huge area, replacing their batteries is almost impossible. Among the main functions of a sensor node, which include sensing, data processing, and data communication, data communication consumes the most energy of a sensor node. Therefore, managing data communication in the sensor network to deliver both reliable delay-constrained and non-delay constrained traffic to the base station(s), while considering the desired longevity of the network and making efficient use of the limited energy resource, is an important research topic, and is the objective of this thesis.

1.1 Problem Definition

We consider deploying of a wireless sensor network in an underground mine in order to constantly monitor the mine environment and detect and report any conditional change that might cause a hazardous situation, such as mine collapse or danger of an explosion. Apart from *regular* traffic which is the result of constant monitoring and measurements, we consider occasional occurrence of *emergency* traffic. Such traffic can be the result of a sudden and drastic change in the mine environmental condition, such as sever increase of temperature or toxic gas levels, or can be an alarm signal sent by one of the miners. Emergency traffic needs to be routed through highly reliable and minimum-delay path to prevent dangerous accidents. However, since the regular traffic is the dominant traffic in the network, consequently it is the major consumer of sensor node's energy. Furthermore, since the emergency traffic is unexpected and can be originated anywhere in the network, reserving a specific route for relaying emergency traffic is not feasible in such sensor networks. As we mentioned earlier in this chapter, redeployment of sensor nodes in harsh and narrow mine environments is enormously difficult and occasionally impossible. Therefore, prolonging network lifetime is one of the main objectives of the mining applications. Moreover, radio waves propagation in underground mines faces lots of challenges, such as signal scattering, reflection, and high attenuation [22]. This increases the probability of data loss and thus data re-transmission, which eventually reflects in

increasing the end-to-end delay in the network communication. In summary, our objective is to design a routing protocol for underground mining applications which is capable of delivering emergency traffic with minimum loss (or ideally no loss) and minimum delay, and routing regular monitoring traffic through energy efficient paths that maximize the network lifetime.

1.1.1 Two-Tier Hierarchical Network Architecture

We consider two-tier network architecture for the large-scale homogenous WSN distributed in mine galleries. The network consists of three types of nodes: sensor node (SN), sink nodes, and base station (BS). Sensor nodes are low-cost energy-constrained devices deployed in large numbers to monitor the environment and transmit the necessary report to the sink nodes. Sink nodes are devices that are more powerful than SNs in terms of transmission range and energy supply, and are deployed in relatively fewer number. In our design, we take advantage of the pre-established Mesh network in the mines similar to what is proposed in [49]. Thus, we assume all the sink nodes belong to the Mesh network and are connected to constant source of energy. There is a single base station in the network. The BS is the final destination of all the sensory data generated by the SNs in the network. The BS is assumed to be located outside of the mine and to be connected to constant power source. Table 1 summarizes the three types of nodes in the network and their functions.

Node Type	Function
Sensor Node (SN)	Senses the environment and transmits the sensed data towards one of the sink nodes, depends on the traffic type requirements.
Sink Node	Receives data from the sensor nodes and/or other sink nodes, and forwards it to the base station.
Base Station (BS)	Receives data from the sink nodes. The base station is a single point in the network that is the final destination for all sensor data.

Table 1: Types of nodes and their function in the 2-tier hierarchical WSN

1.1.2 Routing Traffic with Reliability, Delay and Energy Constraints

The proposed two-tier hierarchical design partitions the large-scale WSN into smaller sized clusters of sensor networks, connected through the Mesh backbone. This makes the network more scalable and reliable. Figure 1 illustrates an example of this network architecture deployed in mines. We assume the backbone Mesh network is not energy-constrained and is capable of delivering the emergency traffic with minimum loss and within acceptable time. Thus, in this thesis, our objective is to find the optimal paths for delivering both emergency and non-emergency traffic from a sensor node to a sink (mesh node) destination under their own respective constraints. From the point of view of SNs, the sink nodes are the final destination of data. It is with this consideration that we call the nodes on the second tier of the network “sink nodes” and not “relay nodes”, since these nodes play the role of the base station for each cluster of the WSN. In this thesis, everywhere we mention WSN we refer to one of the small sized cluster of sensor nodes.

Every small sized WSN can be connected to more than one sink nodes. The choice of the sink node as the final destination depends on the specific requirements of each traffic type. For example, routing for *emergency* traffic tries to choose the nearest sink to report the emergency situation, while for *regular* traffic it may choose even a distant sink that is reachable through the least energy consuming path. We assume the all sinks are equally of serving as traffic destination. This assumption simplifies the routing and improves the load-balancing of the traffic in the sensor network. Moreover, by having more than one sink nodes for each WSN, it is more likely that data can be delivered over fewer hops to the destination and experiencing low delay.

Figure 1: The two-tier hierarchical network topology in mines

1.2 Contributions

The work we reported in this thesis makes three important contributions. First, we demonstrate the viability of architecture of a Wireless Sensor Network (WSN) that can be deployed in mines, which takes care of severe geographical and environmental constraints found inside mines. The proposed architecture is a two-level hierarchy of small sized WSNs that employs a wireless Mesh network as the backbone connecting small sized WSNs scattered inside mines. The backbone mesh network is currently deployed as basic communication infrastructure in mines [23]. We also proposed a routing protocol that is optimized for both emergency and non-emergency data routing.

Since our main goal is to provide safety in the mining environment, the main consideration of the routing protocol is to provide reliable and low delay paths for vital emergency traffic, and energy efficient paths for regular non-emergency traffic that increases the network lifetime. We present a new cost-based routing protocol called MDML, which provides reliable Minimum Delay and Maximum Lifetime routing for such networks. The proposed MDML routing defines separate cost metrics for emergency and non-emergency traffic. It finds the least-cost path for the reliability and delay-constrained emergency traffic considering the impact of link error rate and residual energy of a node on the quality of paths. It is an energy efficient routing scheme for non-emergency regular data traffic routing that maximizes the network lifetime, which is an important consideration for mines where sensor node deployment is extremely difficult. However, for emergency traffic energy efficiency is compromised to achieve high reliability and minimal delay. Regular traffic is delay-insensitive that is generated through periodic monitoring of mine environment. We aim to maximize the network lifetime which is equivalent to the time of the first loss of coverage; hence the MDML exploits an energy-aware approach to deliver this type of traffic. For regular traffic delivery, a shortest path routing algorithm is employed which uses link costs that include both the cost due to energy consumption during transmission and reception, and the residual energy level of the two end nodes of a link. Third, we developed a simulation model for the proposed routing protocol, and evaluated its performance under variety of network topologies and conditions. The performance evaluation and results are discussed in Chapter 4.

Our solution considers the challenges of routing in an underground mining environment with high bit error-rate. We present a routing system which does not have a large overhead to establish the routes, and does not require recurrent updates to keep the network functioning. The protocol does not require a large routing table to keep the next-hop information. We have tried to keep the number of protocol messages in the network, as low as possible to prevent energy loss and minimize the signal propagation difficulties. We have calculated the link-cost based on each traffic type requirement. The link-cost for routing *regular* or non-emergency periodic sensing data considers the end nodes' residual

energy and the energy consumed for the communication over that link. We aim to route the *regular* traffic through the least cost path to maximize the lifetime of the network. The link-cost for *emergency* traffic is calculated based on the number of expected retransmissions over the link, and the expected lifetime of the end nodes. We manage to optimize routing for both emergency and non-emergency traffic through their respective least-cost paths in the network, which satisfy their specific constraints.

Furthermore, this routing approach can be used for any similar applications with reliability, delay and energy constraints. Our cost function formulation does not make any particular assumptions about the network topology (i.e. placement of sensor nodes, sink nodes, or base station) and can be adapted for applications with different traffic loads. Our approach can be used for relatively small-size sensor networks, or large-size sensor networks where deploying relay nodes or gateways to play the role of sink nodes is feasible.

Through simulation, we explore how the choice of refreshment period of the protocol under varying topologies and traffic condition, may affect the network lifetime and quality of routes in the network. Simulation results also confirm the effectiveness of the MDML protocol in minimizing losses and reducing the end-to-end delay for emergency data.

1.3 Organization of Thesis

The remainder of this thesis is organized as follows. Chapter 2 reviews the wireless sensor networks characteristics and factors that influence the sensor network design. The chapter discusses current sensor network routing challenges and introduces some of the well-known WSN routing protocols, as well as some novel routing approaches proposed in the literature. Some existing and potential sensor network applications and their specific design requirements are presented as well. Chapter 3 discusses the specific requirements of a wireless sensor network designed for monitoring underground mines. Related work in sensor networks, on relaying delay-constrained traffic and energy-aware

routing for network lifetime maximization are discussed. Finally, the chapter introduces MDML routing protocol which is proposed in this thesis for timely delivery of emergency messages in underground mining applications. The network architecture and cost functions to calculate the optimum paths are explained. Chapter 4 provides the simulation model and results, and presents performance evaluation of the MDML approach. Finally, chapter 5 summarizes the work presented in this thesis and suggests some directions for future research.

2 Background

Wireless Sensor Networks (WSN) consist of small low-cost, low-power sensor nodes with sensing, computation, and wireless communications capabilities. Sensor nodes are usually scattered in a sensor field, which is an area where the sensor nodes are deployed. Usually, WSNs are deployed randomly without pre-planning of node locations in inaccessible or inhospitable terrains.

The WSNs are useful for wide range of application areas, for example health care, military surveillance, and environmental monitoring etc. They can be used to detect foreign chemical agents in the air and the water. They can help to identify the type, concentration, and location of pollutants. In essence, sensor networks provide the end user with intelligence and a better understanding of the environment over a long period of time.

However, due to their small sizes, sensor nodes have constraints and limitations in terms of energy, communication range, and data rate. Also, due to their ad-hoc method of deployment sensor networks lack infrastructure support, experience error prone communication channels and unpredictable topology. These limitations raise many research challenges in wireless sensor networks, for example, node localization, efficient routing and MAC design, and data dissemination.

In this chapter, we describe the concept of sensor networks. We provide an overview of the current issues in establishing a WSN as well as the solutions proposed in the literature. Nevertheless, the focus is on routing challenges and techniques. Reviews including the pros and cons of different routing protocols for sensor networks are presented. As sensor networks are strongly application dependant, some of the sensor networks applications and their specific routing protocols have been presented in this chapter.

2.1 WSN Characteristics and Challenges

Sensor nodes coordinate among themselves to produce high-quality information about the physical environment. Each of these scattered sensor nodes has the capability to collect and route data either to other sensor nodes or back to an external base station(s). A base station (BS) or sink may be a fixed node or a mobile node capable of connecting the sensor network to the backbone communications infrastructure or to the Internet where a user can have access to the reported data. A sensor node usually consists of four sub-systems: Computing subsystem, Communication subsystem, Sensing subsystem, and Power supply subsystem. Figure 2 shows sensor nodes in a sensor field.

Figure 2: The components of a sensor node [1]

2.1.1 Differences from Other Wireless Networks

Although many protocols and algorithms have been proposed for traditional wireless ad hoc networks, they are not well suited for the unique features and application

requirements of sensor networks. Table 2 shows a comparison between WSNs and other wireless networks. These differences are described below:

- 1) Due to the relatively large number of sensor nodes, it is not possible to build a global addressing scheme for the deployment of sensor nodes as the overhead of ID maintenance is high. Since IP addressing cannot be used, many IP protocols cannot be applied directly to WSN without modifying packet headers etc.
 - 2) Sensor nodes that are deployed in an ad hoc manner need to be self-organizing to form connections and cope with the resultant nodal distribution especially that the operation of the sensor networks is un-attended.
 - 3) Sensor nodes are tightly constrained in terms of energy, processing, and storage capacities. Thus, they require careful resource management.
 - 4) Sensor networks are application specific, i.e., design requirements of a sensor network change with application. For example, the challenging problem of low-latency precision tactical surveillance is different from that required for a periodic weather-monitoring task.
 - 5) Position awareness of sensor nodes is important since data collection is normally based on the location.
 - 6) Due to dense deployment of sensor nodes, neighbor nodes may be very close to each other. Hence, multihop communication in sensor networks is expected to consume less power than the traditional single hop communication. Furthermore, the transmission power levels can be kept low, which is highly desired in stealthy operations. Multi-hop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication.
- [2]
- 7) Sensor nodes carry limited, generally irreplaceable, power sources. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisions, sensor network protocols must focus primarily on power conservation. They must have mechanisms that prolong network lifetime even at the cost of lower throughput or higher transmission delay.

Other Wireless Networks	Wireless Sensor Networks
Network's role: data transport	Network's role: information collection and dissemination
Network nodes compete for resources	Nodes collaborate on resource allocation
High data rates (e.g. full images transmitted)	Low data rates (e.g. image attributes transmitted)
Metric: maximize network throughput	Metric: Maximize network lifetime

Table 2: Comparison between WSNs and other wireless networks [3]

2.2 Routing

Sensor nodes are constrained in energy supply and data rate. Thus, innovative techniques that eliminate energy inefficiencies that would shorten the lifetime of the network are highly required. Such constraints combined with a typical deployment of large number of sensor nodes pose many challenges to the design and management of WSNs and necessitate energy-awareness at all layers of the networking protocol stack. At the network layer, it is highly desirable to find methods for energy-efficient route discovery and relaying of data from the sensor nodes to the BS so that the lifetime of the network is maximized. [1]

2.2.1 Routing Design Challenges in WSNs

The design of routing protocols in WSNs is influenced by many challenging factors. In the following, some of the routing challenges and design issues that affect routing process in WSNs are summarized. [1]

- **Node deployment:** Node deployment in WSNs is application dependent and affects the performance of the routing protocol. The deployment can be either deterministic or randomized. In deterministic deployment, the sensors are manually placed and data is routed through pre-determined paths. However, in

random node deployment, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner.

- ***Energy consumption without losing accuracy:*** In a multihop WSN, each node plays a dual role as data sender and data router. The malfunctioning of some sensor nodes due to power failure can cause significant topological changes and might require rerouting of packets and reorganization of the network.
- ***Data Reporting Model:*** The routing protocol is highly influenced by the data reporting model with regard to energy consumption and route stability. Data sensing and reporting is dependent on the time criticality of the application. Data reporting can be categorized as time-driven (continuous), event-driven, query-driven, and hybrid. The time-driven delivery model is suitable for applications that require periodic data monitoring. In event-driven and query-driven models, sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute due to the occurrence of a certain event or a query is generated by the BS. As such, these are well suited for time critical applications.
- ***Node/Link Heterogeneity:*** Depending on the application a sensor node can have different role or capacity in terms of computation, communication, and power. Although many studies assume that all sensor nodes are homogenous, the existence of heterogeneous set of sensors raises many technical issues related to data routing.
- ***Fault Tolerance:*** Some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. Ideally the failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, MAC and routing protocols must accommodate formation of new links and routes to the data collection base stations in the most energy-efficient way.
- ***Scalability:*** The number of sensor nodes deployed in the sensing area may be in the order of hundreds or thousands, or more. Any routing scheme must be able to work with this huge number of sensor nodes. In addition, sensor network routing protocols should be scalable enough to respond to events in the environment.
- ***Network Dynamics:*** Most of the WSN architectures assume that sensor nodes are stationary. However, mobility of both BSs and sensor nodes is sometimes

necessary in many applications. Routing messages from or to moving nodes is more challenging since route stability becomes an important issue, in addition to energy, data rate etc. Moreover, the sensed phenomenon can be either dynamic or static depending on the application. Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the BS.

- **Connectivity:** High node density in sensor networks precludes them from being completely isolated from each other. Therefore, sensor nodes are expected to be highly connected. This, however, may not prevent the network topology from changing and the network size from shrinking due to sensor node failures. In addition, connectivity depends on the, possibly random, distribution of nodes.
- **Data Aggregation:** Data aggregation is the combination of redundant data from different sources according to a certain aggregation function, e.g., duplicate suppression, minima, maxima and average. This technique has been used to achieve energy efficiency and data transfer optimization in a number of routing protocols.
- **Quality of Service:** In some applications, data should be delivered within a certain period of time from the moment it is sensed; otherwise the data will be useless. Therefore bounded latency for data delivery is another condition for time-constrained applications.

2.2.2 Routing Protocols in WSNs

Routing protocols in WSNs can be classified either on the basis of the network structure or the protocol operation. On the basis of network structure we have *flat-based*, *hierarchical-based*, or *location-based* routing. In flat networks, all nodes play the same role, while hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy. Location-based protocols utilize the position information to relay the data to the desired regions rather than the whole network. Routing protocols are also classified on the basis of the approach used in the protocol into *multipath-based*, *query-based*, *negotiation-based*, *QoS-based*, and

coherent-based. The classification based on network structure and protocol operation is shown in Figure 3.

There is an additional classification of routing protocols as, *proactive, reactive, and hybrid* protocols depending on how the source finds a route to the destination. In proactive protocols, all routes are computed before they are really needed, while in reactive protocols, routes are computed on demand. Hybrid protocols use a combination of these two ideas. When sensor nodes are static, it is preferable to have table driven routing protocols rather than using reactive protocols. A significant amount of energy is used in route discovery and setup of reactive protocols. In the rest of this section, we present a detailed overview of the main routing paradigms in WSNs. These routing techniques are the base of most of the other WSN routing protocols.

Figure 3: Routing protocols in WSNs [1]

2.2.2.1 Network Structure Based Protocols

The underlying network structure can play significant role in the operation of the routing protocols in WSNs. In this section, we review in details some of the protocols that fall in this category.

A. Flat Routing

In flat networks, each node typically plays the same role and sensor nodes collaborate together to perform the sensing task. Due to the large number of such nodes, it is not

feasible to assign a global identifier to each node. This consideration has led to data centric (DC) routing, where the BS sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data. The main idea of the DC paradigm is to combine the data coming from different sources enroute (in-network aggregation) by eliminating redundancy, and minimizing the number of transmissions; thus saving network energy and prolonging its lifetime. Unlike traditional end-to-end routing, DC routing finds routes from multiple sources to a single destination that allows in-network consolidation of redundant data.

SPIN: Sensor Protocols for Information via Negotiation (SPIN) disseminate all the information at each node to every node in the network. This enables a user to query any node and get the required information immediately. SPIN make use of the property that nodes in close proximity have similar data, and hence there is a need to only distribute the data that other nodes do not possess. The SPIN family of protocols uses data negotiation and resource-adaptive algorithms. Nodes running SPIN assign a high-level name to completely describe their collected data (called meta-data) and perform meta-data negotiations before any data is transmitted. This assures that there is no redundant data sent throughout the network. The semantics of the meta-data format is application-specific and is not specified in SPIN. In addition, SPIN has access to the current energy level of the node and adapts the protocol it is running based on how much energy is remaining. These protocols work in a time-driven fashion.

SPIN is a 3-stage protocol as sensor nodes use three types of messages ADV, REQ and DATA to communicate. ADV is used to advertise new data, REQ to request data, and DATA is the actual message itself. The protocol starts when a SPIN node obtains new data that it is willing to share.

One of the advantages of SPIN is that topological changes are localized since each node needs to know only its single-hop neighbors. Therefore SPIN family protocols are well-

suited for an environment where the sensors are mobile. SPIN provides much energy savings than flooding and meta-data negotiation almost halves the redundant data. However, SPIN's data advertisement mechanism cannot guarantee the delivery of data. To see this, assume that nodes interested in the data are located far away from the source node and the nodes between source and destination nodes are not interested in that data, such data will not be delivered to the destination at all. [1]

Directed Diffusion: In directed diffusion the base station requests data by broadcasting interests. As the interest is propagated throughout the network, gradients are setup to draw data satisfying the query towards the requesting node. Each sensor that receives the interest setup a gradient toward the sensor nodes from which it receives the interest. This process continues until gradients are setup from the sources back to the BS. Figure 4 shows an example of the working of directed diffusion ((a) sending interests, (b) building gradients, and (c) data dissemination). When interests fit gradients, paths of information flow are formed from multiple paths and then the best paths are reinforced so as to prevent further flooding according to a local rule. In order to reduce communication costs, data is aggregated on the way. The goal is to find a good aggregation tree which gets the data from source nodes to the BS. The BS periodically refreshes and re-sends the interest when it starts to receive data from the source(s). This is necessary because interests are not reliably transmitted throughout the network.

Figure 4: An example of directed diffusion (a) propagate interest (b) set up gradient (c) send data

All sensor nodes in a directed diffusion-based network are application-aware, which enables diffusion to achieve energy savings by selecting empirically good paths and by caching and processing data in the network. Caching can increase the efficiency, robustness and scalability of coordination between sensor nodes which is the essence of the data diffusion paradigm. Other usage of directed diffusion is to spontaneously propagate an important event to some sections of the sensor network. Such type of information retrieval is well suited only for persistent queries where requesting nodes are not expecting data that satisfy a query for duration of time. This makes it unsuitable for one-time queries, as it is not worth setting up gradients for queries, which use the path only once. Also, directed diffusion may not be applied to applications that require continuous data delivery to the BS (e.g., environmental monitoring). This is because the query-driven on demand data model may not help in this regard. Moreover, matching data to queries might require some extra overhead at the sensor nodes.

B. Hierarchical Routing

In a hierarchical architecture, higher energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing in the proximity of the target. This means that creation of clusters and assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime, and energy efficiency. Also, performing data aggregation and fusion inside a cluster decrease the number of transmitted messages and reduce energy consumption. Hierarchical routing is mainly two-layer routing where one layer is used to select cluster-heads and the other layer is used for routing. However, most techniques in this category are not about routing, rather on "who and when to send or process/aggregate" the information, channel allocation etc., which can be orthogonal to the multi-hop routing function.

LEACH: Low Energy Adaptive Clustering Hierarchy (LEACH) is a cluster-based protocol, which includes distributed cluster formation. LEACH randomly selects a few

sensor nodes as clusterheads (CHs) and rotates this role to evenly distribute the energy load among the sensors in the network. In LEACH, the clusterhead nodes compress data arriving from nodes that belong to the respective cluster, and send an aggregated packet to the base station. LEACH uses a TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions. However, data collection is centralized and is performed periodically. Therefore, this protocol is most appropriate when there is a need for constant monitoring by the sensor network. A user may not need all the data immediately. Hence, periodic data transmissions are unnecessary which may drain the limited energy of the sensor nodes. After a given interval of time, a randomized rotation of the role of the CH is conducted. Simulation shows that only 5% of the nodes within a cluster need to act as cluster heads [1].

The operation of LEACH has two phases: setup phase and steady state phase. In the setup phase, all sensor nodes candidates themselves for becoming CHs. Clusterhead election method is explained in [1, 2]. After election, the CH node broadcast an advertisement message to the rest of nodes. The other nodes will choose which cluster they want to belong to and send a membership message to the corresponding CH. After receiving all the messages, the CH create a TDMA schedule and assigns each node a time slot when it can transmit.

After all clusters are set and organized, the steady state phase begin to transfer actual data to the base station. Each cluster communicates using different CDMA codes to reduce interference from nodes belonging to other clusters. The duration of the steady state phase is longer than the duration of the setup phase in order to minimize overhead.

Although LEACH is able to increase the network lifetime, there are still a number of issues about the assumptions used in this protocol. LEACH assumes that all nodes can transmit with enough power to reach the BS if needed and that each node has computational power to support different MAC protocols. Therefore, it is not applicable to networks deployed in large regions. It also assumes that nodes always have data to send, and nodes located close to each other have correlated data. It is not obvious how the

number of the predetermined CHs is going to be uniformly distributed through the network. Therefore, there is the possibility that the elected CHs will be concentrated in one part of the network. Hence, some nodes will not have any CHs in their vicinity [1]. Furthermore, the idea of dynamic clustering brings extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption. Finally, the protocol assumes that all nodes begin with the same amount of energy capacity in each election round, assuming that being a CH consumes approximately the same amount of energy for each node [1].

Table 3 compares SPIN, LEACH, and the Directed Diffusion routing techniques according to different parameters. It is noted from the table that Directed Diffusion shows a promising approach for energy-efficient routing in WSNs due to the use of in-network processing. [1]

	SPIN	LEACH	Directed Diffusion
Optimal Route	No	No	Yes
Network Lifetime	Good	Very Good	Good
Resource Awareness	Yes	Yes	Yes
Use of Meta-Data	Yes	No	Yes

Table 3: Comparison between SPIN, LEACH and Directed Diffusion

C. Location-based Routing

In this kind of routing, sensor nodes are addressed by means of their locations. The distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors. Alternatively, the location of nodes may be available directly by communicating with a satellite, using Global Positioning System (GPS), if nodes are equipped with a small low power GPS receiver. To save energy, some location based schemes demand that nodes should go to sleep if there is no activity. More energy

savings can be obtained by having as many sleeping nodes in the network as possible. The problem of designing sleep period schedules for each node in a localized manner has also been discussed.

Geographic Adaptive Fidelity (GAF): GAF is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. The network area is first divided into fixed zones and forms a virtual grid. Inside each zone, nodes collaborate with each other to play different roles. For example, nodes will elect one sensor node to stay awake for a certain period of time and then they go to sleep. This node is responsible for monitoring and reporting data to the BS on behalf of the nodes in the zone. Hence, GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Such equivalence is exploited in keeping some nodes located in a particular grid area in sleeping state in order to save energy. Thus, GAF can substantially increase the network lifetime as the number of nodes increases. There are three states defined in GAF. These states are discovery, for determining the neighbors in the grid, active reflecting participation in routing and sleep when the radio is turned off. GAF is implemented both for non-mobility and mobility of nodes.

The issue is how to schedule roles for the nodes to act as cluster-heads. A cluster-head can ask the sensor nodes in its cluster to switch on and start gathering data if it senses an object. Then, cluster-head is responsible for receiving raw data from other nodes in its cluster and forward it to the BS. It is assumed that sensor nodes can know their locations using GPS cards, which is inconceivable with the current technology. Simulation results show that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy. [1] Although GAF is a location-based protocol, it may also be considered as a hierarchical protocol, where the clusters are based on geographic location. The leader node however, does not do any aggregation or fusion as in the case of other hierarchical protocols.

2.2.2.2 Routing Protocols Based on Protocol Operation

In this section we review routing protocols with different routing functionality. It should be noted that some of these protocols may fall under one or more of the above routing categories.

Multipath Routing: Multipath routing protocols use multiple paths between the source and destination rather than a single path, in order to enhance network performance and increase the resilience (fault tolerance) of a protocol. The drawback is increased energy consumption and traffic generation. Directed diffusion is a good candidate for robust multipath routing.

Query-Based Routing: In this kind of routing, the destination nodes propagate a query for desired data (target) through the network, and a node with this data sends the data that matches the query back to the node that initiated the query. All the nodes have tables consisting of the queries they receive, and send data that matches these queries when they receive it. Directed diffusion described earlier is an example of this type of routing.

Negotiation-Based Routing: The motivation is that the use of flooding to disseminate data will produce implosion and overlap between the sent data. So, these protocols use high-level data descriptors in order to eliminate redundant data transmissions through negotiation. Communication decisions are also made based on the resources available to them. The SPIN protocol is an example of negotiation-based routing protocols.

Coherent and Non-coherent Processing: In noncoherent data processing routing, nodes will locally process the raw data before it is sent to other nodes for further processing. The nodes that perform further processing are called aggregators. In coherent routing, the data is forwarded to aggregators after minimum processing. The minimum processing typically includes tasks like time stamping and duplicate suppression. To perform energy-efficient routing, coherent processing is normally selected.

QoS-based Routing: In QoS-based routing protocols, the network have to balance between energy consumption and data quality. In particular, the network has to satisfy certain QoS metrics (delay, energy, bandwidth, etc.) when delivering data to the BS. One

of the first routing protocols for WSNs to introduce the notion of QoS into routing decisions is SAR.

Sequential Assignment Routing (SAR): A routing decision in SAR is dependent on three factors: energy resources, QoS on each path, and the priority level of each packet. To avoid single route failure, a multi-path approach and localized path restoration schemes are used. To create multiple paths from a source node, a tree rooted at the source node to the destination nodes (i.e., the set of BSs) is built. The paths of the tree are built while avoiding nodes with low energy or QoS guarantees. At the end of this process, each sensor node will be part of a multi-path tree. As such, SAR is a table-driven multi-path protocol that aims to achieve energy efficiency and fault tolerance. In essence, SAR calculates a weighted QoS metric as the product of the additive QoS metric and a weight coefficient associated with the priority level of the packet. The objective of SAR is to minimize the average weighted QoS metric throughout the lifetime of the network. If topology changes due to node failures, path recomputation is needed. As a preventive measure, a periodic recomputation of paths is triggered by the BS to account for any changes in topology. A handshake procedure based on a local path restoration scheme between neighboring nodes is used to recover from a failure. Failure recovery is done by enforcing routing table consistency between upstream and downstream nodes on each path. Simulation results showed that SAR offers less power consumption than the minimum energy metric algorithm, which focuses only the energy consumption of each packet without considering its priority. SAR maintains multiple paths from nodes to BS. Although this ensures fault tolerance and easy recovery, the protocol suffers from the overhead of maintaining the tables and states at each sensor node, especially when the number of nodes is huge.

We observed that there are some hybrid protocols that fit under more than one category. Recent results on data routing in WSNs are summarize in Table 4.

	Classification	Mobility	Position Awareness	Power Usage	Negotiation based	Data Aggregation	Localization	QoS	State Complexity	Scalability	Multipath	Query based
SPIN	Flat	Possible	No	Limited	Yes	Yes	No	No	Low	Limited	Yes	Yes
Directed Diffusion	Flat	Limited	No	Limited	Yes	Yes	Yes	No	Low	Limited	Yes	Yes
LEACH	Hierarchical	Fixed BS	No	Maximum	No	Yes	Yes	No	CHs	Good	No	No
GAF	Location	Limited	No	Limited	No	No	No	No	Low	Good	No	No
SAR	QoS	No	No	N/A	Yes	Yes	No	Yes	Moderate	Limited	No	Yes

Table 4: Classification and comparison of routing protocols in WSN [1]

2.2.3 Some Recent Routing Approaches

Design and architecture of a wireless sensor network has a very close association with the application requirements. Depend on the application necessities, different methods of routing have been proposed in literature. Sensor networks can be used in variety of applications such as continuous sensing and monitoring, event detection, event identification, location sensing, and local control of actuators. Usually the main constraint for realizing a practical sensor network is energy cost. However some applications demand a secondary metric to be met as well, such as load balance, end-to-end delay, scalability, handling dynamic topology, survivability or fault tolerance, and guaranteed data delivery. For instant, an underwater WSN has to deal with the node mobility in a three-dimension space environment, while fire detection in a national park area can benefit from boundary recognition routing methods. We review some of these novel techniques in the following part.

Gradient-based Routing

Every physical event produces a fingerprint in the environment which results a natural information gradient in the proximity of the phenomenon. Many physical phenomena follow diffusion laws. Faruque and Helmy, have used this natural information gradient to route a query in a sensor network, find the source and get the desired data information. Their routing protocol, called RUGGED, is an information-driven routing.

Their environmental model consists of flat information region (with zero information), and gradient information region. Environmental noise is presented only in the gradient region, while malfunctioning nodes are uniformly distributed in both regions. To prevent

loop, each querier or sink, generates unique sequence number for the query it sends. The query starts by 'flat' mode. In the flat region, the query will be forwarded to all neighbors. Upon reaching the gradient information region, the query changes its mode to 'gradient' and will start forwarding greedily. If the gradient of the node is less than its parents' gradient, the node will use probabilistic forwarding to avoid local maxima or minima. After finding the node with the maximum information, the nodes use the reserve path to send the reply towards the sink.

RUGGED has the ability to query multiple sources. It works without location information. [44] However, if location information is available, make the algorithm more energy efficient and robust. Paper [43] evaluates RUGGED through both analytical model and simulation model, with three performance metrics: query success rate, energy dissipation, and path length. Wireless link loss and malfunctioning nodes has been considered as well. The results show that RUGGED is highly energy efficient and reliable. Since RUGGED is a query-based protocol, it is more suitable for those application which has persistent queries and fewer data generation rate.

Boundary Recognition Routing

If we assume that the information of interest is the event boundary and not the individual sensor readings within the event region, then it becomes a waste of network resources to report the sensor readings of all nodes in the event region. [40] Additionally, even if only the nodes along the event boundary report their sensor data then there is the added overhead of passing the boundary data through the sensor network in order to reach the user. Ideally, an algorithm should take into account the event boundary path and utilize that path to aggregate the event boundary data and reduce overall number of nodes reporting to the sink.

A novel approach for event boundary detection is proposed in [40], where autonomous software agents are deployed in order to minimize the number of transmissions required to discover an event boundary. The goal of the algorithm is to localize node transmission

along the event boundary, since the sensory data from nodes not along the boundary is not required for event boundary detection.

The protocol could be started by any sensor node which has detected the event of interest. Such nodes will randomly generate an agent based on a preset threshold probability. A node is defined as a boundary node if it has a neighbor which has not seen the event. Once an agent is first created, it defines a random direction vector and moves in that direction to discover the edge of the event region. If the agent discovers another agent has visited this node then it knows that another agent exists and therefore ceases operation. In order to reduce transmissions, during the boundary discovery phase, the agent requests responses from only nodes that have not seen the event. When an agent has found the boundary, a second agent (or child agent) is produced. Both agents move along the boundary but in opposite directions. When a parent agent meets the path of a child agent, the node hosting the agent combines the stored agent paths and reports to the sink. The basic operation of this algorithm requires that the detection of an event be separated within individual periods or time windows.

Simulations demonstrate that the algorithm has a linear efficiency function when related to event radius of sufficient size and further demonstrates that the boundary of an event may be successfully mapped using agents. One of the main challenges in event boundary recognition is to be able to detect the network holes. Holes could be defined as the regions inside the boundary with insufficient coverage and connectivity, or with no event information. The algorithm is much more scalar than traditional algorithms and can detect and bypass holes in the event region with an acceptable precision.

Although event boundary detection algorithms are designed to reduce the number of network transmission for some especial applications, they can also be used for network boundary detection and topology recognition where nodes' location information is not known. In [38] a topological method to identify the network topology is proposed. Reference [37] has used the network topology information to propose a routing protocol

that does not require location information, makes routing decisions locally, and achieves good load balancing.

Mobile Underwater WSN (UWSN)

The characteristics of mobile UWSNs, such as low communication bandwidth, large propagation delay, floating node mobility, and high error probability are significantly different from ground-based wireless sensor networks. The first problem that underwater sensor network have to overcome, is mobility of sensor nodes. Sensor nodes can be either completely mobile or they might be fixed at the bottom of the ocean with anchors. In the former case, nodes should be able to relocate themselves within a specified area of interest. So the main problem is high energy consumption used for relocation, especially in a 3-D environment. In the latter case, sensor movement is around a very limited area. In either case, nodes should be aware of their locations at any time. Therefore in most of underwater applications, geographical routing is used. The other challenge is data transmission delay, since radio transmission is not generally suitable for underwater communications, acoustic transmission is used. The signal propagation speed in an underwater acoustic channel is five orders of magnitude lower than the radio propagation speed [14]. References [14], [15] and [16] have addressed the challenges of routing in underwater WSN applications.

Using Mobile Base Stations for Energy Savings

The base station relocation method aims to change the location of BS along the periphery of the sensing field such that the energy consumption of individual sensors is balanced and overall energy consumption of all sensors is minimized [5]. Such method is usually used in sparse sensor networks, where the distance between sensor nodes is beyond the transmission power of the node's antenna, or it consumes excessive transmission power in a multihop network. Road traffic control is one of such applications. Sensors are placed on roads to observe vehicles. As the number of cars along the road segment is highly correlated, a small number of sensors are sufficient for data collection. Such sparse deployment scenarios suffer from connectivity problems. Therefore mobile sinks

have been proposed as an alternative solution for data gathering in this type of wireless sensor networks. This method is similar to message ferrying approach for data delivery in sparse mobile ad hoc networks proposed by Ammar et. al. in [45].

2.3 Summary

The flexibility, high sensing fidelity, low-cost and rapid deployment characteristics of sensor networks create many new and exciting application areas for remote sensing. In the future, this wide range of application areas will make sensor networks an integral part of our lives. However, realization of sensor networks needs to satisfy the constraints introduced by factors such as fault tolerance, scalability, cost, hardware, position awareness, topology change, and above all power consumption. Besides, sensor networks are application specific, and design requirements of a sensor network change with application. Since these constraints are highly stringent and specific for sensor networks, new routing techniques other than developed for wireless ad hoc networks need to be developed.

3 A WSN Routing Specifically Designed for Underground Mines

3.1 Motivation

The design of a routing protocol for any wireless sensor network typically depends on the application requirements since there are many restricting factors that should be considered, as became apparent from our review of routing protocols for WSN in chapter 2.

Among the potential applications for WSN, we consider the application of sensor networks in underground mines to achieve mine safety. In spite of strong safety standards used in mines today, there are still more than 10,000 miners killed every year around the world according to CNN. Saskatchewan mine accident in Canada (January 2006), Sago mine disaster in USA (January 2006), and Siberian coal mine explosion in Russia (March 2007) are among the recent mine tragedies. In most mine disaster cases, the rescue team could not find the trapped miners' locations fast enough to save their lives. Also, due to lacking communication with the trapped miners they are not guided to a safe escape route or to refuge rooms with oxygen, water and food supply.

Wireless sensor networks can be used effectively for increasing mine safety. Monitoring the mine environment for timely detecting and reporting of the accident-causing situations can complement the promulgation of safety standards in preventing mine disasters. A wireless sensor network can be designed and deployed inside the mines for monitoring and measuring physical parameters in the mines such as temperature, pressure, gas leakage, etc so that abnormalities can be detected and may be used to predict and prevent catastrophes. These sensors can also monitor vital life signs of workers such as heartbeat, body temperature, etc which are very useful to track and detect the workers that may still be alive soon after a mine disaster. The monitored information

will help locating the miners, guiding them to safe rooms, and accelerating the rescue operation.

To the best of our knowledge, this work is one of the first attempts of designing a WSN routing system to route emergency data for mining applications. This research is focused on reliability, delay and energy constraints in sensor networks because reporting some emergency events, such as lack of oxygen in some parts of a mine, are loss and delay-sensitive. If the network cannot deliver the emergency information within a time limit to the main station, it will be of no help in preventing the disaster or in rescuing operation. In other words, all our efforts in deployment and maintenance of the network will go in vain. This thesis proposes a routing algorithm which can save enough energy in the network to be able to transmit the emergency data within an acceptable time.

3.2 Problem Definition

The underground mine is a challenging environment for wireless communication. Current wireless communication systems cannot be engineered to operate reliably in closed environments, since the rough or complex surfaces of these environments compromise the signal quality. In the underground mine the environmental factors like humidity, temperature, and vibration are extremely harsh as well. Underground mine galleries can be considered as complex transmission lines in which the following factors affect the transmission performance:

- Multipath
- Attenuation
- Reflection
- Diffraction
- Scattering

These factors are based on random functions that make it very hard to predict the extent of these effects [23]. In addition, the interference and multipath propagation are acute due to the high signal reflection onto the rough walls of the mine.

The other difficulty in mine routing is caused by high error rate or packet loss. Based on the empirical data [22] there are three propagation zones in a mine segment, and the typical distance between the access points or sink nodes for the reception of radio waves signal in rough mining tunnels appears to be of the order of 20-35 meters. Beyond this distance, it is expected that over 75% of the useful signals will be lost.

With all the difficulties mentioned above, modeling the radio propagation in such a mining environment is a big challenge. However, the objective here is not to study the challenges of signal propagation in mines, but to highlight factors involved in the radio wave propagation in underground mines which affect the methods for reliable system design in open space.

The above mentioned factors affect the packet routing and increase power consumption in a wireless sensor network. We summarize the challenges of a WSN routing protocol designed for mining applications as below:

1. Sensor nodes deployment in underground mines is rather difficult; so the lifetime of the network should be extended in order to avoid the frequent need for re-deployment.
2. Due to high bit error rate and consequently high packet loss probability, the number of communication messages between the nodes to run the protocol should be limited. This includes both control packets (small packets that are required to run the protocol) and data packets. Since the transmission is the main cost of energy consumption in WSN, this will contribute to save the battery power of sensor nodes.
3. Due to high packet loss in mines, reliability of the sensor network is hard to maintain. Multipath routing is proposed in the literature to maintain network reliability. However, multipath routing carry the drawback of increased energy consumption and traffic generation that makes it unsuitable for underground mine applications.
4. Data speed limitation and propagation delay in underground mines, increase the difficulty of timely delivery of data information to the base station.

5. WSN routing protocols should consider reducing the size of routing tables at sensor nodes because of memory space limit on the sensor board.

We believe, however, that limited processor speed and memory space are temporary constraints in sensor networks. They will disappear with fast developing fabrication techniques. The energy constraints on the other hand are more fundamental. According to reference [8], battery capacity only doubles in 35 years. Energy constraints are unlikely to be solved in the near future with the slow progress in battery capacity and energy scavenging. Moreover, the unattended nature of sensor nodes in mines and the hazardous sensing environment preclude manual battery replacement. In addition, the error-prone environment of underground mines reduces the network reliability and therefore increases the packet re-transmission rate, which ends up in consuming more energy. For these reasons, energy awareness becomes one of the key research challenges for our underground sensor network routing protocol design. However, since our goal is to provide mine safety, reliable and timely delivery of emergency messages in the network is the other major consideration in our design.

In summary, our goal is to design a WSN system for underground mining applications, to constantly monitor the mine environment and provide a safe and hazard-free working space for miners. This requires a sensor network that is able to route emergency messages in a reliable and timely manner and has a sufficient lifetime. In other words, our goal is to maximize the lifetime of the sensor network to save enough energy to be able to route the emergency data in a timely manner. The problem of routing of emergency data in WSN in an underground mine has not been studied in the literature so far. In the next section, we present some of the available approaches which are similar to our system design goals and have inspired us to design our WSN routing algorithm. We demonstrate our system design and algorithm in section 3.4.

3.3 Related Methodologies

Energy-Aware QoS Routing Protocol: A QoS aware protocol for sensor networks is proposed by Akkaya and Younis [18]. Real-time traffic is generated by imaging sensors. The proposed protocol finds a least cost and energy efficient path that meets certain end-to-end delay during the connection. The link cost used is a function that captures the nodes' residual energy, transmission energy, error rate and other communication parameters. In order to support both best effort and real-time traffic at the same time, a class-based queuing model is employed. The queuing model allows service sharing for real-time and non-real-time traffic. The bandwidth ratio r , is defined as an initial value set by the gateway and represents the amount of bandwidth to be dedicated both to the real-time and non-real-time traffic on a particular outgoing link in case of a congestion. As a consequence, the throughput for normal data does not diminish by properly adjusting such r value. Their queuing model is depicted in Figure 5. The protocol finds a list of least cost paths by using an extended version of Dijkstra's algorithm and picks a path from that list which meets the end-to-end delay requirement. Simulation results show that the proposed protocol consistently performs well with respect to QoS and energy metrics. The protocol is extended by assigning a different r -value for each node in order to achieve a better utilization of the links.

Figure 5: Queuing model in a particular sensor node [17]

Maximum Lifetime Routing Algorithm: Chang and Tassiulas have proposed a heuristic solution for maximizing the lifetime of a sensor network, called Flow Augmentation algorithm [32]. The performance objective of this paper is to maximize the overall lifetime of the sensor network, rather than minimizing the total energy consumed for routing. The authors discuss that if all the traffic is routed through the minimum energy path to the destination, the nodes in that path will run out of batteries quickly rendering other nodes useless due to a network partition even if they do have available energy resource. The network lifetime is defined as the time to the first node failure. The authors have considered two cases; one with constant information generation rates, and the other with arbitrary information generation in the network. Here we summarize the latter case, which is closer to our WSN scenario.

The authors have presented three equations to formulize the system lifetime as an integer programming problem. The first equation is called ‘the conservation of flow condition’ which says the total of packets generated at each node plus the total of packets it receives though its neighbors during time T , should be equal to the total of packets the node transmit to the network during that time. The second equation is ‘the total energy constraint’ condition, which declares the total energy a node consumes for transmission and reception the messages, should be less than or equal to the initial energy of the node. The third equation is ‘the necessary feasibility condition’ which states that the total information generated in a set of nodes V , should not be greater than the capacity of all outgoing flow paths. Solving an integer problem is complicated and time-consuming. So the authors have proposed the Flow Augmentation (FA) algorithm.

The objective of FA is to find the best link cost function which will lead to the maximization of the system lifetime. A good candidate for the flow augmenting path should consume less energy and should avoid nodes with small residual energy since we would like to maximize the minimum lifetime over all nodes. The FA algorithm defines link cost for link (i, j) according to the cost of transmitting and receiving over the link, plus the initial energy and residual energy of the end nodes i and j . The link cost function is:

$$cost_{ij} = (e_{ij}^t)^{x_1} \underline{E}_i^{-x_2} E_i^{x_3} + (e_{ij}^r)^{x_1} \underline{E}_j^{-x_2} E_j^{x_3} \quad (\text{Eq. 1})$$

where e_{ij}^t and e_{ij}^r are energy cost for unit data transmission and reception over the link (i, j) , E_i and E_j are initial energy, $\underline{E}_i$ and $\underline{E}_j$ are residual energy of nodes i and j . x_1 , x_2 and x_3 are nonnegative weighting factors for each item. If $x_2 = x_3 \neq 0$ then it means the normalized residual energy is used, while if $x_3 = 0$ then it means the absolute residual energy is used. The authors have assumed the sensor nodes start with different initial energy and have used the normalized residual energy method ($x_1=x_2$). Also based on the simulation result presented in the paper, the best value for x_1 is $x_1 = 1$. The path cost is computed by the summation of the link costs on the path, and the algorithm can be implemented with any existing shortest path algorithms including the distributed Bellman–Ford algorithm. Each sink is satisfied if it receives the λ number of packets, no matter which source sends the packets. In each round of the algorithm, the source node finds the shortest path towards the destination using the updated residual energy information.

The performance of their algorithm is compared with the performance obtained with the linear programming problem solution which has the optimal network lifetime. Simulation results show an excellent performance which is almost the same as the performance of the linear programming.

3.4 Minimum Delay Maximum Lifetime (MDML) Routing Algorithm

In this thesis we show the viability of two-tier network architecture for WSN in mines. We also propose a routing system that carries both emergency and non-emergency periodic sensing data to the sinks. The objective of routing of emergency data is to carry the information from the source to the sink with high reliability and minimum delay. The objective of routing of non-emergency periodic sensing data is to reduce the energy consumption and thus maximize the network lifetime. We call our proposed routing

Minimum-Delay Maximum-Lifetime (MDML) routing algorithm. In the following subsections we discuss the network architecture, our proposed routing metrics, and the MDML routing algorithm.

3.4.1 Network Architecture

We consider deploying a wireless sensor network in mines in order to monitor the mine environment and detect and report hazardous events or situations in timely manner. Implementing wireless networks in confined spaces such as underground mines faces many signal transmission difficulties, such as signal attenuation, scattering, and diffraction which are beyond the scope of this research. We assume there is a suitable MAC protocol for underground mining applications. However, we make our effort to minimize the number of transmissions in our routing protocol in order to reduce the communication difficulties.

As per our investigation we find out that one of the state-of-the-art and reliable communication networks established in mines to transmit both voice and data is Mesh network [23]. We use this existing Mesh network as a backbone for our sensor network. We assume the locations of nodes on the Mesh backbone are fixed, and also these nodes are connected to a continuous power supply hence energy conservation is not an objective for routing in the mesh backbone. The nodes on the Mesh network play the role of sink nodes for our WSN. However, they route the received information to the main Base Station outside of the mine. Thus, we design two-tier sensor network architecture. The first tier consists of sensor nodes scattered in a mine tunnel that gathers local information and transmit it to the sinks. The second tier is a backbone Mesh network. The advantages of the Mesh network are first, to provide redundant routes, which is desirable in a dynamic environment where link failures are frequent as in the mine galleries [49] and second, to provide reliable links since the nodes on the mesh backbone are connected to constant power supply. In the rest of this thesis, we call the nodes on the Mesh backbone the sink nodes to distinguish them from the main Base Station outside of the

mine. All the sinks nodes transmit the data they receive from sensor nodes to the Base Station. Figure 6 depict the network architecture.

Typical optimization techniques for WSN routing are: multipath route setup to increase network reliability, in-network data aggregation to minimize the transmission cost and energy consumption, hierarchical network topology to save energy and increase the network lifetime, and recently changing the location of the base station (i.e. allow the base station to move around the boundary of the network region) to improve the load balance and quality of routes in the network. Mulipath routing is not suitable to be used in underground mines due to high signal attenuation. However, the other three techniques are considered in our proposed algorithm. Our network benefits from the advantage of having more than one stationary sink nodes. This is quite a noticeable help to achieve load balancing and distributing the traffic in the network. From the point of view of sensor nodes, all the sink nodes are equal in their routing capability. The goal is to route a packet to the nearest sink regardless of the position of the sink, which consumes much less transmission energy compared to the case of having only one sink node, and it also automatically achieve load balance in the network.

Since we deal with continuous monitoring of the mine environment, we need either a time-driven or an event-driven data reporting model; query-driven approaches will not be suitable for this type of applications which are time-critical. To reduce the number of messages in the network, we choose event-driven data reporting model; meaning that sensor nodes send reports only when a sudden or drastic change is detected in the value of a sensed attribute.

With our two-tier hierarchical architecture, we can distribute the sensor nodes required to cover the whole mine area, into small clusters of sensor nodes in each mine gallery. The sensor node deployment in a mine gallery is neither very dense nor very sparse. Thus, the problem is finding the best routing scheme for a relatively small sensor network with more than one stationary sinks, in order to increase the overall network lifetime and timely delivery of emergency messages in the network. We choose not to use a cluster-

based architecture, because dynamic clustering brings extra overhead, such as head changes, advertisements etc., which may diminish the gain in energy consumption. For a large WSN such as what we have in mines hierarchical architecture, which divides the network into smaller sensor networks, seems reasonable. Even if there was no Mesh backbone, we had to create some sort of gateway relays in our architecture.

Figure 6: Typical view of wireless sensor network in underground mine

Srinivasan, Ndoh, and Kaluri proposed using 802.11e for communication between sensor nodes and gateways or sink nodes in [49]. We follow their proposed MAC for our sensor network. 802.11e is a variant of 802.11 that has QoS support. It includes different contention technique as compared to 802.11b MAC for supporting different priority class traffics. 802.11e provides this through Enhanced Distributed Coordination Function (EDCF) and Hybrid Coordination Function (HCF). In EDCF, on an average higher priority traffic has lower time delays than the lower priority traffic. On the other hand, HCF is more intelligent in controlling access to the medium and so may be recommended for mine galleries. Nevertheless, the scheme in [49] benefits from either EDCF or HCF to assign the highest priority to voice traffic because it employs a hybrid network

architecture for transmitting both high bandwidth traffic such as voice and video, and low bandwidth traffic such as sensors' readings. We also can take advantage of EDCF feature to assign the highest priority to emergency traffic in our sensor network system.

3.4.2 Network Lifetime

Network lifetime should refer to the capability of the network to serve its design purpose [31]. Various definitions of network lifetime have been proposed for different scenarios. Some of these definitions are:

- The time of the first node failure
- The time of a certain fraction of surviving nodes in a network
- The time to the first loss of some desired coverage
- The time in terms of the packet delivery rate
- The average sensor lifetime

There have been two different approaches for maximizing network lifetime. One indirect approach aims to minimize energy consumption, while the other approach directly aims to maximize network lifetime.

Most of the past research has been focused on the indirect approach, i.e. minimum total energy (MTE) routing approach. The aim was to minimize the total consumed energy to reach the destination, which minimizes the energy consumed per unit flow or packet. Although these efforts help extend network lifetime, they do not address precisely the problem of maximizing network lifetime [31].

The direct approach argues that, if all the traffic is routed through the minimum energy path to the destination, the nodes in that path will run out of batteries quickly. Thus the other nodes become useless due to a network partition even though they do have available energy resource. Therefore, instead of trying to minimize the total consumed

energy on the path, the performance objective of maximizing the lifetime of the system, should be considered.

In our routing protocol, our first preference is to define the network lifetime as the time until the network is partitioned or it becomes non-functional. We call the network non-functional when some sensors detect an event but cannot route the message to the sinks due to path loss or lack of route connectivity between nodes. This is the same as defining network lifetime as the time to the first loss of coverage. In this definition, as long as the network is able to report the detected event, the network is considered functional and alive. However, since loss of coverage is hard to detect, we consider the network lifetime as the time until the first node run out of battery energy, similar to [18 and 32], for simulation purposes. Since emergency event can arise at any point in the network, the failure of one node could prevent the delivery of emergency traffic to the sink and hence can be a sufficient metric for lifetime of the network.

We choose the direct approach of maximizing the network lifetime, similar to what is proposed in [32]. Our goal is to maximize the overall lifetime of the network, which is equivalent to maximizing the time until the first loss of coverage. In fact, we aim to increase the lifetime of each node in order to increase the network lifetime.

3.4.3 Assumptions

We assume that sensor nodes are aware of their geographic locations. We assume that sensor nodes are uniformly distributed in the area (mine gallery) and their deployment is not very dense or sparse. Two sensor nodes are called neighbors if they can directly communicate with each other. Neighbor nodes are considered one hop away from each other. All sensor readings are assumed to be accurate. A sensor node is called malfunctioning if it is out of battery energy, or cannot transmit and receive data due to some hardware problem. But sensor misreading has not been considered in this research. All sensor nodes are stationary, and randomly deployed. We assume all sensor nodes are homogenous, meaning that they are equipped with the identical hardware. We assume

that the energy consumed while there is no communication is negligible. Sensor nodes are assumed to be equipped with an omni-directional antenna.

All the nodes on the backbone Mesh network are considered as the sink nodes for our wireless sensor network. All the sink nodes are stationary, manually deployed along the boundary of the sensor network, and are connected to infinite power supply. All the sink nodes are connected to each other and to the unique outdoor Base Station, which gathers all the network messages and monitors the whole network activities. Sinks also have enough energy to route the packets to the main base station outside of the mine, in case of a power loss or blackout. We assume all packets from sensor nodes are destined to the sinks. There is no difference between the sinks from sensor nodes point of view. This means that sensor nodes can and should deliver their packets to any sink node which is closer to them according to the cost model. All the sinks are assumed homogenous.

3.4.4 Calculation of Link Cost

Our aim is to find an optimal path to at least one of the sink nodes in terms of energy consumption and error rate while considering maximizing the lifetime of the network and minimizing the transmission delay. Delay constraints are associated only with emergency traffic. Both emergency and non-emergency (or regular) traffic coexist in the network. Therefore, we not only should find paths that meet the requirements for emergency traffic, but also need to find optimal paths for regular traffic in order to increase the network lifetime as well.

The described QoS routing problem is very similar to that of [18]. Our approach is based on associating two different cost functions for each link, and use a least cost path algorithm to find the two different optimal routes, one for each type of network traffic. Before explaining the details of the proposed algorithm and link costs, we introduce the queuing model.

Queuing Model

Queuing model is proposed in [18] for the case of coexistence of real-time and non-real-time traffic in each sensor node as shown in Figure 5. We use the same concept in our network model to separate emergency and non-emergency traffic. We use different queues for these two different types of traffic. On each sensor node, there is a classifier, which checks the type of the incoming packet and sends it to the appropriate queue. There is also a scheduler, which determines the order of packets to be transmitted from the queues according to the priority of each type of traffic. Since the emergency traffic is delay constrained, we assign the highest priority to the emergency data. As the amount of emergency traffic generated in the network is trivial compared to the non-emergency traffic, assigning the highest priority to emergency data will not cause the regular traffic to starve for bandwidth or to endure a long delay. Both classes can borrow bandwidth from each other when one of the two types of the traffic is non-existent.

Figure 7: Priority Queue on a particular sensor node. Emergency traffic has the highest priority.

3.4.4.1 Link Costs for Emergency Traffic

As mentioned before, emergency traffic is loss and delay constrained. In mine applications, emergency messages contain some vital information about workers safety. Therefore, our main objective is to find a shortest delay path for emergency traffic which

is as reliable as possible. We consider reliability in terms of the least probability of retransmission required along the path. Due to high error-rate in underground mine spaces, retransmissions increase path delay. Thus for emergency traffic, our objective is to find the cost function that can be used in selecting paths with minimum delay and higher path survivability. Reducing power consumption is not our concern when dealing with vital emergency traffic.

Since emergency traffic is generated rarely in the network and it has the highest priority in the nodes queue, we can safely assume the queuing delay is negligible. The propagation delay on the link (i, j) , depends both on the distance between nodes i and j , and the link quality. As per [50] there are two different propagation zones in a coal mine. Also, high error rate on the link will reduce the delivery reliability and will cause several re-transmissions to send the packet, which is undesirable in the network. The third parameter which is important to select an optimal path for emergency data is the nodes residual energy along the path. Since we do not reserve these optimal paths for emergency traffic, chances are that these selected paths are over used by the regular traffic in the network and are not available when emergency traffic needs them. So, we consider choosing nodes with higher residual energy when setting up the route for emergency traffic to reduce the possibility of path loss. This will increase the reliability of message delivery, and eventually contributes to achieve less transmission delay.

With the above thoughts in mind, the path cost $path\ cost_{p-emergency}$ is proposed to be:

$$path\ cost_{p-Emergency} = f(hop\ count_p, link - quality_p, residual\ energy_p) \quad (Eq. 2)$$

We choose to use the $hop\ count_p$ as a distance representative along the path; therefore each link (i, j) is counted as one hop. This decision is based on our strategy for routing emergency traffic without considering the energy expenses. Since the goal is to find the shortest path which decreases the transmission delay, hop count would be the ideal choice.

In the above (Eq. 2), $link - quality_p$ represents the $link_{ij} - quality$ along the path p .

Link quality is considered in order to choose a more reliable link which has less error rate and reduces the probability of re-transmission. Such link ultimately cooperates in reducing the delay in transmitting the message to the sink.

In order to measure the error rate or link-quality in underground mines, some researchers have proposed comprehensive models for wireless propagation prediction in underground mines [22, 51, and 52]. Their models consider signal reflection, attenuation, scattering, and diffraction caused by rough mine surfaces, and provide equations to calculate the received signal power. Although these references have adequately modeled the wireless propagation, their proposed equations are very complicated and depend on too many factors. In this research, we have selected the Expected Transmission Count (ETX) as a measure for the link-quality. ETX predicts the number of transmissions (including retransmissions) on each link. Therefore it is a suitable metric to calculate the path delay.

The third parameter in selecting the best path is $residual\ energy_p$, which indicates the residual energy of nodes along the path p . Considering nodes' residual energy is essential for survivability of the path. Otherwise, nodes' energy level is not important in forwarding emergency traffic when delay is the main consideration. To illustrate more, consider the case depicted in Figure 8. On each iteration of the algorithm, the best path for emergency traffic is selected and will be used for the whole duration of the cycle. The next calculation of the best path will take place after τ seconds, which τ is the time period of the algorithm. If we choose the least cost path without considering the residual energy of the nodes along the path, we might end up in losing the path before arrival of the emergency data.

Figure 8: Occurrence of emergency data after one of the nodes along the path is out of energy and before the next refreshment cycle (τ); E_r is the node's residual energy.

In order to avoid such path loss situations, we need to find the node with minimum residual energy along the path, and find the lifetime of such node. The lifetime of the node with minimum energy will determine the lifetime of the path. Our goal is to avoid a path with survivability less than τ seconds.

Let $E(T)$ to be the expected lifetime of a node. Based on (Eq. 11) in Appendix A, $E(T)$ could be calculated as a function of the residual energy of the node, E_r , as:

$$E(T) = \frac{E_r}{(\lambda_i - \lambda_s) e_{id_o}^r + \lambda_i e_{id_o}^t} \quad (\text{Eq. 3})$$

We define $f(E_r)$ such that:

$$f(E_r) = \begin{cases} 1 & , \text{ if } E(T) \geq \tau \\ \infty & , \text{ if } E(T) < \tau \end{cases} \quad (\text{Eq. 4})$$

The link cost function for emergency traffic could be written as shown in (Eq. 5), in which E_r is the residual energy of the receiver node.

$$link\ cost_{ij-Emergency} = ETX_{ij} \times f(E_r) \quad (Eq. 5)$$

Based on the above discussion, the (Eq. 2) could be written as follow:

$$path\ cost_{p-Emergency} = \sum_p \left(ETX_{ij} \times f(E_r) \right) \quad (Eq. 6)$$

In fact, the algorithm looks for the paths which fulfill the survivability condition, but among these survivable paths the one with the lease ETX cost will be chosen for relaying the emergency traffic. The cost function (Eq. 6), emphasis on our main design goal, which is finding the minimum delay path.

3.4.4.2 Link Costs for Non-Emergency Traffic

As previously stated, emergency situation and therefore emergency traffic rarely occur in the network. The sensor network is mainly busy with monitoring and reporting the non-emergency events. This task will consume the major energy of the nodes and might cause network partitioning. Our second objective is to increase the network longevity to be able to route the emergency data in case of a critical incident. Therefore, for regular and common traffic, our aim is to find the best link cost function which will lead to the maximization of the system lifetime. Here we consider the energy consumption, since it is important to not use extra energy; however, the transmission delay is not crucial since the regular traffic is not delay constrained.

We don't reserve or protect any path to be used specifically for emergency traffic; therefore we don't know which sensors belong to the emergency routes. As a result, our aim is to increase the longevity of each and every sensor node. A good candidate for our algorithm should consume less energy and should avoid the nodes with small residual energy, since we would like to maximize the minimum lifetime over all nodes. We use (Eq. 1), the cost function used in reference [32], with a little modification to find the optimal path for regular traffic. First, we use the best values obtained for x_1 , x_2 , and x_3

in [32] which are 1, x, x correspondingly. Second, since we assume all sensor nodes start with equal initial energy, we have excluded the initial energy from (Eq. 1) and have used absolute residual energy. Therefore our link cost function for regular or non-emergency traffic is:

$$\text{link cost}_{ij-Regular} = e'_{ij} \cdot \underline{E}_i^{-x} + e''_{ij} \cdot \underline{E}_j^{-x} \quad (\text{Eq. 7})$$

where $\text{cost}_{ij-Regular}$ is the cost of link (i, j) for transmitting regular traffic from node i to node j . e'_{ij} and e''_{ij} , are the energy consumption for unit data transmission over the link, and $\underline{E}_i$ and $\underline{E}_j$ are the residual energy of nodes i and j .

Note that link quality is also a significant factor in selecting the optimal route for non-emergency traffic. A link with higher error rate or path-loss probability will increase the retransmission and will consume more energy to deliver the message. However, we have decided that link quality feature is hidden in transmission cost, e'_{ij} factor, since the sender will consume more energy to overcome the transmission obstacles on a high error rate link. In fact, e'_{ij} could be defined as:

$$e'_{ij} = e^T + \alpha PL(d_{ij}) \quad (\text{Eq. 8})$$

where e^T is a constant (refer to [32]), α is a constant, and path-loss on link (i, j) with distance of d , $PL(d_{ij})$, is defined in [50]¹ for mines as:

$$PL(d) = \begin{cases} 20.5 + 20.5 \log_{10}(d) & , \text{ for a straight wide drive} \\ -22.2 + 64.5 \log_{10}(d) & , \text{ for a drive with sharp bend} \end{cases} \quad (\text{Eq. 9})$$

We consider the factors for the cost function on each particular link separately. The path cost is computed by the summation of the link costs on the path, and the algorithm can be implemented with an existing shortest path algorithm such as the distributed Bellman-

¹ As per their study for a 900 MHz radio communication network in underground mines, the typical path losses (PL) in dB as a function of distance (d) in meters are likely to fall within the two extreme conditions: straight wide drive, and sharp bend drive.

Ford algorithm, similar to what we have used for calculating the path cost for emergency traffic.

3.4.5 MDML Routing Algorithm

We consider a wireless sensor network that is denoted by weighted directed graph $G = (V, L)$, where V is the set of vector nodes and L is the set of directed links. Each node is labeled with a unique ID $i \in [1 \dots |V|]$ and has a maximum transmission power of $\underline{E}_i$. Let e_{ij}' denote the minimum transmission power required to maintain a reasonably good quality link from node i to node j . G contains link (i, j) if and only if $e_{ij}' \leq \underline{E}_i$. We define $S = \{s_1, s_2, \dots, s_n\}$ to represent all the sink or destination nodes for the sensor network G .

Summary of the MDML Algorithm

1. the algorithm starts with the sinks broadcasting the *Sink Announcement Packet* (SAP)
2. use the Bellman-Ford shortest path algorithm and the two link costs defined in section 3.4.4, to find the least cost path from each sensor node to the sink S
3. all the sinks belong to S are indifferent for the sensor nodes in terms of the ultimate destination, meaning that each sensor node tries to route its packets to the closets sink s_i
4. each sensor node has a routing table to keep its two next hop, one for each type of the traffic (emergency, and regular); each sensor node also keeps the cost to reach the destination
5. each sensor node has a priority queue to separate the incoming traffic: the emergency data has the highest priority

6. sensor nodes update their routing table only on reception of a new route which has a smaller cost; the sensor node will also advertise this new route to its neighbors; otherwise the new message will be ignored and dropped
7. the algorithm will repeat every τ second to repair the routes. Since re-constructing the trees consume energy and is costly, our goal is to increase the refreshment time periods. The refreshment time τ is reversely proportional to the number of messages produced in the network, and the energy consumption per packet transmission, so it also reversely proportional to the error-rate in the network.
8. We have introduced an Acknowledgment message (ACK) in the network, used only for emergency data. When a sensor node transmits a packet of emergency traffic, it waits to receive the ACK from the recipient node. If no ACK is received, the sender assumes its next hop neighbor is malfunctioning and decides to broadcast the emergency packet to all its neighbors in order to deliver the emergency message as quick as possible. This will cause extra traffic in the network, but will prevent losing the emergency message. Plus, since the emergency traffic is generated on exceptional occasions, the overload of ACK won't be noticeable.
9. In order to reduce the number of communications in the network, we have used data aggregation. All the sinks are synchronized and data has a time stamp. If a node receives more than one packet of the same message, it will aggregate the received messages into one packet and will transmit it to the sink. This will eliminate redundancy; minimize the number of transmissions and thus save energy in the network.

4 Simulation and Results

We developed a simulation model to validate the effectiveness of MDML routing protocol and evaluate its performance. This chapter describes the simulation model, performance metrics, and experimental results. We have used an open-source simulator, J-Sim [36], which provides the opportunity of using a complete protocol stack for simulation experiments.

4.1 Implementation

In order to implement MDML, we need to implement a routing protocol to disseminate the sink announcement packet (SAP) periodically, a routing table (RT) to keep the cost and next hop information, and Bellman-Ford shortest path algorithm to find the least cost path for each type of data packets. The sink node broadcast a sink announcement packet on every refreshment cycle (τ). Every SAP contains the residual energy of the transmitter node, as well as the accumulated path cost for both emergency and regular type of data. Figure 9 shows the internal fields of a SAP. The energy of the sink is set to be unlimited. Every SAP also contains a time stamp field to represent the original time it was generated by the sink. The time stamp it used both to update the routing table entries and to avoid the loop in broadcasting the SAP. When a sensor node receives the SAP, it extracts the cost and energy metrics, calculates the new path costs for both emergency and regular traffic based on the newly arrived SAP, compares the new cost with the one in the routing table, and decides whether to update its routing table or discards the SAP. Figure 10 depicts the external fields of a routing table entry. The sensor node only updates its routing table in one of the following cases:

1. A freshly generated SAP is received : in this case the sensor node updates all the fields of its routing table (RT)
2. The time-stamp of the SAP is the same, but it has a less path cost for emergency traffic: in this case, only the emergency-cost and emergency-nexthop fields of the RT is updated

3. The time-stamp of the SAP is the same, but it has a less path cost for regular traffic: in this case, only the regular-cost and regular-nexthop fields of the RT is updated

When a sensor node updates its routing table, it broadcasts the received SAP to advertise the newly computed route to its neighbors. Otherwise it suppresses the SAP and stops the forwarding process. Figure 11 show a flowchart of processing a received SAP by a sensor node. The sink announcement packet and routing entry fields are shown below.

regular-path-cost	emergency-path-cost	sender-residual-energy	time-stamp
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Figure 9: the internal fields of a Sink Announcement Packet (SAP)

regular- nexthop	emergency-nexthop	regular-cost	emergency-cost	time-tag
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Figure 10: the internal fields of a routing table (RT) entry

We have also implemented a two-level priority queue to classify incoming packets based on the packet type. Each target packet has a priority field that is used to classify the packets in the priority queue. Moreover, each target packet is time-stamped when it is generated to allow the calculation of average delay per packet.

4.1.1 Implementation Limitations

The implementation of MDML has some shortcomings compared to what we proposed in Section 3.4. The Acknowledgment message (ACK) for emergency traffic is not implemented yet. The ACK packet was introduced to assure the reception of an emergency packet and repair the route if the next hop for emergency data is no longer available. Data aggregation along the path is another feature of MDML that has not been implemented in the software. Sensor nodes are supposed to be able to aggregate the redundant or similar data packets they receive through neighbors, before transmitting

such data towards the sink node. We consider adding these features in the future version of MDML software. These features are expected to improve the protocol efficiency, but they do not qualitatively affect the main optimization objectives of the MDML protocol.

We used free space path loss model and did not implement path loss model given in Eq. 8. We are not able to simulate the power control for wireless transmission in the simulator. All the packets are transmitted with the same power consumption. So, in the link cost calculation for regular traffic (Eq. 7), e_{ij}^t and e_{ij}^r are assumed to be fixed values, independent of the link. Also, when calculating the path cost for emergency traffic, we have used hop-count instead of ETX in Eq. 5. Another assumption we made in the simulation is to consider the same expected cost¹ for all the nodes for simplicity. Therefore, the expected lifetime of each sensor node is directly associated with its residual energy. Nevertheless, the abovementioned shortcomings do not invalidate the simulation results.

Moreover, the actual MDML assumes availability of multiple sinks in the region. We have simulated MDML with only one sink node positioned in the corner of the simulating area. However, this is not a big disadvantage of the implementation. Apparently if we could deploy more than one sink the performance results would be better, but not different.

¹ We refer to the denominator of the fraction in Eq. 3, as expected cost.

Figure 11: Flowchart of processing a received SAP in the MDML routing protocol

4.2 Experimental Setup

In the experiments the sensor network consists of 40 sensor nodes randomly distributed in a 100x100 square meter area from (10, 10) to (110, 110). The sink is deterministically located at the corner of the region at (10, 10). Sensor nodes assumed to have omnidirectional antennas with wireless radio transmission range of 30 meters. Each sensor node starts with initial energy of 20 Joules. A node is considered non-functional if its energy level reaches 0. We assume that the energy consumed in the idle mode, i.e. while there is no communication, is negligible. We used J-Sim's default transmission power consumption of 0.660 J/s and reception power consumption of 0.395 J/s.

Events (or stimuli) are generated by target nodes. We created two different types of target nodes in order to generate two types of traffic events: *emergency* and *non-emergency* or *regular*. The regular events are generated by a mobile target node which moves with the constant speed of 30 m/s in a randomly chosen direction within the boundary of the region, and generates a non-emergency message every 2 seconds. The regular target node is initially located at (110, 110). The emergency events are generated by a mobile emergency target node initially deployed at (100, 100). The emergency target moves in a random direction with the constant speed of 10 m/s to simulate random emergency messages. The rate of emergency packet generation is very small and the total number of emergency messages generated during the simulation period is about 5% of the total regular packets. Except for the target nodes, all the other nodes including the sink, and all the sensor nodes are stationary. Each target's transmission radius is 20 meters, so as the mobile targets moves around the network all the sensor nodes within 20 meters distance will receive the event packets. This is sufficient to simulate the periodic regular traffic in the sensor network, as well as the random emergency events.

Packet sizes are 70 bytes for data packets and 24¹ bytes for protocol routing and refresh packets. We implemented a two-level priority queue with highest priority allocated to

¹ This is the packet size used in J-Sim for AODV protocol.

emergency packets. The priority queues size is 40¹ packets. A free space wireless propagation channel model is applied with radio bandwidth of 2 Mbps. We have assumed uniform propagation model in the entire region. This does not simulate the real mine environment, however, it does not invalidate the results. The seismic propagation model is used on the sensor channel (to broadcast target events to sensor nodes). We have used the IEEE 802.11 MAC protocol with power saving mode (PSM). The simulation time, T, is 2000 seconds. Figure 12 show the architecture of a sensor node in J-Sim. Appendix B presents a summary of the simulation configuration.

Figure 12: Internal view of a sensor node (dashed line) with its connections to other components [46]

¹ Default queue size in J-Sim. The total buffer size in the priority queue is 40 packets.

4.3 Performance Metrics

We used the following metrics to capture the performance of our MDML routing protocol:

- **Average delay per packet:** the average time a target packet takes from a sensor to the sink.
- **Network Lifetime:** time when the first node runs out of energy.
- **Protocol overhead:** defined as the average number of protocol packets¹ (SAP) advertised by each sensor node to run the protocol.
- **Standard Deviation (SD) of energy:** defined as the SD of sensor nodes' residual energy at time = 1000 sec (almost half way through the simulation period), to evaluate the quality of route.

4.4 Performance Results

In this section we study the behavior of the MDML protocol. We are interested in evaluating the performance of MDML with respect to improving the network lifetime and reducing the end-to-end delay for the emergency packets.

4.4.1 Maximizing Lifetime

We varied the refreshment cycle of the protocol, τ , and monitored how it affects the network lifetime, protocol overhead, and quality of routes in the network. The experiments are repeated for six different topologies to show the trend is independent of topology changes.

¹ In this thesis, we refer to all the packets generated by the protocol as the protocol packets. In other terms, protocol packets are needed to run the routing protocol and establish the routes. In MDML, the protocol packet is called SAP (Sink Announcement Packet).

Figure 13: Affect of τ on protocol overhead – Topology 3 is used.

Affect of τ on the protocol overhead is shown in Figure 13. The protocol overhead decreases as we increase the update cycle, τ . This behavior is expected, since as we increase τ , the sink broadcasts the control packets (SAP) less frequently, meaning that the protocol is updated fewer times. Therefore the total number of route discovery packets (SAP) advertised by each sensor nodes is decreased and as a result the protocol overhead is decreased. Figure 13 depicts the affect of increasing τ on the average number of protocol packets generated per node in topology_3. It also shows the minimum and maximum overhead of nodes. For small values of τ , the overhead is large. When τ is increased from 100 to 300 seconds, the overhead decreased noticeably. For τ between 400 and 700 seconds the overhead does not change that much, and after 700, the overhead falls.

Although, the small amount of overhead is desirable, it is not the only performance metric we aim to improve. Increasing the update cycle of the protocol also affects the lifetime of the network and the quality of routes in the network region, the two other performance metrics we wish to improve.

Figure 14 depicts the affect of τ on the network lifetime. As shown, increasing τ improves the network lifetime up until τ equal 400 seconds in topology 3, but after that the lifetime decreases with increasing τ . This result is reasonable, since when τ is increased, the number of times that protocol generates update packets (SAP) is decreased. Therefore, some of the routes will be overused and the nodes on those routes will run out of energy earlier. The smaller value of τ causes more frequent route update in the network. Hence, the network is flooded with extra route update packets (SAP), causing the sensor nodes to consume more energy in transmission and reception of the protocol packets. Increasing the update cycle (τ) improves this situation, but on the other hand because of less amount of route updates, some of the routes will be overused and nodes on the routes will fail earlier.

Figure 14: Affect of τ on network lifetime

We have also studied the effect of τ on the quality of route. Figure 15 depicts the standard deviation of nodes' residual energy at different times. We want to examine the affect of τ on distribution of nodes' energy. As we increase τ , the route quality becomes

worse. While we increase the update cycle of the protocol, the load balance in the network becomes poorer. This is because some nodes are pounded with data packets while other nodes are never or rarely used. The smaller amount of τ means more frequent route updates and thus fair utilization of network resources.

Figure 15: Affect of τ on standard deviation of nodes' residual energy

We have repeated the experiments for different topologies to confirm the accuracy of the results. Figures 16-18 respectively show the affect of τ on network lifetime, quality of route, and protocol overhead using four different topologies. Although selecting the optimal update cycle (τ) depends on topology, the trend of changes is the same in all the topologies. Figure 17 shows that in some topologies, very small value of τ has a greater standard deviation compared to the mid range of τ . This shows that extra recurrent updates could worsen the balance of energy distribution among the nodes, since some of the nodes end up broadcasting more protocol packets (SAP) than other nodes, resulting in extra energy expenditure. Increasing τ will improve this satiation, but for large value of τ the standard become worse, since some of the routes will be overused. Therefore, the update cycle should be chosen with caution.

Figure 16: Affect of τ on network lifetime, in different topologies

Figure 17: Affect of τ on standard deviation of nodes' residual energy in different topologies

Figure 18: Affect of τ on protocol overhead in different topologies

In summary, we have studied the effect of MDML update cycle, τ , on the network lifetime, quality of route in the network and protocol overhead. The results show that increasing τ improves the protocol overhead, but weaken the quality of route in the network. Increasing τ also improves the lifetime of the network, but large amount of τ will decrease the lifetime. Based on the experiments, the amount of τ should not be too small or too large. The value of τ equal to 400 seconds seems to satisfy all the performance requirements for most topologies.

4.4.2 Minimizing the Delay

In the following experiments the update cycle τ is set to 400 seconds. Here the goal is to measure the average end-to-end delay per packet for emergency and regular traffic. We expect emergency traffic to experience a much less delay compared to the dominant regular traffic. We have increased the rate of emergency event generation to one third of the regular event packet generation to compare the average delay per packet. Since the delay is correlated with the distance of the target node from the sink, six different

topologies have been used to ensure the result is topology-insensitive. Appendix C enclosed all the six randomly generated topologies we used in the simulation. Figure 19 shows the average delay for both type of traffic under different topologies. As result confirms, the average delay for emergency traffic is less than the average delay for regular traffic in all the topologies.

Figure 19: Ave. delay per packet, compared Emergency and Regular packet delays using both MDML and Non-MDML approaches

In order to verify the effectiveness of the MDML approach in reducing the delay for emergency traffic, we have simulated a Non-MDML routing protocol, which is the simulation of the Maximum Lifetime Routing proposed in [32]. The Non-MDML approach uses FIFO queues instead of the priority queues in the wireless stack. The Non-MDML protocol also does not differentiate between emergency and regular packets in routing; meaning that the same routes are used for both type of traffic in the network. The link cost function Non-MDML uses to find the next hop for both regular and emergency packet, is the one we used for regular traffic in the MDML protocol. We have used the same topologies and target generation rate under both MDML and Non-MDML routing approaches and have measured the average end-to-end delay for regular and emergency traffic. The results are shown in figure 19. As shown, using MDML improves the delay

for emergency traffic. On the other hand, in Non-MDML approach, sometimes the average delay for emergency traffic is more than average delay for regular traffic. This happens due to the high volume of the regular traffic in the FIFO queue that causes the emergency data to experience even longer delay.

Figure 19 also shows that the average delay for regular traffic in both routing approaches is almost equal or very close. We expect that in Non-MDML approach, more emergency traffic will be lost since they are routed through paths that do not guarantee the lifetime of the next hop node. It is a part of our future work to study the affect of MDML on emergency packet loss.

We have varied the emergency target generation interval to study its affect on the emergency packet delay. Figure 20, is based on topology 5, with τ equal to 400 seconds, and regular packet generation interval of 5 (i.e. one regular packet is produced in every 5 seconds). The emergency packet generation interval is changed from small interval of 10 to large interval of 600. As the interval is increased the difference between average delay of emergency and regular traffic becomes smaller. The reason for this is that the emergency target moves in a random direction inside the terrain. When emergency target produces events more frequently, the traffic is received evenly by almost every node in the network at different locations and different distances from the sink, thus the average delay is a suitable metric for delay comparisons. However, for large values of emergency interval, the better metric should be used such as setting up an upper bound delay and measure the percentage of packets that exceed this threshold delay for each type of traffic.

Figure 20: Average delay per packet; comparison between regular and emergency traffic

We have used a stationary emergency target located in the middle of the topology 5, to verify the affect of interval changes. The stationary target will remove the effect of random movement of the target and hence topology change due to random movement. The simulation ends when the first node runs out of energy. The result is shown in Figure 21.

Figure 21: Average delay per packet; comparison between regular and emergency traffic with a stationary emergency target

We also have studied the packet loss for both emergency and regular traffic for different topologies. We have increased the number of regular target nodes to increase the regular traffic and have used a buffer size equal to 20 for priority queue. Four regular target generation nodes are placed in different places of the network. The protocol update time, τ is set to 400 seconds. The simulation ends when the first node runs out of energy. Figure 22 shows the average delay per packet for emergency and regular traffic. Figure 23 shows the ratio of packet loss for regular data. Simulation results in all the different topologies used confirm that there is no packet loss for emergency traffic. This result confirms the reliability of MDML for emergency traffic. The packet loss ratio for regular data varies from 1.5% to 4.9% in different topologies.

Figure 22: Average delay per packet, with four stationary regular targets

Figure 23: The packet loss ratio of regular traffic

Finally, we have compared the lifetime of MDML with the Non-MDML (Maximum Lifetime Routing [32]) approach. Figure 24 shows the lifetime comparison between MDML and Non-MDML in topology 3 versus τ . In most cases Non-MDML has a better lifetime. Figure 25 also shows that Non-MDML has a slightly better quality of route compared to MDML. The reason is that MDML does not consider energy efficiency method when routing the emergency packets. Thus in MDML we compromise in lifetime to achieve less delay for emergency traffic. However, since the number of emergency traffic generated in the network is not considerable, the lifetime and quality of route of MDML is not significantly lower than Non-MDML.

Figure 24: Network lifetime vs. τ , in topology 3, comparing MDML and Non-MDML

Figure 25: Comparing quality of route of MDML and Non-MDML approach

5 Conclusions and Future Work

In this thesis we showed the viability of architecture of a Wireless Sensor Network (WSN) for mining applications to achieve mine safety. We introduced Minimum Delay Maximum Lifetime (MDML) routing protocol in wireless sensor network to achieve low loss and low delay routing of emergency data traffic and increased lifetime of the network by employ energy efficient routing for periodic non-emergency traffic. MDML is specifically designed according to mining application requirements. Two types of network traffic have been considered with respect to delay constraints. The objective is to minimize the losses and end-to-end delay for emergency traffic and maximizing the lifetime of the sensor network. Specific radio communication challenges in underground mine environments which end up to extra path loss has been considered. The sensor network architecture which is scalable is introduced. Two different link cost functions has been introduced to calculate the optimal path for each type of traffic. Lifetime maximization has one main goal: to be able to route any emergency event at any time from any location of the terrain to the sink, and one secondary goal: to route the dominant periodic monitoring packets (or regular packets) with energy aware techniques. The secondary goal is in line with the main goal and these both serve the benefit of minimum delay objective. Simulation results confirm the effectiveness of MDML in minimizing the delay for emergency traffic and maximizing the overall lifetime of the network. Based on the results, the network lifetime can be improved by choosing a suitable value of update cycle (τ). The update cycle also affects the quality of route in terms of fair usage of nodes' energy. Although choosing τ depends on the network topology, the results show that an update cycle between 300 to 600 seconds is suitable for most topologies studied. Beyond and above these values, the performance of network becomes worse noticeably. Also, the average delay per packet for emergency traffic is always less than that of regular traffic for all the topologies studied. Finally, our simulation shows that emergency traffic experience zero loss.

Based on the work presented in this thesis, the following are some suggestions for future work:

- to study the effect of traffic load, network density and terrain size (e.g. an underground mine tunnel) on the performance and overhead of the algorithm, to apply different wireless propagation models on different link and verify the behavior of the protocol to improve the delay under difficult propagation conditions.

- Extend the current model to incorporate data aggregation along the paths.

Redundant events can be detected by the intermediate sensor nodes, or similar target events can be aggregated to one to limit the data communication in the network.

- In MDML, sink is the final destination for all the targets. Sending a specific signal to another sensor node could be considered in the future to distribute safety alarms in the mines.

- Link cost for regular data should be changed in order to provide balanced load distribution in the network. Considering node degree is one suggestion.

- Update cycle τ is reversely proportional to the number of messages generated in the network; the higher traffic need more frequent updates, while low traffic does not require frequent updates; node can save their residual energy for longer time. Considering setting different τ for different region of the network, while achieving the synchronization is another future work.

- Investigating the miss ratio (ratio of lost packets over total number of received packets) for each type of network traffic in the current model on MDML.

- To incorporate local repair methods into current model and study its affect on delay and miss ratio.

A Expected Lifetime of a Sensor Node

In this section, we explain the calculation of the expected lifetime of a sensor node based on its residual energy. References [54 and 55] presented mathematical estimates for calculating the expected lifetime of a sensor node. In this research, we have made a simplified version of the expected lifetime of a sensor node based on what presented in reference [55]. We have considered a multi-hop sensor network of N randomly deployed nodes, all with the same capabilities and same initial energy. According to reference [55], the expected lifetime of a sensor node i can be obtained as:

$$E(t_i) = \frac{E_0}{\lambda_s \epsilon_s + (\lambda_i - \lambda_s) \epsilon_{re} + \lambda_i \left(\epsilon_{tx} + \epsilon_{rf} \left(\frac{d}{d_0} \right)^n \right)} \quad (\text{Eq. 10})$$

where,

n is the path-loss component,

E_0 is the nodes initial energy

λ_s is the traffic rate generated by the node itself

$(\lambda_i - \lambda_s)$ is the rate of traffic forwarded to the node by neighbors, and therefore

λ_i is the total traffic sent out by the node

ϵ_s is the energy consumed to sense a bit of data

$\left(\epsilon_{tx} + \epsilon_{rf} \left(\frac{d}{d_0} \right)^n \right)$ is the energy needed to transmit a bit of data to a reference distance d_0

ϵ_{re} is the energy consumed to receive a bit of data

To simplify the (Eq. 10), we assume that the energy consumed for sensing data is negligible compared to the energy consumed for data transmission. Also, as we have declared in subsection 3.4.4.2, e'_{ij} and e''_{ij} is the energy consumption for unit data transmission over the link, therefore we can write:

$$\left(\varepsilon_{ix} + \varepsilon_{rf} \left(\frac{d}{d_0} \right)^n \right) = e'_{id_0} \quad , \text{ and } \quad \varepsilon_{re} = e^r_{id_0}$$

Thus, (Eq. 10) could be simply written as follow:

$$E(t_i) = \frac{\underline{E}_i}{(\lambda_i - \lambda_s) e^r_{id_0} + \lambda_i e'_{id_0}} \quad (\text{Eq. 11})$$

where $E(t_i)$ is expected lifetime of sensor node i with residual energy of $\underline{E}_i$.

As in [54], we assume that an event can occur at any point in the network with equal probability, which implies that we assume the rate of data aggregation at each point in the network is the same. In addition, we assume that the occurrence of every event is both temporally and spatially independent of all the other events in the network. Based on these statements, we can assume that λ_i and λ_s are the same for every sensor nodes in our network. Consequently, the expected lifetime of each node can be obtained as a function of its residual energy.

In [55], λ_s is assumed to be the same for all nodes when we have periodic traffic. In this part, we briefly explain how λ_i is calculated according to [55]. Let s_i to be the i -th sensor node in the sensor network denoted by $S = \{s_1, s_2, \dots, s_N\}$, where $|S| = N$. Let G be the set of sensors that can communicate directly with the sink node and that all traffic has to be transmitted to the sink through one of the members of G . It is easy to conclude that the lifetime of set G determines the lifetime of the network. In each node $s_i \in G$ the traffic is composed by traffic generated by the node itself, λ_s , and the traffic received from other nodes outside of G , denoted by λ_r, i . We need to determine which part of traffic outside G will be relayed to each node $s_i \in G$. Let A_0 denote the area where nodes are able to communicate with the sink and A_i denote the area that is within the transmission range of node $s_i \in G$ but outside $A_j, j < i$ (Figure 26). Based on the assumption the sensor nodes are uniformly distributed in the area, the total traffic in A_i is given as follows:

$$\lambda_{r,i} = \frac{A_i}{\left(\sum_{j=1}^{|G|} A_j\right)(|S| - |G|)\lambda_s} \quad (\text{Eq. 12})$$

Then λ_i the traffic at s_i can be determined as: $\lambda_i = \lambda_s + \lambda_{r,i}$.

Figure 26: Sensor Network [55]

B Simulation Configuration

Terrain size	100 m x 100 m
Num. of sink nodes	1
Num of sensor nodes	40
Sensor node placement	random
Sensors transmission range	30 m
Nodes' initial energy	20 J
Num of emergency target nodes	1 , mobile node
Rate of emergency target generation	One packet every 100 sec
Num of regular target nodes	1 , mobile node
Rate of regular target generation	One packet every 2 sec
Targets transmission range	20 m
Transmission power consumption	0.660 J/s
Reception power consumption	0.395 J/s
Radio Bandwidth	2 Mbps
Data packet size	70 bytes
Protocol packet size	24 bytes
MAC Protocol	802.11 (PSM)
Routing Protocol	MDML
wireless propagation model	free space
sensor propagation model	seismic
Priority queue buffer size	40 packets (total size of the queue for both high and low priority)
Simulation time	2000 s

Table 5: Simulation Configuration

C Topologies Used in the Simulation

Bibliography

- [1] J. N. Al-Karaki, A. E. Kamal, "Routing techniques in wireless sensor networks: A survey", *IEEE Wireless Communications*, v 11, n 6, December, 2004.
- [2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless sensor networks: A survey", *Computer Networks*, v 38, n 4, Mar 15, 2002.
- [3] <http://wsnl.stanford.edu/overview.php>.
- [4] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, D. Culler, "An analysis of a large scale habitat monitoring application", *SenSys'04 - Proceedings of the Second International Conference on Embedded Networked Sensor Systems*, p 214-226, 2004.
- [5] E. Ekici, Gu. Yaoyao, D. Bozdag, "Mobility-based communication in wireless sensor networks", *IEEE Communications*, v 44, Issue 7, July, 2006.
- [6] G. Ferrari, M. Martalo, "Extending the lifetime of sensor networks through adaptive reclustering", *Eurasip Journal on Wireless Communications and Networking*, v 2007, p 31809, 2007.
- [7] Th. Arampatzis, J. Lygeros, S. Manesis, "A survey of applications of wireless sensors and wireless sensor networks", *IEEE International Symposium on Intelligent Control and 13th Mediterranean Conference on Control and Automation (IEEE Cat. No. 05CH37647)*, 2005.
- [8] T. He, S. Krishnamurthy, J.A. Stankovic, T. Abdelzaher, L. Luo, R. Stoleru, T. Yan, L. Gu, J. Hui, B. Krogh, "Energy-efficient surveillance system using wireless sensor networks", *MobiSys 2004 - Second International Conference on Mobile Systems, Applications and Services*, 2004.
- [9] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, J. Anderson, "Wireless sensor networks for habitat monitoring", *Proceedings of the ACM International Workshop on Wireless Sensor Networks and Applications*, 2002.
- [10] H. Wang, J. Elson, L. Girod, D. Estrin, K. Yao, "Target classification and localization in habitat monitoring", *IEEE International Conference on Acoustics, Speech, and Signal Processing (Cat. No.03CH37404)*, 2003.
- [11] J. Burrell, T. Brooke, R. Beckwith, "Vineyard computing: sensor networks in agricultural production", *IEEE Pervasive Computing*, v 3, n 1, Jan.-March 2004.
- [12] M. Srivastava, R. Muntz, M. Potkonjak, "Smart kindergarten: Sensor-based wireless networks for smart developmental problem-solving environments", *Proceedings of the*

Annual International Conference on Mobile Computing and Networking, MOBICOM, 2001.

[13] Y. Li, S. S. Panwar, and S. Mao, "A wireless bio-sensor network using autonomously controlled animals," *IEEE Network, Special Issue on Wireless Sensor Networking*, vol.20, no.3, May/June 2006.

[14] J.H. Cui, J. Kong, M. Gerla, and S. Zhou, "The challenges of building scalable mobile underwater wireless sensor networks for aquatic applications", *IEEE Network*, v 20, n 3, May/June, 2006.

[15] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking", In *Proceedings of the IEEE Wireless Communications and Networking Conference*, April, 2006.

[16] D. Pompili, T. Melodia, and I. F. Akyildiz, "Routing Algorithms for Delay-insensitive and Delay-sensitive Applications in Underwater Sensor Networks", In *Proc. of ACM MobiCom.*, September, 2006.

[17] K. Akkaya, M. Younis, "A survey on routing protocols for wireless sensor networks", *Ad Hoc Networks*, v 3, n 3, May, 2005.

[18] K. Akkaya, M. Younis, "An energy-aware QoS routing protocol for wireless sensor networks", In *Proceedings 23rd International Conference on Distributed Computing Systems Workshops (ICDCSW'03)*, May, 2003.

[19] Silvia Siu-Kei Tai, "Relaying Traffic with Energy-Delay constraints in Wireless Sensor Networks", M.A.Sc thesis, Queen's University, 2006.

[20] N. Boughanmi, Y.-Q. Song, "A new routing metric for satisfying both energy and delay constraints in Wireless Sensor Networks", *2nd International Conference on Sensor Networks and Applications (SNA06)*, 2006.

[21] J. C. Dagher, M.W. Marcellin, and M. A. Neifeld, "A Theory for Maximizing the Lifetime of Sensor Networks", *IEEE Transactions on Communications*, v 55, n 2, February, 2007.

[22] M. Ndoh, G. y. Delisle, "Underground mines wireless propagation modeling", *IEEE Vehicular Technology Conference (VTC)*, v 60, n 5, 2004.

[23] W. Farjow, "Mobile Networks in Confined Spaces Environments Difficulties and Challenges", Technical report, Ryerson University, March, 2007.

[24] W. Wang, V. Srinivasan, and K. Chua, "Using mobile relays to prolong the lifetime of wireless sensor networks", *Proceedings of the Eleventh Annual International Conference on Mobile Computing and Networking (MobiCom)*, 2005.

- [25] N. Aakvaag, M. Mathiesen, and G. Thonet, "Timing and power issues in wireless sensor networks - An industrial test case", *Proceedings of the International Conference on Parallel Processing Workshops*, 2005.
- [26] J. Wu, P. Havinga, "Reliable cost-based data-centric routing protocol for wireless sensor networks", *Proceedings - Seventh ACIS International Conference on Software Eng., Artific. Intelligence, Networking, and Parallel/Distributed Computing, SNPD*, 2006.
- [27] F. Ye, G. Zhong, S. Lu, L. Zhang, "GRAdient broadcast: A robust data delivery protocol for large scale sensor networks", *Wireless Networks*, v 11, n 3, May, 2005.
- [28] K. Sha, J. Du, W. Shi, "WEAR: a balanced, fault-tolerant, energy-aware routing protocol in WSNs", *International Journal of Sensor Networks 2006*, Vol. 1, No.3/4, p 156-68, 2006.
- [29] M. Younis, K. Akkaya, M. Eltoweissy, A. Wadaa, "On handling QoS traffic in wireless sensor networks", *Proceedings of the Hawaii International Conference on System Sciences*, v 37, 2004.
- [30] H. S. Kim, T. F. Abdelzaher, W. H. Kwon, "Dynamic delay-constrained minimum-energy dissemination in wireless sensor networks", *ACM Transactions on Embedded Computing Systems (TECS)*, Volume 4, Issue 3, August 2005.
- [31] Q. Dong, "Maximizing system lifetime in wireless sensor networks", *Fourth International Symposium on Information Processing in Sensor Networks, IPSN*, 2005.
- [32] J.H. Chang, L. Tassiulas, "Maximum lifetime routing in wireless sensor networks", *IEEE/ACM Transactions on Networking*, v 12, n 4, August, 2004.
- [33] E. Jung, D.M.H. Walker, "Reliable energy efficient routing in wireless sensor networks", *2nd IEEE International Conference on Mobile Ad-hoc and Sensor Systems, MASS*, 2005.
- [34] E. Egea-Lopez, J. Vales-Alonso, A. Martinez-Sala, P. Pavon-Marnio, and J. Garcia-Haro, "Simulation tools for wireless sensor networks", *International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)*, 2005.
- [35] E. Egea-Lopez, J. Vales-Alonso, A. Martinez-Sala, P. Pavon-Marnio, and J. Garcia-Haro, "Simulation scalability issues in wireless sensor networks", *IEEE Communications Magazine*, v 44, n 7, July, 2006.
- [36] J-SIM simulator, <http://www.j-sim.org/>

- [37] J. Bruck, J. Gao, A. Jiang, "MAP: medial axis based geometric routing in sensor networks", In *Proc. ACM/IEEE Internat. Conf. on Mobile Computing and Networking (MobiCom)*, 2005.
- [38] Y. Wang, J. Gao, and J. S.B. Mitchell, "Boundary recognition in sensor networks by topological methods", In *Proc. ACM/IEEE Internat. Conf. on Mobile Computing and Networking (MobiCom)*, 2006.
- [39] A. Jaffer, "Event boundary detection using autonomous agents in a sensor network", M.Eng. thesis, Ryerson University, 2006.
- [40] A. Jaffer, M. Jaseemuddin, M. Jafarian, and H. El-sayed, "Event boundary detection using autonomous agents in a sensor network", in *the Proceedings of the 5th ACS/IEEE International Conference on Computer Systems and Applications (AICCSA-067)*, May, 2007.
- [41] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance", *Wireless Networks*, v 11, n 4, July, 2005.
- [42] I. F. Akyildiz, and E. Stuntebeck, "Wireless underground sensor networks: Research challenges", *Ad Hoc Networks*, v 4, n 6, November, 2006.
- [43] J. Faruque, K. Psounis, and A. Helmy, "Analysis of gradient-based routing protocols in sensor networks"; *International Conference on Distributed Computing in Sensor Systems (DCOSS)*, IEEE/ACM, June, 2005.
- [44] J. Faruque, and A. Helmy, "RUGGED: Routing on fingerprint gradients in sensor networks", *Proceedings - the IEEE/ACS International Conference on Pervasive Services (ICPS)*, 2004.
- [45] W. Zhao, M. Ammar, and E. Zegura, "A message ferrying approach for data delivery in sparse mobile ad hoc networks", *ACM MobiHoc*, 2004.
- [46] A. Sobeih, W. Chen, J. Hou, L. Kung, N. Li, H. Lim, H. Tyan, and H. Zhang, "J-Sim: A Simulation and Emulation Environment for Wireless Sensor Networks", online, <http://www.jsim.org/v1.3/sensor/JSim.pdf>, 2005.
- [47] L. Sydanheimo, M. Keskilammi, M. Kivikoski, "Reliable mobile computing to underground mine", *IEEE International Conference on Communications*, v 2, 2000.
- [48] M. Ndoj, G. Y. Delisle, "Geolocation in underground mines using wireless sensor networks", *Antennas and Propagation Society International Symposium*, IEEE, July, 2005.

[49] K. Srinivasan, M. Ndoh, K. Kaluri, "Advanced wireless networks for underground mine communications", *First International Workshop on Wireless Communications in Underground and Confined Areas (IWWCUCA 2005)*, Canada, NRC 48303, June, 2005.

[50] K. Chung, "A radio communications network for voice and data in underground mines", in *2000 TENCON Proceedings. Intelligent Systems and Technologies for the New Millennium*, IEEE, vol.1, 2000.

[51] M. Ndoh, G. Delisle, R. Le, "A novel approach to propagation prediction in confined and diffracting rough surfaces", *The International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, v 16, n 6, December, p 535-55, 2003.

[52] Y. P. Zhang, Y. Hwang, R. G. Kouyoumjian, "Ray-optical prediction of radio-wave propagation characteristics in tunnel environments - Part 2: Analysis and measurements", *IEEE Transactions on Antennas and Propagation*, v 46, n 9, Sep., 1998.

[53] Y. P. Zhang, G. X. Zheng, J. H. Sheng, "Radio propagation at 900 MHz in underground coal mines", *IEEE Transactions on Antennas and Propagation*, v 49, n 5, May, 2001.

[54] V. Rai, and R. N. Mahapatra, "Lifetime modeling of a sensor network", *Proceedings -Design, Automation and Test in Europe, (DATE '05)*, v I, 2005.

[55] J. Zhu, and S. Papavassiliou, "On the energy-efficient organization and the lifetime of multi-hop sensor networks", *IEEE Communications Letters*, v 7, n 11, Nov. 2003.

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